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TWO-DIMENSIONAL VIDEO ANALYSIS IN SWIMMING:
A TOOL FOR SCIENTIFIC PURPOSES AND COACHING PRACTICES

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SUMMARY

INTRODUCTION

The motion analysis systems allow the quantitative study of the human movement permitting, for example, to measure the angle between two body segments, the position of the center of mass, the distribution of the forces in the limbs and many others parameters.

In the last years of the XIX century, Muybridge studied the human and animal’s movements by a sequence of pictures.

The medical science was the first field of application for the motion analysis, that was used in order to study the pathophysiology of the skeletal-muscle system; currently the motion analysis systems are employed in many fields and ergonomics is one of these.

The motion analysis systems are used to design tools and instruments respecting the biomechanical principles; it is also employed in the production of videogames and digital animations.

One of the most important and interesting field of application of motion analysis systems are the sport sciences.

Many data can be obtained by the motion analysis.

- Kinematic data, related to body movements and for which motion capture systems are used.
- Dynamic data, such as angular forces and moments that are measured by force platforms and sensors of various types.
- Electromyographic data, electrical signals coming from the muscles that are detected by means of surface or needle electrodes.

In this dissertation I will focus mainly on motion capture systems that allow to obtain kinematics data. These data are very important for motion analysis and from them it is possible also to estimate some dynamic magnitudes (Borghese, 2007).

MOTION CAPTURE SYSTEMS

Motion capture systems are divided into two major categories: optical and non-optical systems; the most accurate and widespread systems, but also the most expensive ones, are the passive markers optical systems.

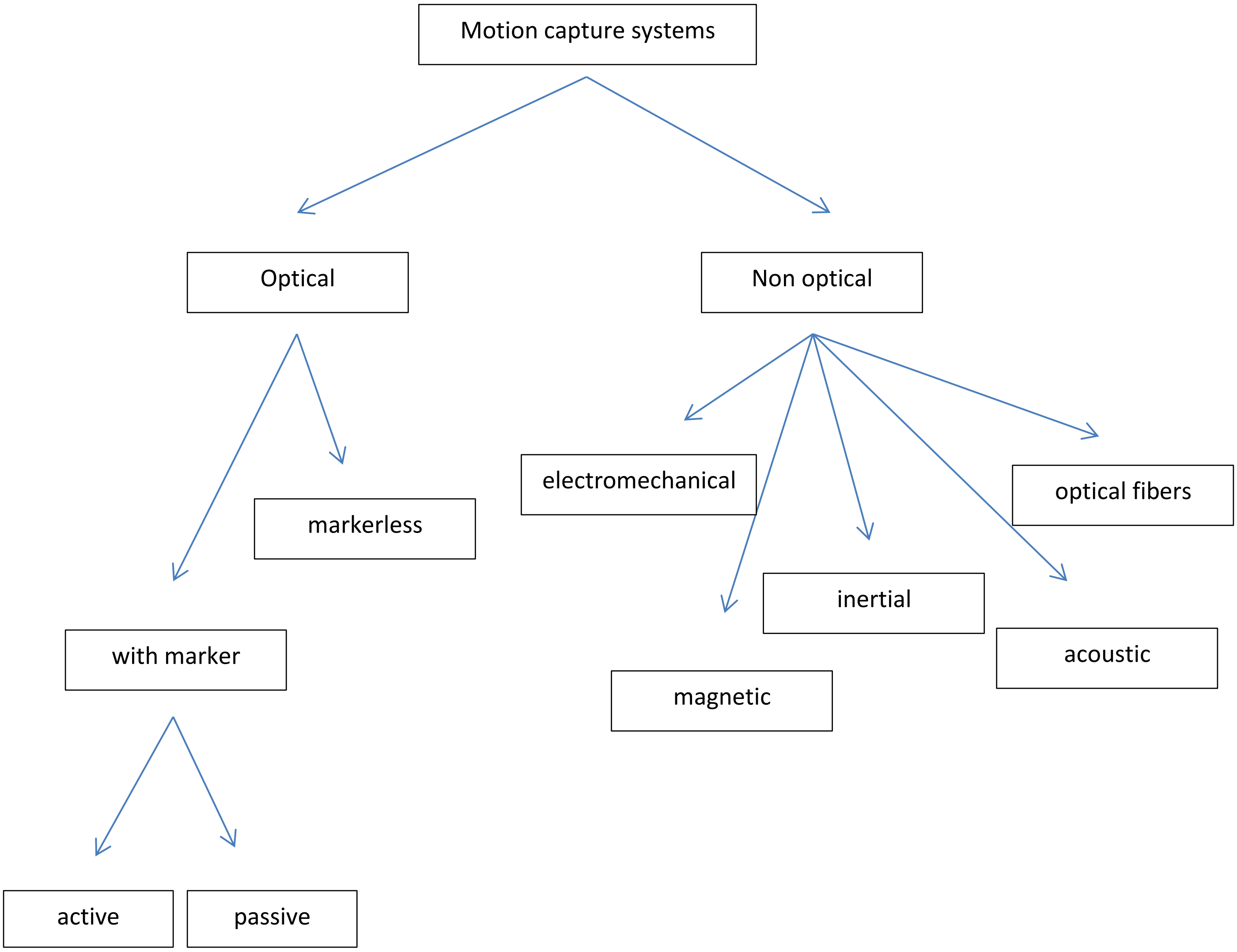


Fig.1 Flow chart representing the motion capture systems (Borghese, 2007).

Here will be illustrated the various approaches to building motion capture systems, describing the principles of operation and the main advantages and limitations. Particular attention will be given to the description of the optical systems.

Electromechanical systems: electro-goniometers

The simplest mechanical systems for motion analysis are electro-goniometers; they measure the angle between two body segments. At one time it was necessary to connect the electro-goniometer to the capture system via wires; currently no connections are necessary, thanks to the development of the wireless technology.

A motion capture system can be built by integrating several electro-goniometers.

- ADVANTAGES: cheap, easy to use;

- DISADVANTAGES: low accuracy, the sensors could hinder the movement and they can only provide angular measures (no position of the body segments or tridimensional orientation).

- APPLICATIONS: study of the movement of specific body's sections.

Inertial systems: accelerometers and gyroscope

Micro-accelerometers are small sensors that measure the accelerations. Starting with accelerations and a model describing the position of the accelerometers on the subject it is possible to calculate the position and the orientation of the various body segments. They are often coupled with gyroscopes: these sensors are able to measure angular accelerations. By integrating micro accelerometers, gyroscopes and a human body model, it is possible to build a motion capture system.

- ADVANTAGES: cheap, not bulky, do not suffer from occlusion;

- DISADVANTAGES: accuracy is limited, decreases further for long acquisitions.

- APPLICATIONS: low quality digital animation (videogames), research.

Magnetic systems

The intensity and orientation of a magnetic field can be measured using the appropriate sensors.

It is possible to generate a magnetic field of known orientation and intensity using the appropriate generators.

It is therefore possible to calculate the position and orientation of a sensor with respect to a magnetic field generator.

By rigidly positioning a magnetic sensor on a body segment, the position and orientation of the body segment with respect to the field generator can be calculated.

By integrating a magnetic field generator and magnetic sensors it is possible to build a motion capture system.

- ADVANTAGES: it does not suffer from the occlusion problem.

- DISADVANTAGES: expensive, poor portability (the magnetic field generator must be kept in the lab), the accuracy depends on the distance from the generator.

- APPLICATIONS: study of the movement that can’t be analyzed with optical systems, digital animation (small scale).

Optical fibers systems

Optical fibers technology has been recently employed for the building of motion capture systems.

It is, indeed, possible to build tubular sensors and measure the position of its initial and terminal parts.

A motion capture system can be realized integrating different tubular sensors.

- ADVANTAGES: it does not suffer from the occlusion problem, high portability (it can be used out of the laboratory);

- DISADVANTAGES: bulky tubular sensors, limited accuracy;

- APPLICATIONS: low quality digital animation (videogames), teaching.

Ibrid system

By integrating different technologies, it is possible to build flexible, discreetly accurate and economical motion capture systems.

Integrating a portable magnetic field generator, magnetic sensors, accelerometers and gyroscopes a motion capture system can be realized.

However, from a technological point of view, the integration of different approaches is problematic.

•ADVANTAGES: it does not suffer from the occlusion problem, discreet accuracy for the dislocation of the body segments, portability.

• DISADVANTAGES: integration of different technologies, poor accuracy on absolute position of the body.

• APPLICATIONS: digital animation, real time animation.

Acoustic system

Some researchers have suggested using ultrasonic generators, coupled with special sensors, to measure human motion.

Some important applications have already been developed in the medical field, such as ultrasound 4D (moving 3D ultrasound).

However, with regard to applications related to the world of classic motion capture, these systems are still at a state of embryonic development.

Optical system

Optical systems use photo / video cameras for the study of the human movement.

Already in the late nineteenth century, Muybridge studied human and animal movement using series of photographs.

An optical motion capture system consists of a set of cameras that film the scene where the subject moves; cameras are often calibrated, fixed.

The movement of the subject is calculated by processing the data (images) captured by the cameras.

Markerless optical system

Some of the optical systems automatically recognize the different body segments in the captured images and then calculate their position and orientation in three-dimensional space.

Other systems recognize the entire figure of the subject acquired by the cameras and calculate the volume occupied by the subject in the space.

Since data processing is very expensive and limited accuracy, these systems are still being studied, but they are the future of motion capture.

Passive markers optical system

A passive marker optical motion capture system consists of: a set of at least two cameras, flash for scene lighting, a set of spherical markers covered by reflective material attached to the subject, a computer receiving images from cameras, extracts marker marks from the images and rebuilds the three-dimensional positions.

With the combined use of flash and reflective markers, it is possible to generate high contrast images where markers are easy to identify.

The flashing light is reflected by the marker. In the captured image, reflective markers are very bright (so easily identifiable) while the rest of the image is dark.

Each video-camera is described by a simple mathematical model.

The acquired image is a two-dimensional projection of a three-dimensional scene; virtually all light rays pass from the lens's center before coming to the camera sensor.

It is possible to calculate the three-dimensional position of a marker seen by at least two cameras; this procedure is called triangulation.

To reconstruct a marker's three-dimensional position, the position and orientation of each camera must be known.

These and other parameters that describe the projection process on each camera, indispensable for three-dimensional reconstruction, are calculated in the calibration phase of the system.

The optical motion capture system reconstructs the three-dimensional position of the markers at any given time. In the tracking phase, three-dimensional points are grouped to reconstruct the trajectories of each marker. Finally, a model is applied which assigns a specific anatomical meaning to each trajectory.

ADVANTAGES: High accuracy, markers do not obstruct movements.

DISADVANTAGES: Expensive, markers may be obstructed to the view of cameras.

APPLICATIONS: study of movement (medicine, sports), digital animation (film).

Active markers optical system

Active marker systems are similar to passive markers, but markers are constituted, for example, by colored LEDs. Since each marker can have a different color, or can be switched on or off at different times, the tracking phase of the data is simplified.

Other tools for analysis

For a complete analysis of the human movement, it is also necessary to study the forces that the human body exchanges with the ground; for this purpose it can be used force platforms.

It is also important to understand where the forces are generated, which muscles activate for generation of the movement. For this purpose, suitable electrodes can be used on the skin of the subject (electromiography).

Multifactorial analysis

Complete motion analysis is obtained by integrating the kinematic data (coming from a motion capture system) with dynamic and electromyographic data; we speak in this case of multifactorial analysis.

THE VIDEO ANALYSIS IN THE SPORT

In literature there are many studies in which video analysis is applied to analyze kinetic, kinematical and biomechanical data of many sports.

The video analysis can be performed both with 2D technology and in the context of the 3D motion analysis; in the following two paragraphs this topic will be debated, referring to the studies of Bartlett (2007) and De Froda (2016).

2D video analysis and 3D motion analysis

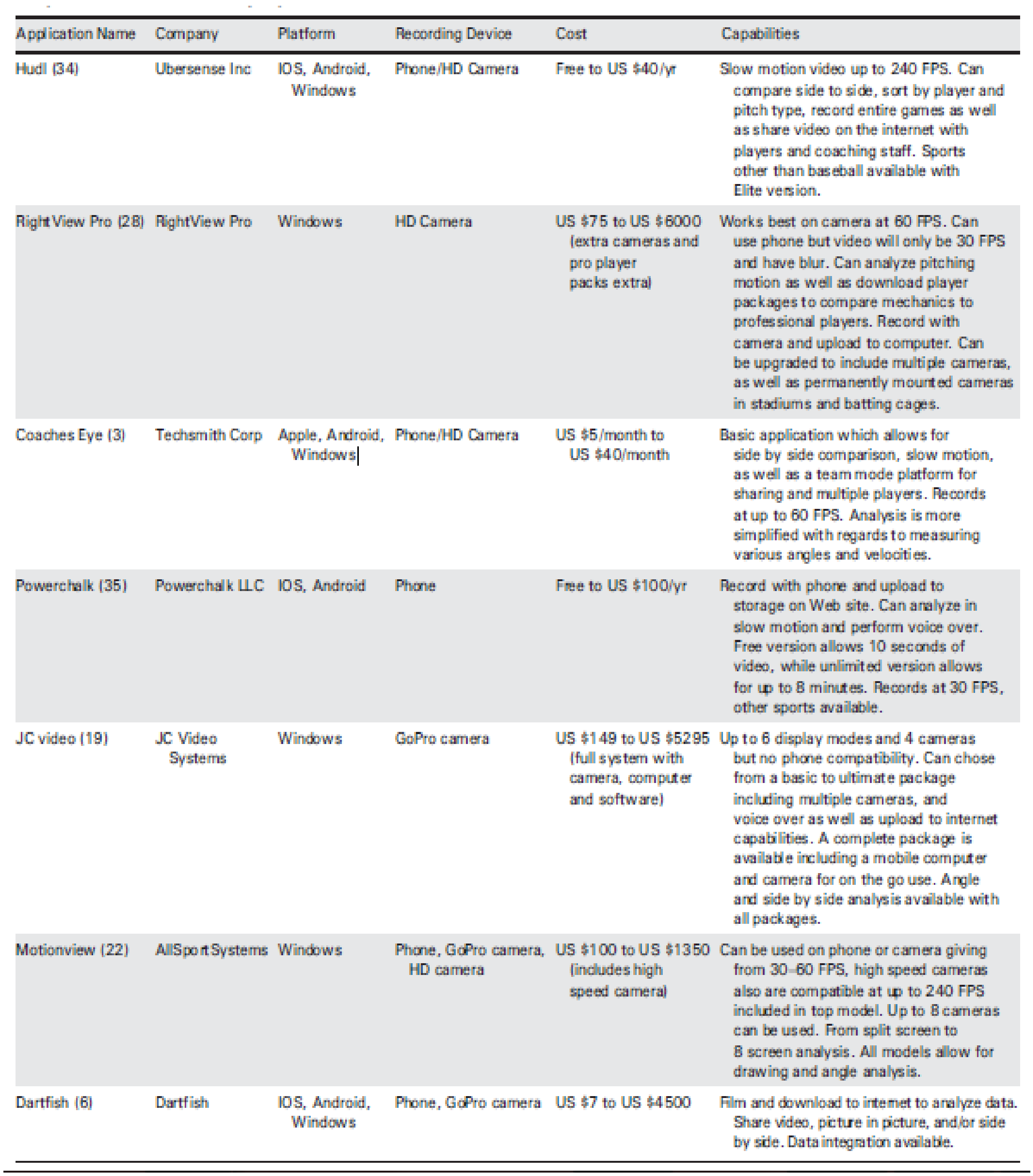
Video analysis can be performed either with 2D or with 3D technology

The human eye is capable of processing images at a rate of only 32 frames per second (FPS), assessment of sport actions without high-speed motion analysis is an imprecise exercise which evaluates the entire sequence of events inefficiently.

2D video analysis is relatively inexpensive and appears to provide an effective means for coaches, athletes and sports medicine providers to record and analyze the human movement (De Froda et al., 2016). Thanks to the popularity and accessibility to high-quality video cameras and smart phones, the number of platforms available for filming and analyzing the movements ranging from very basic to more complex has increased (Table 1). There are basic free applications which can be installed on a smart phone and allow users to record video and compare multiple videos side by side. These applications allow also for frame-by-frame review but lack the resolution of high-end motion analysis. Most phone cameras record at 30 frames per second (FPS), whereas some action video cameras can record 240 FPS in high-definition resolution. More complex phone and camcorder applications allow the video to be uploaded to Internet-based software programs, which vary in the level of analysis. Software programs offer the ability to sync with up to eight cameras depending on the package purchased, and even include high-speed cameras and computers to analyze the data (Table 1). Joint angles, distances and biomechanical timing are all measurements that can be evaluated using 2D video analysis.

3D motion analysis is traditionally performed in an indoor laboratory setting with data captured using a motion analysis system (MAS), which includes 1) multiple, high-speed, light-sensitive cameras with frame rates ranging from 200 to 1000 FPS; 2) reflective markers placed over bony prominences on the bare skin of a subject, which are automatically tracked by the MAS; 3) real-time 3D digitizing which is required for quantitative analysis; and 4) force plates built into the floor or simulated mound.

3D movement-space coordinates are reconstructed from the video images (Bartlett et al., 2007). Kinematic and kinetic data are generated from 3D motion analysis. Historically, 3D motion analysis has been available to elite athletes or those undergoing complex biomechanical studies or for an expensive fee.



Application Name	Company	Platform	Recording Device	Cost	Capabilities
Hudl (34)	Ubersense Inc	IOS, Android, Windows	Phone/HD Camera	Free to US $40/yr	Slow motion video up to 240 FPS. Can compare side to side, sort by player and pitch type, record entire games as well as share video on the internet with players and coaching staff. Sports other than baseball available with Elite version.
RightView Pro (28)	RightView Pro	Windows	HD Camera	US $75 to US $6000 (extra cameras and pro player packs extra)	Works best on camera at 60 FPS. Can use phone but video will only be 30 FPS and have blur. Can analyze pitching motion as well as download player packages to compare mechanics to professional players. Record with camera and upload to computer. Can be upgraded to include multiple cameras, as well as permanently mounted cameras in stadiums and batting cages.
Coaches Eye (3)	Techsmith Corp	Apple, Android, Windows	Phone/HD Camera	US $5/month to US $40/month	Basic application which allows for side by side comparison, slow motion, as well as a team mode platform for sharing and multiple players. Records at up to 60 FPS. Analysis is more simplified with regards to measuring various angles and velocities.
Powerchalk (35)	Powerchalk LLC	IOS, Android	Phone	Free to US $100/yr	Record with phone and upload to storage on Web site. Can analyze in slow motion and perform voice over. Free version allows 10 seconds of video, while unlimited version allows for up to 8 minutes. Records at 30 FPS, other sports available.
JC video (19)	JC Video Systems	Windows	GoPro camera	US $149 to US $5295 (full system with camera, computer and software)	Up to 6 display modes and 4 cameras but no phone compatibility. Can chose from a basic to ultimate package including multiple cameras, and voice over as well as upload to internet capabilities. A complete package is available including a mobile computer and camera for on the go use. Angle and side by side analysis is available with all packages.
Motionview (22)	AllSport Systems	Windows	Phone, GoPro camera, HD camera	US $100 to US $1350 (includes high speed camera)	Can be used on phone or camera giving from 30–60 FPS, high speed cameras also are compatible at up to 240 FPS included in top model. Up to 8 cameras can be used. From split screen to 8 screen analysis. All models allow for drawing and angle analysis.
Dartfish (6)	Dartfish	IOS, Android, Windows	Phone, GoPro camera	US $7 to US $4500	Film and download to internet to analyze data. Share video, picture in picture, and/or side by side. Data integration available.

Tab.1 Comparison of different video analysis platforms (image from De Froda et al., 2016).

2D video versus 3D motion analysis: pros and cons

2D video analysis is an attractive alternative to 3D motion analysis for many reasons. 2D video analysis is simpler and cheaper, requiring fewer cameras, hardware, and software to record and analyze sports movements. Setup time is minimal, and acceptable results are achieved for planar movements that are typically preselected (Bartlett et al., 2007). Conceptually, 2D video analysis is easier for athletes and coaches to comprehend. Limitations of 2D video analysis include 1) the relative subjectivity of kinematic measurements, such as angles, distances, etc., which are calculated by eye/hand rather than using reflective markers placed on the athlete's body; 2) inferior image resolution and sampling (i.e., frame) rates of video cameras, which further reduces accuracy of kinematic measurements during movement analysis; 3) most digital video cameras cannot be ‘‘genlocked’’ to allow the shutter openings to be synchronized when using more than one camera to record movement, as in 3D motion analysis. While some action video cameras (e.g., GoPro series) allow multiple cameras to be synchronized with a single remote control, without genlock capability, cameras can take pictures up to half of a field (or 0.01 s) apart. Genlocking is feasible with action video cameras, but often requires purchasing of third-party hardware (e.g., MewProi) to synchronize multiple cameras. 3D motion analysis has the advantage of capturing the body's true 3D movements, with minimal distortion due to superior image resolution and high sampling rates. Angles between body segments can be calculated accurately due to multiple camera views. Limitations include expense, time, and resource-intensive requirements, including a laboratory setting and an onsite biomechanist to assist with analysis performance and interpretation. Although the computational complexity of 3D motion analysis allows reconstruction of movement and time synchronization of data, the statistical reports generated from analysis can be difficult for the layperson to understand and for biomechanists to translate into practical information that athletes and coaches can use to enhance performance (De Froda et al., 2016).

VIDEO ANALYSIS IN SWIMMING

A review of the literature into the application of video analysis for swimming was conducted; article selection was based on a systematic search for publications on PubMed database.

The keyword string used for the search was “(swimming OR front crawl OR freestyle OR backstroke OR back crawl OR breaststroke OR butterfly) AND (video analysis OR video recorder)”.

The inclusion criteria were that the publication: (I) was written in English; (II) was related to the analysis of human swimming.

Exclusion criteria included: (I) animal studies and (II) publications not directly related to the topics of the search.

The initial search yielded 477 results, than the human filter was applied and the final number of publications was 152.

The title and the abstract of each publication was reviewed and evaluated based on the relevance to the review topic; for the most relevant articles, full text was read in order to know in detail the video analysis methodology applied.

From the review emerged that both 2D video analysis and 3D motion analysis are applied in swimming; video analysis is used in many fields such as performance analysis, biomechanical, kinetic and kinematical analysis of specific gesture, motor organization related to swim energy cost, trajectory study.

Energy cost

Some studies applied video analysis systems to investigate swimming’s energy cost.

Seifert et al., in 2010, published a work about the effects of swim specialty on the energy cost and motor organization; the authors compared sprinter and endurance swimmers on energy cost and stroking parameters during an incremental exercise test (Seifert et al., 2010).

Results showed that for the same relative intensity, sprinters accumulated more lactate and swam more slowly than long-distance swimmers; they showed greater change in their arm coordination but their swimming economy was lower.

To analyze motor organization, aerial and underwater side-view cameras (Panasonic NV-GS17, 50 Hz) were superposed and fixed on the right side of the pool. A video timer was included in the underwater view; this view was then synchronized and genlocked to the aerial view with Adobe Premiere. A calibration frame of 5 m in the horizontal axis and 2 m in the vertical axis was positioned on the floor of the pool, orthogonally to the external side-view camera, for measuring time over a 5-m distance to obtain the swim speed. When the front of the swimmer's head reached the edge of the frame and left the second edge of the frame, time was recorded.

The same video setting was employed by Komar et al. (2012); they analyzed the changes in stroke parameters, motor organization and swimming efficiency with increasing energy cost in aquatic locomotion. Seven elite sprint swimmers performed a 6 x 300-m incremental swimming test.

Stroke parameters (speed, stroke rate and stroke length), motor organization (arm stroke phases and arm coordination index), swimming efficiency (swimming speed squared and hand speed squared) and stroke index were calculated from aerial and underwater side-view cameras. The energy cost of locomotion was assessed by measuring oxygen consumption and blood lactate.

Results showed that the increase in energy cost of locomotion was correlated to an increase in the index of coordination and stroke rate, and a decrease in stroke length. Furthermore, indicators of swimming efficiency and stroke index did not change significantly with the speed increments, indicating that swimmers did not decrease their efficiency despite the increase in energy cost. In parallel, an increase in the index of coordination and stroke rate were observed, along with a decrease in stroke length, stroke index and hand speed squared with each increment, revealing an adaptation to the fatigue within the 300 m.

Inter-limb coordination

Chollet is one of the most important author who employed video analysis to study inter limb coordination and the factors that may affect it.

In 1999 he analyzed stroke phases and arm and leg coordination during front crawl swimming as a function of swim velocity and performance level (Chollet et al., 1999). Forty-three swimmers constituted three groups based on performance level. All swam at three different swim velocities, corresponding to the paces appropriate for the 800 m, 100 m, and 50 m. The different stroke phases and the arm and leg coordination were analyzed underwater with two video cameras (S. VHS Panasonic) set at a rapid shutter speed (1/1000 of a second); 50 pictures per second were recorded.

One camera filmed the swimmer from a frontal view, while the other in profile.

Cameras were connected to a double-entry audiovisual mixer, a chronometer, a monitoring screen and a video recorder that recorded the mixed picture (camera 1, in the upper half of the screen and camera 2 in the lower half, with a chronometer). A third independent camera filmed all trials of each swimmer in a side view, from above the pool. This camera allowed to quantify the swim velocity and stroke rate, from which stroke length was calculated.

Arm coordination was quantified using an index of coordination (IdC), which expresses the three major modalities: opposition, catch-up and superposition. Opposition, where one arm begins the pull phase when the other is finishing the push phase; catch up, which has a lag time (LT) between propulsive phases of the two arms; and superposition, which describes an overlap in the propulsive phases. The IdC is an index which characterizes coordination patterns by measure of LT between propulsive phases of each arm. The most important results showed that duration of the propulsive phases (B + C) increased significantly with increasing velocity. The arm and leg synchronization was modified in the sense of an increase in six-beat kick. The IdC increased significantly with velocity and with performance level.

In the wake of this Chollet’s work, other studies were conducted using the video analysis to investigate inter-limb coordination.

In 2005 Seifert analyzed the relationships among arm coordination symmetry, motor laterality and breathing laterality during a 100-m front crawl, as a function of expertise (Seifert et al., 2005). Ten elite swimmers (G1), 10 mid-level swimmers (G2), and 8 non-expert swimmers (G3) composed three skill groups, which were distinguished by velocity, stroke rate, stroke length, breathing frequency (BF) and the mean number of strokes between two breaths – the stroke breath (SB) – over a 100-m front crawl.

Two underwater video cameras (Sony compact FCB-EX10L) with rapid shutter speed (1/1000 s) were used at 50 Hz. Each camera was fixed on a trolley which ran along the side of the pool to ensure filming of the swimmers. One camera filmed the swimmer from a right-side view, the other from a left-side view. The trolleys were pulled by operators at the same velocity as the swimmers, with each subject’s head being the mark followed by the operators to control parallax. The cameras were connected to a double-entry audio–visual mixer, a video recorder and a monitoring screen to mix the right and left lateral views on the same screen, in accordance with the protocol of Chollet et al. (1999). A video timer was incrusted in the mixer to synchronize these two views.

A third camera, mixed with the right-side view for time synchronization, filmed the 100-m of each swimmer in profile from above the pool. This aerial view enabled us to have the entire length of the pool on the video screen. Four bollards delimited the five 5-m zones constituting each 25-m length. The swimmer’s head delimited the entry and exit of the middle 15-m of each length, which was used to calculate the velocity (m*s^{-1}). The mean stroke rate (stroke*min^{-1}) was calculated from the underwater videos for 6–10 strokes of the middle 15-m swim zone. The calculation of the mean stroke length (m stroke^{-1}) was based on these values of velocity and mean stroke rate (stroke length = 60*velocity/stroke rate).

Four stroke phases were identified by video analysis (catch, pull, push and recovery) and the index of coordination (IdC) measured the lag time between the propulsive phases of the two arms. The three modes of coordination are catch-up (IdC < 0%), opposition (IdC = 0%) and superposition (IdC > 0%). The IdC was established as the mean of IdC1 and IdC2, which measured the lag time between the propulsive phases of the left and right arms, respectively. The coordination symmetry was analyzed by comparing IdC1 and IdC2, and the breathing effect was studied by distinguishing IdC1 (and IdC2) with and without breathing.

Motor laterality was determined by an adaptation of the Edinburgh Handedness Inventory.

Breathing laterality was determined by a questionnaire and observation during the 100-m trial.

Most of the front crawl swimmers showed asymmetric arm coordination, with propulsive discontinuity on one side and propulsive superposition on the other. This asymmetry was most often related to breathing laterality (a preferential breathing side for a unilateral breathing pattern) and motor laterality (arm dominance), with different profiles noted. More than the breathing laterality itself, the breathing actions of the non-expert swimmers amplified their asymmetric coordination on the breathing side. Conversely, the elite swimmers, who had higher and more stable spatial–temporal parameters (velocity and stroke lengths), a high coordination value (IdC) and lower breathing frequency (BF), managed their race better than the less proficient swimmers and their asymmetric arm coordination was not disturbed by breathing actions. By determining the dominant arm and the preferential breathing side, the coach can obtain a swimmer profile that allows both coach and swimmer to better understand and respond to excessive coordination asymmetry.

Seifert used the same video analysis setting in many other studies related to inter limb coordination; in 2005 he published a paper aimed to analyze the spatial temporal and coordinative structures in 12 elite male 100m front crawl swimmers (Seifert et al., 2005).
In 2007 he carried out a study to identify the constraints (organismic, environmental and task) on front crawl performance, focusing on arm coordination adaptations over increasing race paces (Seifert et al., 2007).
The same year a work on butterfly arm-to-leg coordination was published; the study compared the arm-to-leg coordination in the butterfly stroke of three groups of male swimmers of varying skill (10 elite, 10 non elite and 10 young swimmers) at four race paces (400 m, 200 m, 100 m, 50 m) (Seifert et al., 2007).
In this work the video analysis setting was different and more elaborate than the previous cited studies; an aerial lateral video camera was superimposed on an underwater lateral video camera (Sony Compact FCV-EX10L, Paris, France) with a rapid shutter speed (1/1000s) and a sampling rate of 50Hz. Both cameras were fixed on a trolley, pulled along the side of the pool by an operator who followed the swimmer. The cameras were connected to a four-entry audio-visual mixer, a video timer, a video recorder and a monitoring screen to mix the lateral underwater and aerial views on the same screen. A third camera (fixed on the wall, 50Hz, Sony Compact FCV-EX10L, Paris, France) filmed the swimmer from a frontal underwater view and was mixed and genlocked by the audio-visual mixer with the underwater lateral view on another screen. A fourth camera (50Hz, Sony Compact FCV-EX10L, Paris, France), mixed with the lateral underwater view for time synchronization filmed all the trials of each swimmer with a profile view from above the pool.

In 2009 Seifert published a paper that modelled the changes in spatial–temporal and coordinative parameters through race paces in the four swimming strokes (Seifert et al., 2009). The arm and leg phases in simultaneous strokes (butterfly and breaststroke) and the inter-arm phases in alternating strokes (crawl and backstroke) were identified by video analysis to calculate the time gaps between propulsive phases. The relationships among velocity, stroke rate, stroke length and coordination were modelled by polynomial regression. Twelve elite male swimmers swam at four race paces.

Quadratic regression modelled the changes in spatial–temporal and coordinative parameters with velocity increases for all four strokes. First, the quadratic regression between coordination and velocity showed changes common to all four strokes. Notably, the time gaps between the key points defining the beginning and end of the stroke phases decreased with increases in velocity, which led to decreases in glide times and increases in the continuity between propulsive phases. Conjointly, the quadratic regression among stroke rate, stroke length and velocity was similar to the changes in coordination, suggesting that these parameters may influence coordination. The main practical application for coaches and scientists is that ineffective time gaps can be distinguished from those that simply reflect an individual swimmer’s profile by monitoring the glide times within a stroke cycle. In the case of ineffective time gaps, targeted training could improve the swimmer’s management of glide time.

In 2010 Seifert published an article aimed to quantify the effects of breathing compared to non-breathing and "race pace" on arm to leg coordination in the butterfly stroke (Seifert et al., 2010). Twelve elite male swimmers swam at four paces: 400 m, 200 m, 100 m and 50 m. The arm and leg stroke phases were identified by video analysis to calculate the total time gap (TTG), which is the sum of T1 (hands' entry in the water/high point of first kick), T2 (beginning of the hands' backward movement/low point of first kick), T3 (hands' arrival in a vertical plane to the shoulders/high point of second kick) and T4 (hands' release from the water/low point of second kick). Two strokes with breathing were compared to two strokes with breath-holding. The TTG was greater with breathing (23.3% VS. 19%), showing less propulsive continuity between arm and leg actions ($p<0.05$). This was due to the shorter downward leg kick and longer arm catch and upward leg kick that led to longer glide time. Conversely, breathing leads to greater coupling between the hand exit and the end of leg propulsion, which was due to a shorter arm push phase to facilitate the head exit to breathe.

Other authors employed video analysis systems to study inter limb coordination.
Applying the above mentioned 4 cameras system, Schnitzler et al. (Schnitzler et al., 2008) investigated the link between modifications in arm coordination (IdC) and intracyclic velocity variation (IVV) as a function of swim pace and gender.
Twelve elite swimmers performed 5 different swim paces. Video analysis allowed IdC determination. The IVV was determined with a velocity-metre system. Results showed a

significant increase in IdC with swim pace ($p < 0.05$) but no significant change in IVV, and a gender effect for the mean values of both IdC and IVV ($p < 0.05$). This suggests that the increase in IdC with swimming velocity helps to maintain IVV stability, and the mean IdC and the IVV level are determined by the relationship between anthropometric parameters and mechanical power output. Indeed, compared to males, the females generally had a lower mechanical power output, and lower drag to overcome, which explains the lower IVV found. It was concluded that increasing IdC could be a strategy adopted by elite swimmers to maintain IVV at a constant level, despite increases in both propulsive and drag forces and in relation to individual characteristics. Thus, the IVV-IdC relationship may be an interesting tool to determine a swimmer's misadaptation to the swim pace and to orient individual coaching in coordination analysis.

Another study explored the functional role of inter-individual variability in inter-limb coordination (Bideault et al., 2013).

Sixty-three front crawl swimmers with a range of characteristics (gender, performance level, specialty) performed seven intermittent graded speed bouts of 25m in front crawl.

Speed, stroke rate, stroke length and index of arm coordination (IdC) were analysed for three cycles. Cluster analysis was used to classify the swimmers through speed and IdC values.

The swimmers were video-taped by two underwater video cameras (Sony compact FCB-EX10L, f = 50 Hz), with one camera placed to obtain a frontal view and the other to obtain a side view. The frontal underwater camera was fixed on the edge of the pool, 0.4m below the water. The side underwater camera was fixed on a trolley and an operator followed the swimmer’s head to avoid parallax.

Both cameras were connected to a timer, a video recorder and a screen to mix and genlock the frontal and side views on the same screen. A third camera mixed with the side view for time synchronization video-taped all trials with a profile view from above the water.

Cluster analysis and validation showed four profiles of IdC management expressing the swimmers’ characteristics as cluster 1: mainly national distance male swimmers, cluster 2: mainly international male sprinters, cluster 3: distinguished by female characteristics, and cluster 4: swimmers with the lowest level of performance.

These profiles generated different IdC-speed regression models, which showed how the swimmers adapted their motor behaviour to overcome task constraints and supported the key idea that there is not a single ideal expert model to be imitated, but rather adapted behaviour emerging from individually encountered constraints.

Race analysis

The race analysis is one of the application fields of video analysis in swimming and many researchers focused their attention on this topic.

Veiga et al., for example, carried out a study aimed to develop a new application based on the "individual distances" method to analyze swimming races, and to compare it with the traditional "fixed distances" method (Veiga et al., 2013). One hundred and seventy-nine national level 100 m (four strokes) performances obtained from the 2008 "Open Comunidad de Madrid" (Spain) were analyzed using a two-dimensional Direct Linear Transformation (2D-DLT) video analysis system.

The video analysis setting was made by three fixed video-cameras recording at 25 Hz. They were positioned at the stands, 7 m above and 7 m away from the side of the pool. Each camera captured a specific segment of the race: start (0-15 m), free swimming (20-30 m), turn (35-50 m) segments.

Average velocities in all race segments ($P < 0.001$) were faster using the "individual distances" method than when employing the "fixed distances" method. Specifically, start and turn times were shorter ($P < 0.001$) while free swimming times were longer ($P < 0.001$) when using the "individual distances" method. Correlations between methods were moderate to high, but several gender and stroke groups showed poor to no correlation, especially during the start and turn segments. Differences between methods were higher in some groups (female swimmers and freestyle stroke) where the start and turn distances were shorter. Measurements with the 2D-DLT technique provide distances and times employed during the race segments, which do not completely agree with times at fixed distances. Therefore, when evaluating swimming races, a combination of the individual and fixed distances methods should be used.

A recent study focused on the relation between time-trial and competition performance (Tor et al., 2014).

Time trials are commonly used in the lead-up to competition. A method that evaluates the relationship between time trial and competition performance in swimming would be useful for developing performance-enhancement strategies.

The aim of Tor’s study was to use linear mixed modeling to identify key parameters that can be used to relate time-trial and competition performance.

Ten swimmers participated in the study. Each swimmer was analyzed during 3 time trials and 1 competition.

Race video footage was analyzed to determine several key parameters. Pooling of strokes and distances was achieved by modeling changes in parameters between time trials and competition within each subject as linear predictors of percent change in performance using mixed modeling of log-transformed race times.

A single camera analysis system was used to collect swimming race analysis data during each of the four trials. A camera, sampling at 50 Hz, was positioned at the 25 m mark of a 50 m pool during time trial and competition sessions. At the completion of each race the proprietary software GreenEye (Sidney, Australia) was used to analyze each of the race and generate a report for coaches and athletes.

Results showed that when parameters were evaluated as the effect of 2 SD on performance time, there were very large effects of start time (2.6%, 90% confidence interval 1.8-3.3%) and average velocity (-2.3%, -2.8% to -1.8%). There was also a small effect for stroke rate (-0.6%, -1.3% to 0.2%). Further analysis revealed an improvement in performance time of 2.4% between time trials and competition, of which 1.8% (large; 1.4-2.1%) was due to a change in average velocity and 0.9% (moderate; 0.6-1.1%) was due to a change in start time; changes in remaining parameters had trivial effects on performance.

This study illustrates effective analytical strategies for identifying key parameters that can be the focus of training to improve performance in small squads of elite swimmers and other athletes.

Kinematical analysis

One of the most important application‘s field of video analysis in swimming is the study of kinematical variables.

In 2015 Barbosa et al. analyzed if there were changes in swimming kinematics and inter-limb coordination behavior in 3 variants, with different step lengths, of an intermittent incremental protocol (Barbosa et al., 2015). Twenty-two male swimmers performed n+d[i] variants of an intermittent and incremental protocol ($n \leq 7$; d1 = 200 m, d2 = 300 m and d3 = 400 m).

Swimmers were videotaped in the sagittal plane for 2D kinematical analysis using a dual-media set-up. Video images were digitized with a motion capture system.

Parameters which were assessed included the stroke kinematics, the segmental and anatomical landmark kinematics, and inter-limb coordination. Movement efficiency was also estimated.

The dual-media set-up for 2D-kinematical analysis was composed by two cameras (Sony, DCR-HC42E, Nagoya, Japan) operating at a sampling frequency of 50 Hz, with 1/250 of digital shutter speed, fixed on a specially designed support for video imaging recording.

This support was placed at the lateral pool wall, 12.5 m from the head wall, with one camera placed 30 cm above the water surface and the other kept underwater in a waterproof housing (Sony SPK-HCB box) at a depth of 0.30 m, exactly below the surface camera (both placed at 7 m from the plane of movement). The images of both cameras were recorded independently, and swimmers were monitored when passing through a specific pre-calibrated space using a calibration frame (6.3 m^2). Each camera recorded a space of 4.5 m long for the x axis, and participants wear specific anatomical markers on upper limbs and trunk. It was used the anthropometric model from Zatsiorsky and Seluyanov (Zatsiorsky and Seluyanov, 1983) adapted by de Leva (de Leva et al., 1996), including nine anatomical landmarks from the upper body (acromion, lateral humeral epycondile, ulnar styloid process, third distal phalanx and prominence of great femoral trochanter). Synchronization of the images was obtained using a pair of LEDs, fixed to the calibration volume, visible in the field of view of each camera. The frame was kept in the same place during all trials. Video images were digitized manually frame-by-frame (f=50 Hz) using a motion capture system (Ariel Performance Analysis System, Ariel Dynamics, USA).

The analysis period comprised one complete stroke cycle in the penultimate lap of each step for each protocol variant (i.e., 175 m, 275 m and 375 m).

Swimmers were instructed to perform non-breathing cycles when passing in the calibrated space since the breathing action imposes changes in the technique turning out to be a potential confounding factor that must be controlled (Seifert et al., 2008). Six calibration points and DLT-algorithm (Abdel-Aziz et al., 1971) were used for 2D-reconstruction.

The results of the study showed that there were no significant variations in any of the selected variables according to the step lengths. A high-very high relationship was observed between step lengths. The bias was much reduced and the 95% CI fairly tight. Since there were no meaningful differences between the 3 protocol variants, the authors suggested that the one with shortest step length (i.e. 200 m) should be adopted due to logistic reasons.

Another study by Seifert et al. analyzed the kinematics and kinetics (jumping ability) of the aerial start phase in 11 elite front crawl sprinters (Seifert et al., 2010). The aim was to determine whether a particular start technique leads to a short 15 m start time or whether several start profiles contribute equally well. The video analysis setting consisted on three aerial video cameras (50Hz, Panasonic NV-MS1 HQ S-VHS, Panasonic, Paris France) with a rapid shutter speed (1/1000 s) connected to an audiovisual mixer, a video timer, a video recorder and a monitoring screen to genlock and mix the three lateral views on the same screen. The first camera was placed at the edge of the pool and videotaped the block phase, enabling to record the take off angles of the body and the total take off angle. The second camera was placed 5 m from the edge of the pool to record the flight phase, the body angles at the hand entry and the total entry angle. The third camera was positioned in front of the 15 m mark, wich was attached on the water line 15 m from the start of the pool, and videotaped the swimmer from the moment when the head broke the surface of the water to the end of the 15 m.

The videotaped of the first and second cameras were digitized with DartFish software (DartFish ProSuite4.0 2005; Switzerland) at a frequency of 50Hz. Four body marks (ankle, hip, shoulder and wrist of the right side) were digitized at take off and hand entry.

All swimmers performed 3 starts using their preferential style, which was the grab start for all, followed by a 25-m swim at maximal velocity. Countermovement jump enabled to determine vertical jumping ability. Using a video device, phase durations, angles at takeoff and entry, and hip velocity were assessed. Correlation between all variables and the 15 m start time established the common features of an effective start but also revealed great inter-subject variability.

Cluster analysis enabled to distinguish 4 start profiles (flat, pike, flight, and Volkov), indicating that several individual profiles lead to short 15 m start times.

In this study the authors concluded that it would be appropriate to consider the variability between subjects in relation to the start time before favoring a unique strategy.

Seifert et al., in 2007, published a study analyzing the kinematic changes during a 100-m front crawl to investigate the effects of performance level and gender, comparing 12 high-speed males, 8 medium-speed males, 8 low-speed males, and 8 high-speed females (Seifert et al., 2007).

Assessments were made throughout the race in a 25-m pool divided into five zones of 5 m. Velocity (V), stroke rate (SR), and stroke length (SL) were calculated for each 25-m length and for each 5-m zone. Four stroke phases were identified by video analysis, and the index of coordination (IdC) was calculated. Three modes of arm coordination were identified: catch-up, opposition, and superposition. The leg kick was also analyzed.

Two underwater video cameras (Sony compact FCB-EX10L) with rapid shutter speed (1/1000 s) were used at 50 Hz. Each camera was fixed on a trolley which ran along the side of the pool to ensure filming of the swimmers both on left and the right side. The trolleys were pulled by an operator at the swimmer's head level, at the same velocity as the swimmers to avoid parallax errors. The cameras were connected to a double-entry audio–visual mixer, a video recorder and a monitoring screen to mix the right and left lateral views on the same screen, in accordance with the protocol of Chollet et al. (1999). A video timer was incrusted in the mixer to synchronize these two views.

A third synchronized camera filmed the 100-m of each swimmer in profile from above the pool. It visualized the entire length of the pool on the video screen and helped in the video analysis of four inter-length comparisons . Four plots delimited the 5, 10, 15 and 20 meters marks on the right and left sides. They delimited five 5-m used for intra-length comparison.

The high-speed male swimmers were distinguished by higher V (1.89 m.s(-1)), SR (0.78 Hz), SL (2.16 m per stroke), propulsive phase (54%) and IdC (3.8%) ($P < 0.05$), and by the stability of these values throughout the race. The medium- and low-speed males had an opposition coordination ($-1\% < IdC < 1\%$) during the third length of the 100 m. Because of fatigue in length 4, they spent more time with the hand in the push phase (possibly because of a decrease in hand velocity) and changed to superposition coordination (medium-speed males: IdC = 2.78%; low-speed males: IdC = 1.12%) ($P < 0.05$). This change was ineffective, however, as SL continued to decrease throughout the 100 m ($P < 0.05$). The main gender findings were the greater SL of the males versus the females (1.81 m per stroke) ($P < 0.05$) and the similar IdC of both high-speed groups (females: 4.4%).

The authors concluded that the high-speed swimmers were characterized by higher and more stable SL and IdC. The principal gender effect was greater SL in the males than in the females.

Pereira et al., in 2015, analyzed the kinematic, kinetic and electromyographic characteristics of four front crawl flip turn technique variants (Pereira et al., 2015). The variants distinguished from each other by differences in body position (i.e., dorsal, lateral, ventral) during rolling, wall support, pushing and gliding phases. Seventeen highly trained swimmers (17.9 ± 3.2 years old) participated in interventional sessions and performed three trials of each variant, being monitored with a 3-D video system, a force platform and an electromyography (EMG) system. Studied variables were: rolling time and distance, wall support time, push-off time, peak force and horizontal impulse at wall support and push-off, center of mass horizontal velocity at the end of the push-off, gliding time, center of mass depth, distance, average and final velocity during gliding, total turn time and electrical activity of Gastrocnemius Medialis, Tibialis Anterior, Biceps Femoris and Vastus Lateralis muscles.

The kinematical variables were study by a 3D video-system made by four underwater and two surface fixed cameras. The surface cameras were fixed on a 3-m high support, one at each lateral wall of the pool, 2.5 m distant from the turning wall. The underwater cameras were fixed on specially designed supports, two of them in each side of the pool, providing right and left views of the turning movement. Eleven high contrast markers were positioned on specific anatomical reference points and image coordinates were transformed to 3D objects-space coordinates using the Direct Linear Transformation Algorithm (Abdel –Aziz and Karara, 1971).

Depending on the variant of the turn technique, total turn time ranged from 2.37 ± 0.32 to 2.43 ± 0.33 s, push-off force from 1.86 ± 0.33 to 1.92 ± 0.26 BW and center of mass velocity during gliding from 1.78 ± 0.21 to 1.94 ± 0.22 $m \cdot s^{-1}$.

The authors concluded that the variants were not distinguishable in terms of kinematical, kinetic and EMG parameters during the rolling, wall support, pushing and gliding phases.

The dissertation on video analysis in swimming is divided into two experimental sections. Part 1 concerns the comparison between two different breathing techniques in the approach phase of the freestyle flip turn in young swimmers. Part 2 focuses on the comparison of two techniques of the breaststroke underwater phase, that differ in the order of execution of technical gestures.

PART 1

VIDEO ANALYSIS OF THE TURN IN YOUNG SWIMMERS

THE FREESTYLE FLIP TURN: DESCRIPTION OF THE MOVEMENT

The swimming turn is the change of direction between two consecutive lengths; there are seven different types of turn, one for each of the four styles and one for each of the three style changes. The turn permits to transfer energy and momentum accumulated during the swim in the shortest possible time.

During freestyle and backstroke races, the flip turn is performed to reverse direction of swimming at the end of the pool.

The flip turn is a forward somersault with a one-eighth twist followed by a push-off from the wall. Swimmers rotate the remaining seven-eighth to a prone position during the drive from the wall and the following glide. For explanatory purposes, the parts of the turn that will be illustrated are: the approach, the turn, the push-off, the glide, the pull-out as described by Costill et al. (1992)

The approach

The swimmer approaching the wall should have sighted the wall several strokes out in order to make modifications in the approach that will allow him to swim into the turn with no loss of speed.

Most swimmers begin that final arm stroke 1.7-2.0 m (5.5-6.5 ft) from the wall (Chow et al., 1984). Sprinters will tend to start the turn sooner because they are traveling into the wall faster. It is very important to maintain race speed as swimmers approach the turn. The majority slow down to anticipate the turn, which costs them precious seconds over the course of race.

The turn

The swimmer has left the opposite arm in the water back at the hip when he began the final arm stroke. He ducks his head underwater and begins to somersault over while completing the second half of the final underwater arm stroke. The action is on of following the hand back and up toward the surface with the head.

The swimmer tucks the legs tight into the stomach and somersaults almost straight over in a tucked position. Notice that he executes a small dolphin kick during the final arm stroke to assist in pushing the hips up.

Once the final arm stroke has been completed, the swimmer leaves both arms back at the hips. When the somersault is half completed, he turns the palms of both hands down and pulls them toward the head to help bring it toward the surface.

The head comes up between the arms as the feet reach the wall so the body is aligned and ready for the push-off at the instant the feet make contact. The hands are also overhead with elbows flexed for the same reason.

The swimmer executes a slight twist to the side as the feet come into the wall so they can be planted with toes facing out and up in to the same direction in which the body is turned. The twist is accomplished by turning the head to the side in the second half of the somersault. Most swimmers will turn the head away from the arm that was used to stroke into the turn.

The speed of the somersault is really controlled by the swimmer’s head movements. As quickly as possible, the swimmers drive the head down, back and then up toward the surface to an aligned position between the arms.

The push-off

When the feet reach the wall, they are planted at a depth of approximately 30-40 cm (12-15 in). The swimmers begin extending the legs immediately when the feet make contact with the wall.

The push-off is executed while the swimmer is on his back (except for the slight rotation to the side, as mentioned earlier). The swimmer rotates toward a prone position while extending the legs so that he is on his side by the time the feet leave the wall. He completes the turn to a prone position during the glide that follows. This rotation in assisted by the movements of the legs. The swimmer comes off the wall with the top leg crossed over the bottom and helps the body rotate to a prone position by uncrossing and bringing the top leg down during the glide.

The drive off the wall should be powerful. The swimmer extends the arm and legs simultaneously to add impetus to the push-off. The push-off should be made horizontally: it should not be angled upward.

The glide

After pushing off, the swimmer glides until he approaches race speed. At that time, the swimmer takes 2-4 flutter kicks and pulls the head up through the surface with the first arm stroke. The glide should be streamlined, with the arms extended overhead and the head down between the arms. The back is straight and the legs and feet are extended and together.

The pull-out

The swimmer begins the pull-out when he feels that one underwater arm stroke will bring the head up through the surface. The arm stroke should be timed so the head breaks through the surface when he is midway through the arm stroke. The swimmer should remain streamlined with the head down until it breaks through the surface. After that, the head can be carried in a normal swimming position.

Costill (1992) suggests that swimmers should not breathe during the arm stroke that carries them into the turn because this can impact on the beginning of the somersault.

The issue of when to take the first breath after the turn is controversial. At present, the most popular technique is to delay that breath at least until the second arm stroke. Swimmers have been taught to take the first stroke out of the turn with the arm that is opposite the breathing side in order to delay breathing until the second stroke is underway. The wisdom behind this technique is that many swimmers delay getting into their race rhythm when they breathe on the first stroke out of the turn.

Delaying the breath out of the turn may be a good technique to use in sprint races.

The turn time represent 1/3 of the total performance time of each length and minimal improvements in the turning performance can therefore significantly influence the results of the race. The improvement of the turn’s variable can affect the others parameters, so when a swimmer tries to improve his turn’s performance, he must take into account the effects produced by all the elements (Hines 1993).

The ability in maintaining the turn’s parameters during a race is also an important factor to maximize the performance.

Veiga et al. (2014) demonstrated that national level swimmers showed the ability to maintain most of the turn’s parameters throughout the race, which assisted them in improving average velocity at the end of races. Therefore, the variations in the turning movements of a swimming race were expertise-related and focused on optimizing average velocity.

Several studies focused on specific parts of the turn technique in order to understand the most important variables that can influence turn performance.

Zamparo et al. (2012) analyzed the glide and the pull-out phases. The authors studied the effects of maximal velocity and acceleration attained during the turn, the deceleration and glide efficiency in the gliding phase after the turn and the efficiency of the dolphin kick in determining the velocity and acceleration in the first 5m and the following 10m after a turn, during a 100m simulated front crawl race. Their results indicate that in the first 5-15m after the turn, velocity is essentially sustained by the force generated by the swimmer on the pool wall and also the authors show the importance of an efficient dolphin kick (and of a streamlined glide) in determining the values of velocity and acceleration in this phase of the race.

Other studies analyzed the wall contact and the push-off phases; Pereira et al. investigated in seventeen swimmers, the kinematic, kinetic and EMG parameters of four front crawl flip turn technique variants. The variants distinguished from each other by differences in body position (i.e., dorsal, lateral, ventral) during rolling, wall support, pushing and gliding phases. The conclusions of the study showed that the variants were not distinguishable in terms of kinematical, kinetic and EMG parameters during the rolling, wall support, pushing and gliding phases (Pereira et al., 2015).

Furthermore, another study analyzed the contact phase during the lateral push-off in the turn of front crawl swimming to determine which biomechanical variables contribute to the performance of this turn technique.

The study concluded that a turn executed with a knee flexion angle of 100°/120° provides optimum peak forces, allowing the swimmer to lose less time in the turn without the need for an excessive force application and with less energy lost (Araujo et al., 2010).

Interesting findings about rotation phase have been highlighted by Puel et al. (2012).

The authors, using a three-dimensional (3D) underwater analysis protocol, identified kinematic and dynamic variables related to the best tumble turn times, in ten elite male swimmers. They evaluated the head-wall distance where rotation starts and they showed that upper body and lower limb extension indexes at first contact were significantly linked to the turn time. Thus, they concluded that the best turn times were associated with a long head-wall distance where rotation starts. By an early transverse rotation, male elite swimmers reached the wall with a slightly flexed posture that resulted in fast extension. These swimmers opted for a oriented forward movement and they focued on reducing the distance covered.

The above mentioned studies aimed to understand what variables, of a specific phase of the freestyle tumble turn, impact on the execution of this technical movement in swimmers.

Assuming that the turns take approximately 36% of freestyle race time in a short course (Thayer and Hay, 1984), and 31% in a 50m pool (Arellano et al., 1994), it has been proven that the reserve gained due to correct turns, results in a clear difference in performance time. Errors during the turn, or just before its execution, can negatively affect the subsequent performance.

For this reason, learning and executing a correct turn technique from a young age, results critical to the performance.

The scientific literature, especially with respect to the approach phase of the turn, is very poor.

This turn phase is the first of the five turn phases and could impact significantly on the subsequent phases.

During the approach phase, the swimmers can adopt different breathing timing: some athletes do not breathe at the last stroke before the turn, while others one breath at the last stroke.

Breathing at the last stroke, could negatively affect the total turn time or the other performance parameters, but to our knowledge there are no study that investigated this particular aspect.

AIM OF THE STUDY

The aim of the study was to evaluate the effects of two different breathing conditions (no breathing at the last stroke vs breathing at the last stroke) during the approach phase in the freestyle turn and their possible influence on the turn's performance in young swimmers.

MATERIALS AND METHODS

Participants

Thirty-two young swimmers were recruited in the study (16 male, 16 female; mean ± SD; age: 10.59 ± 0.97 years, height: 1.43 ± 0.07 m, weight: 34.82 ± 5.09 kg).

At the beginning of the study, all subjects were measured in height (m) and weight (kg) and their anthropometric characteristics were detected.
The measurements of the lengths of the upper limbs were calculated as follows.
With the arm stretched forward and parallel to the ground (or perpendicular to the body), the distance between the acromion and the distal epiphysis of the limb (right arm and left arm) and from the acromion to the last phalanx of the longest finger of the hand (right arm + hand, left arm + hand) were measured.
For the lower limbs the distance from the iliac crest to the lateral malleolus was detected, with the subject in a standing position (right leg, left leg).
The measurement of the foot consists of the distance between the heel and the tip of the longest finger, calculated with the subject in a standing position, barefoot, with the heel resting against the wall (right foot, left foot).
All length measurements were taken using a 1.5 meter long seamstress.

Inclusion criteria for the study were: BMI minor than 24.9 kg/m^2, almost six hours per week training. Exclusion criteria were: trauma or surgery in six previous months, history or clinical signs of cardiovascular or pulmonary diseases.

On the basis of their usual breath technique, subjects were divided into two groups; in the No Breath Group (NB n=15) the swimmers didn't breathe at the last stroke before turning, while in the Breath Stroke Group (BS n=17) the subjects breathed at the last stroke before turning.

Statistical analysis revealed no differences between groups at the beginning of the study.

The characteristics of the subjects are reported in the table 2.

	NB	**BS**
AGE (years)	10.6 ± 1.06	10.59 ± 0.94
SEX (M, F)	7 M, 8 F	9 M, 8 F
YEARS SWIM (years)	5.66 ± 1.59	5.59 ± 2.03
HOURS/ WEEK	8.4 ± 2.92	7.59 ± 2.65
HEIGHT (m)	1.42 ± 0.07	1.43 ± 0.08
WEIGHT (kg)	34.16 ± 4.41	35.41 ± 5.69
BMI (kg/m^2)	16.78 ± 1.65	17.15 ± 1.64
RIGHT ARM (m)	0.48 ± 0.03	0.48 ± 0.04
RIGHT ARM + HAND (m)	0.64 ± 0.04	0.64 ± 0.05
LEFT ARM (m)	0.48 ± 0.03	0.48 ± 0.04
LEFT ARM + HAND (m)	0.64 ± 0.04	0.63 ± 0.05
RIGHT LEG (m)	0.81 ± 0.06	0.81 ± 0.06
LEFT LEG (m)	0.81 ± 0.06	0.81 ± 0.06
RIGHT FOOT (m)	0.22 ± 0.01	0.22 ± 0.02
LEFT FOOT (m)	0.22 ± 0.02	0.22 ± 0.03

Tab.2 Characteristics of BS and NB groups. Data are reported as mean ± standard deviation

Materials

Below are the materials employed in the study.

- Four digital video camera GoPro Hero 4 (GoPro Inc., United States), able to work both in aerial and in underwater conditions, were used with a resolution of 720 pixel and at a sample frequency of 120 frames per second (fps).

- Two specific suction cup supports, useful to fix the cameras to the pool wall.

- One digital chronometer

- One rigid 5 m measuring tape

- One 1.5 m measuring tape

- One black rubber band

- One black tape roll

- One yellow band

- Two plexiglas panels, 1.10 x 0.30 m, with a surface of 0.4 x 0.3 m to fix the underwater cameras on the side wall of the pool.

- Two 25 m pool lanes

- Kinovea software v. 0.8.15

Kinovea

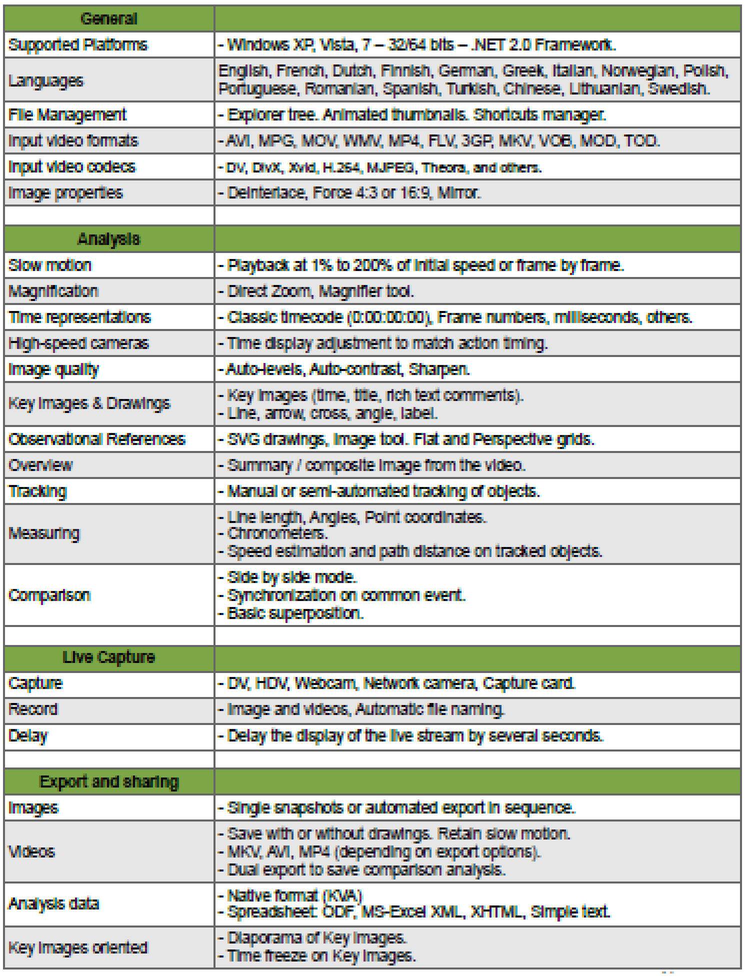
Kinovea is a video-analysis software, it allows to analyze specific actions and movements, exploring the gesture frame by frame, also in slow motion.

It is possible to enrich the video by adding arrows, descriptions and other content to key positions. The tools “line” and “chronometer” allow to measure the distance covered and the time to execution of a movement or a part of it.

Manually or semi-automated tracking system can be used to follow points, measure velocities and check live values or trajectories.

The double view modality permits to see two videos side by side and synchronize them on a common event.

Technical features are resumed in the label below.



General	
Supported Platforms	- Windows XP, Vista, 7 – 32/64 bits – .NET 2.0 Framework.
Languages	English, French, Dutch, Finnish, German, Greek, Italian, Norwegian, Polish, Portuguese, Romanian, Spanish, Turkish, Chinese, Lithuanian, Swedish.
File Management	- Explorer tree. Animated thumbnails. Shortcuts manager.
Input video formats	- AVI, MPG, MOV, WMV, MP4, FLV, 3GP, MKV, VOB, MOD, TOD.
Input video codecs	- DV, DivX, Xvid, H.264, MJPEG, Theora, and others.
Image properties	- Deinterlace, Force 4:3 or 16:9, Mirror.
Analysis	
Slow motion	- Playback at 1% to 200% of initial speed or frame by frame.
Magnification	- Direct Zoom, Magnifier tool.
Time representations	- Classic timecode (0:00:00:00), Frame numbers, milliseconds, others.
High-speed cameras	- Time display adjustment to match action timing.
Image quality	- Auto-levels, Auto-contrast, Sharpen.
Key Images & Drawings	- Key Images (time, title, rich text comments). - Line, arrow, cross, angle, label.
Observational References	- SVG drawings, Image tool. Flat and Perspective grids.
Overview	- Summary / composite image from the video.
Tracking	- Manual or semi-automated tracking of objects.
Measuring	- Line length, Angles, Point coordinates. - Chronometers. - Speed estimation and path distance on tracked objects.
Comparison	- Side by side mode. - Synchronization on common event. - Basic superposition.
Live Capture	
Capture	- DV, HDV, Webcam, Network camera, Capture card.
Record	- Image and videos, Automatic file naming.
Delay	- Delay the display of the live stream by several seconds.
Export and sharing	
Images	- Single snapshots or automated export in sequence.
Videos	- Save with or without drawings. Retain slow motion. - MKV, AVI, MP4 (depending on export options). - Dual export to save comparison analysis.
Analysis data	- Native format (KVA) - Spreadsheet: ODF, MS-Excel XML, XHTML, Simple text.
Key Images oriented	- Diaporama of Key Images. - Time freeze on Key Images.

Tab.3 Technical features – Kinovea 0.8.15 Font: www.kinovea.org

Video analysis setting

In order to obtain common reference point useful for video analysis, all subjects wore tape markers.

The markers were placed on: the frontal bone of the cranium, the acromion, the olecranon, the radio-ulnar distal epiphysis, the big trochanter, the peroneal head and the peroneal malleolus.

The different turns were recorded by two underwater and two aerial digital video cameras (GoPro® HERO4) at 120 fps and a resolution of 720 pixel.

In order to obtain a good fixing, the two underwater cameras were positioned, with a suction cup, on a plexiglas panel fixed to the lateral wall of the swimming pool. The underwater cameras were located at a depth of 0.36 m, respectively at a distance of 0.6 m and 2.10 m from the turning wall, as to allow for setting the axes of the cameras, perpendicular to the objects filmed during the crucial fragments of the turn (Fig.2, Fig.3).

A third aerial video camera was placed on the board of the swimming pool, to a height of 0.30 m from the edge and with a downward inclination of 45 degrees, in order to obtain a frontal view of the swimmer (Fig.4, Fig.6). Finally, the fourth camera was positioned, out of the water, above the lateral wall of the swimming pool, on a ladder situated at a distance of 1.31 m from the turning wall and at a height of 1.87 m from the floor (Fig.4, Fig.5).

A reference points was marked in order to allow the video analysis; in particular a black rubber band was fixed in water, on the pool lane's rope, 5m away from the turning wall. The video recordings were made between 4 pm and 6 pm and the room and water temperature were, respectively, 20°/30° and 25°/28°.

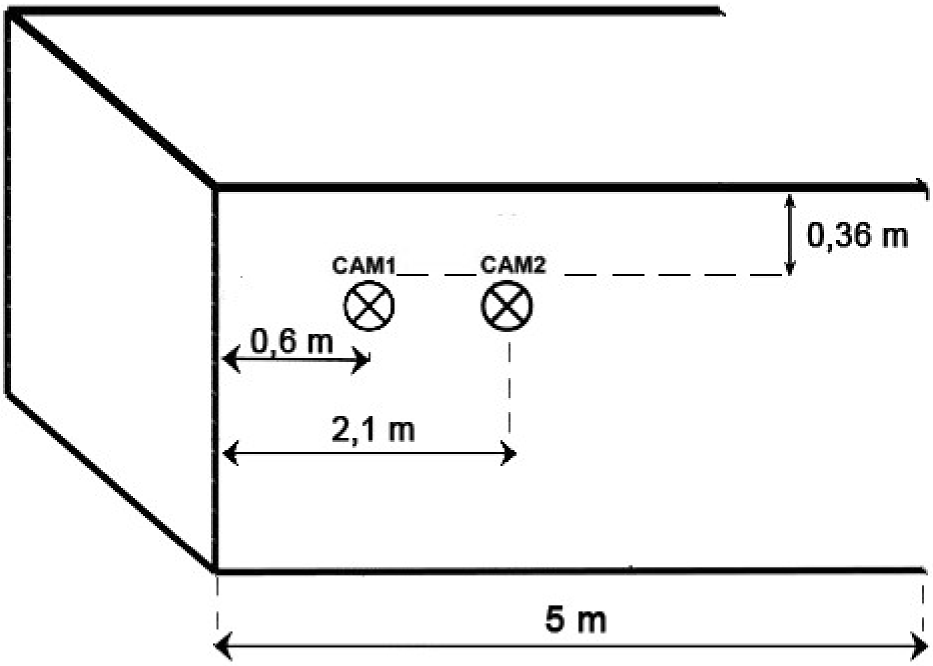


Fig.2 Position of the two underwater video-cameras

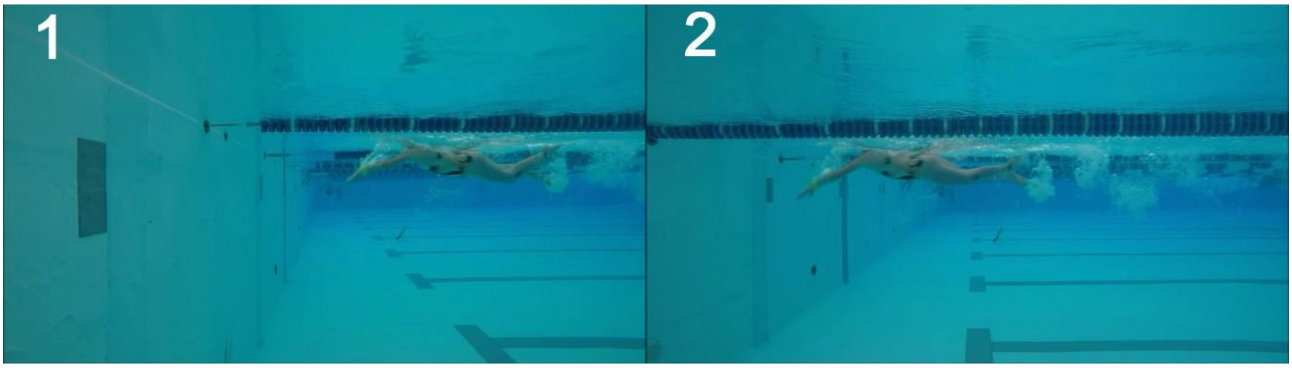


Fig.3 View of the two underwater video-cameras

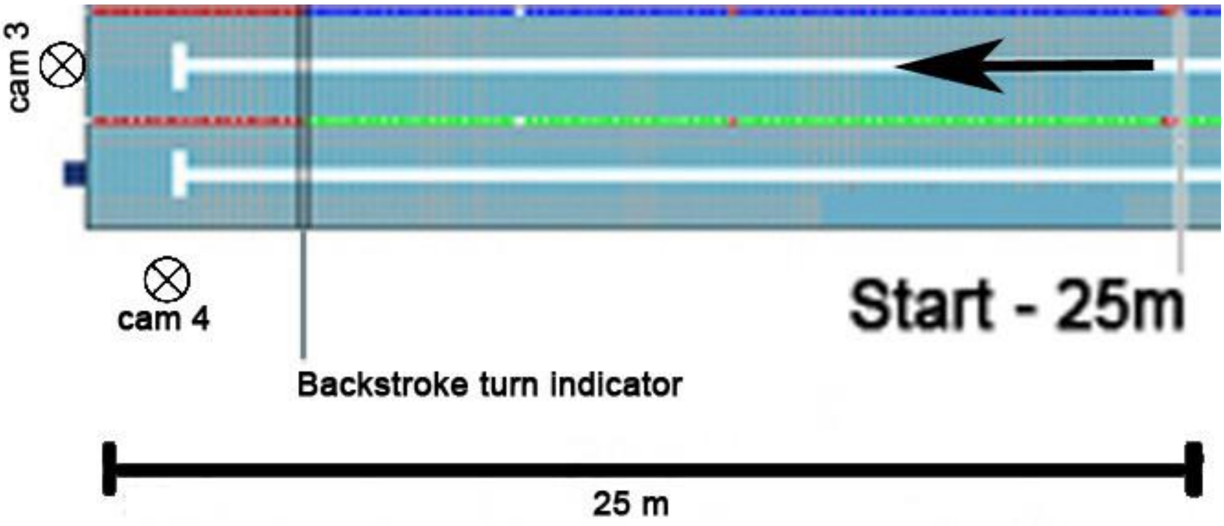


Fig.4 Position of the two aerial video-cameras

Fig.5 View of the side aerial video-camera

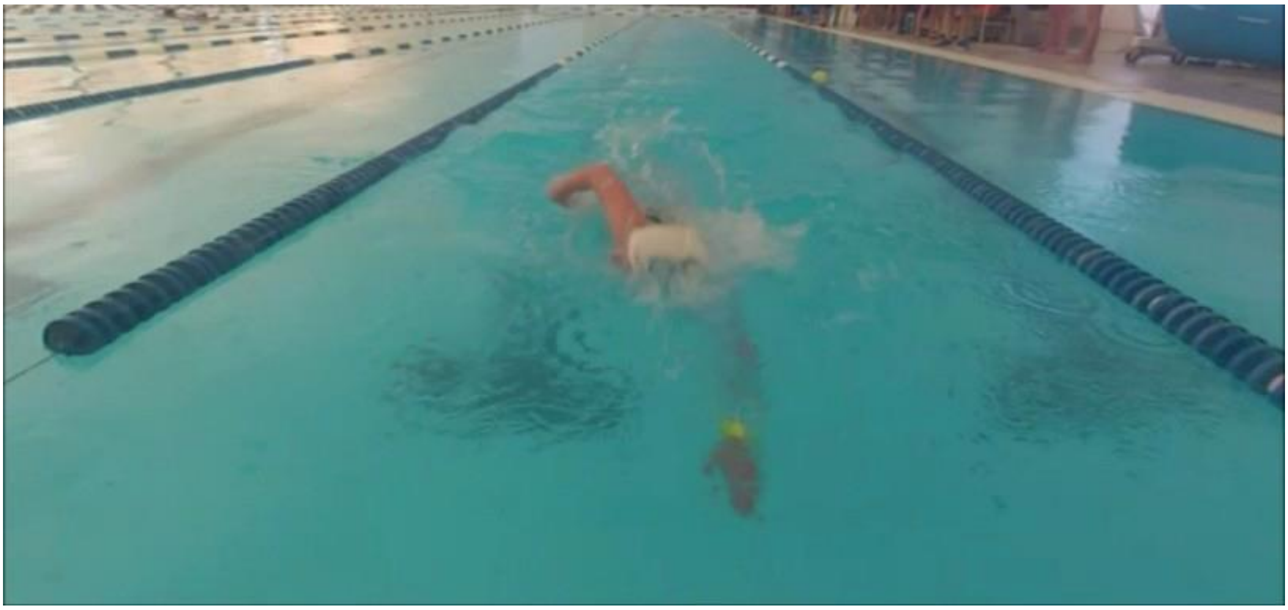


Fig.6 View of the frontal aerial video-camera

Experimental protocol

The athletes were asked to perform the turn in a 50 m freestyle swim. Subjects were asked to swim as fast as possible, like during a race.
This performance was repeated three times, with a complete recovery between the repetitions.

The three executions of each subject were recorded by four video cameras and were video analysed with Kinovea software 0.8.15 (Copyright © 2006–2011, Joan Charmant & Contrib); statistical analysis was performed on the average of the results of the three trials.

Parameters recorded

Time, speed, distance and depth parameters were analyzed.
Time and speed parameters

- Total turn time (s): the time period from the moment when the hip joints swim trough the point placed 5m from the wall before turning, till the moment when the hip joints swim trough the point placed 5m from the wall after turning.
- Swim-in time (s): time period from the moment when the hip joints swim trough the point placed 5m from the wall before turning, till the moment of the turning initiation (downward movement of the head).

- Rotation time (s): time period from the moment of the turning initiation, till the moment when the turning is finished (first moment of the feet contact with the wall).
- Wall contact time (s): time period from the first feet contact with the wall, till the moment when the feet loose contact with the wall.
- Push-off time (s): time period between the moment when the hip joints forward displacement is initiated after contact with the wall, and the moment when the feet loose contact with the wall.
- Time-in (s): time period from the moment when the head moves through the horizontal line initializing the turning, till the moment of the first feet contact with the wall.
- Time-out (s): time period from the moment of the first feet contact with the wall, till the moment when the head moves back to the horizontal line after the turning.
- 50 meters time (s): time to swim 50 meters freestyle.
- Speed-in ($m*s^{-1}$): average speed taken since the hip is 5 meters from the wall to the first contact of the feet to the wall.
- Speed-out ($m*s^{-1}$): the average speed since the last contact of the feet to the wall up to 5 meters.

Distance and depth parameters

- Swim-in distance (m): distance between the head and the wall at the moment of the turn initiation.
- Glide distance (m): distance of the hip joints displacement between the moment when the feet loose contact with the wall and the moment of the first propulsive movement initiation.
- Turn distance (m): the distance of the hip joints displacement from the moment of the turn initiation (lowering of the head starting rotation) till the moment when the feet loose contact with the wall.
- Peroneal malleolus depth (m): depth of the peroneal malleolus at the moment in which feet take contact with the wall.

Statistical analysis

An independent T-test was used to compare the NB group and the BS group, both before the beginning of the study to assess the comparability of the groups and at the end of the study to analyze the differences in the turn performance.

The analyses were performed using IBM SPSS STATISTIC, version 21 for Windows.

The level of significance was set at $p=0.05$.

RESULTS

Table 4 reported the results (mean ± SD) of the two experimental groups (NB, BS) for all the time, speed, distance and depth parameters of the turn.

The NB group showed lower values than BS group in the total turn time (NB 9.31±1.34; BS 10.23±1.77 sec $p<0.05$) (Fig.7), in the swim-in time (NB 3.88 ± 0.63; BS 4.50±0.79 sec $p<0.05$) (Fig.8) and in the rotation time (NB 2.42±0.29; BS 3.03±0.41 sec $p<0.05$) (Fig.9).

Moreover, the NB group expressed a significant higher speed-in than the BS group (NB 1.04±0.14 BS 0.93±0.14 m/s $p<0.05$) (Fig.10). Finally, also the swim-in distance (NB 0.73±0.20 BS 0.47±0.14 m $p<0.05$) and the glide distance (NB 1.06±0.21 BS 0.67± 0.32 m $p<0.05$) were significant higher in the NB group than in the BS group (Fig.11, Fig.12), while no significant differences in the other parameters were found.

	NB group	**BS group**
Total turn time (s)	9.31±1.34	10.23±1.77 *
Swim-in time (s)	3.88±0.63	4.50±0.79 *
Rotation time (s)	2.42±0.29	3.03±0.41 *
Wall contact time (s)	0.57±0.26	0.70±0.25
Push-off Time (s)	0.38±0.21	0.46±0.26
Time - in (s)	0.97±0.18	0.94±0.23
Time - out (s)	0.85±0.29	0.89±0.29
50 meters time (s)	42.60±5.36	45.13±8.47
Speed - in ($m*s^{-1}$)	1.04±0.14	0.93±0.14 *
Speed - out ($m*s^{-1}$)	1.30±0.19	1.23±0.20
Swim-in distance (m)	0.73±0.20	0.47±0.14 *
Glide distance (m)	1.06±0.21	0.67± 0.32 *
Turn distance (m)	1.98±0.19	2.07±0.20
Malleolus depth (m)	0.30±0.16	0.25± 0.12

Tab.4 Measures of the distance and depth parameters of the turn (mean ± SD) in the two experimental groups (NB: no breath stroke; BS: breath stroke); * $p<0.05$

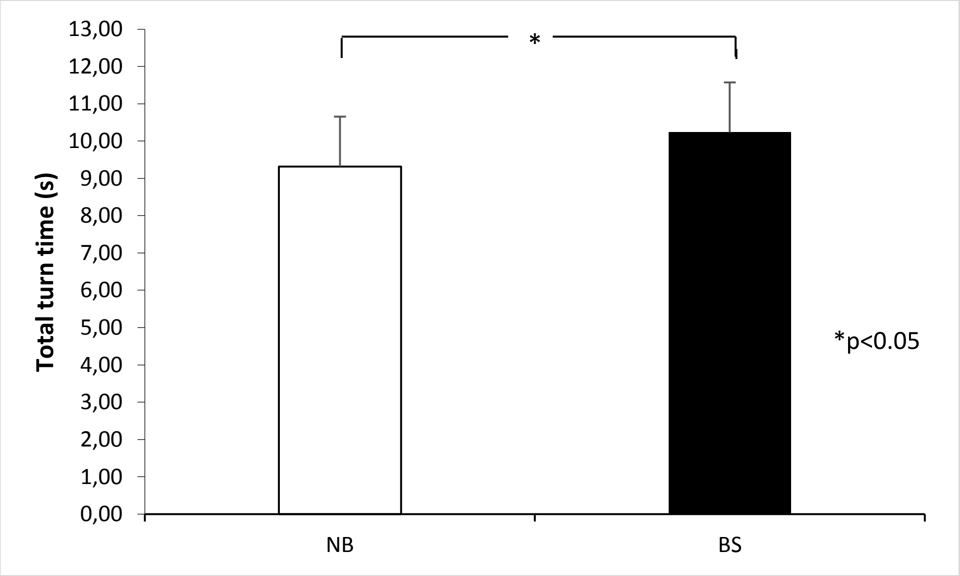


Fig. 7 Total turn time in NB group and BS group. Data are expressed as mean ± standard deviation.

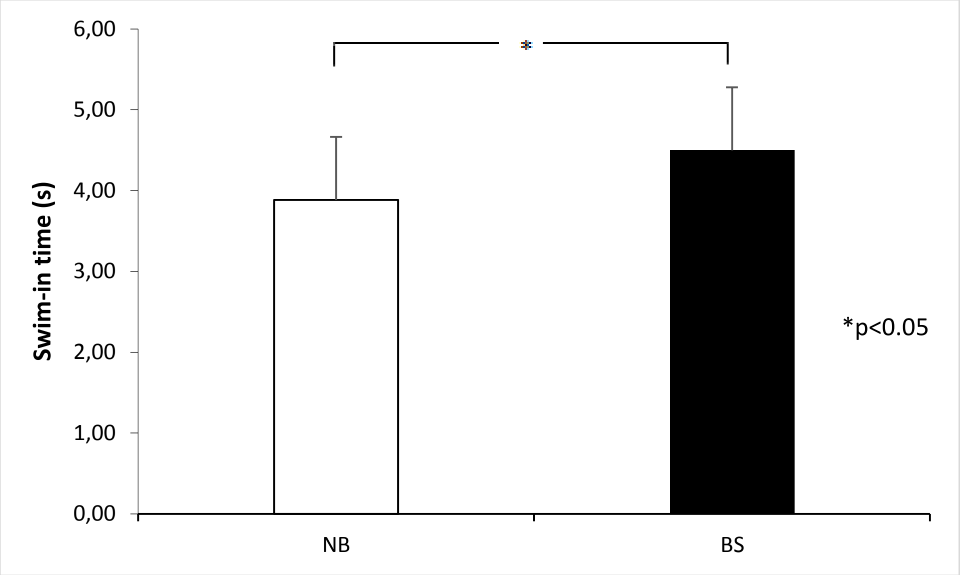


Fig.8 Swim-in time in NB group and BS group. Data are expressed as mean ± standard deviation.

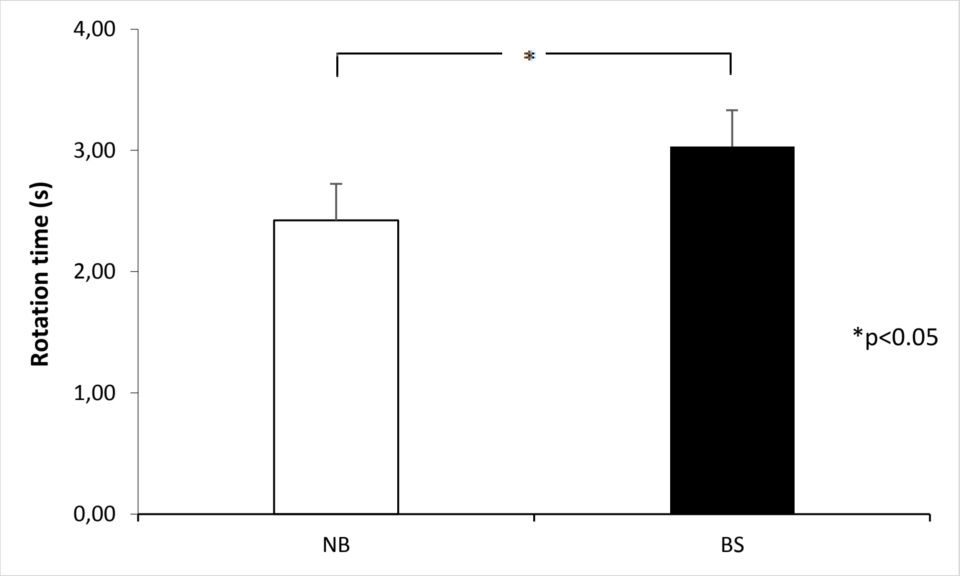


Fig.9 Rotation time in NB group and BS group. Data are expressed as mean ± standard deviation.

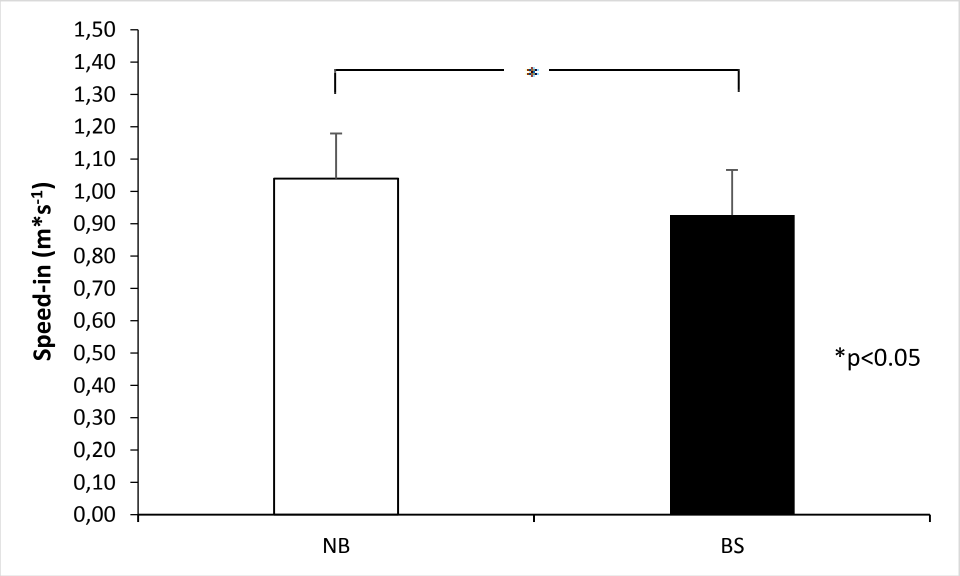


Fig.10 Speed-in in NB group and BS group. Data are expressed as mean ± standard deviation.

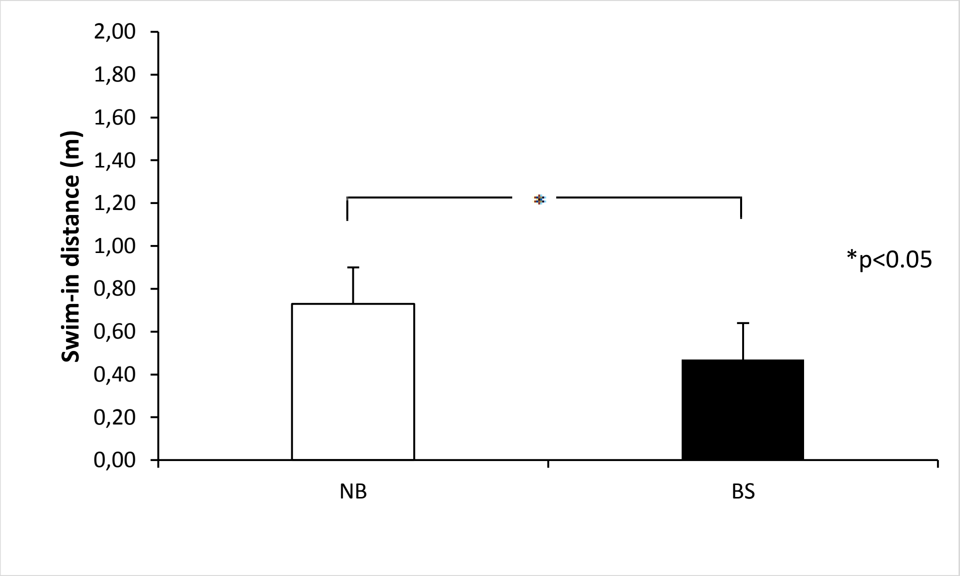


Fig.11 Swim-in distance in NB group and BS group. Data are expressed as mean ± standard deviation.

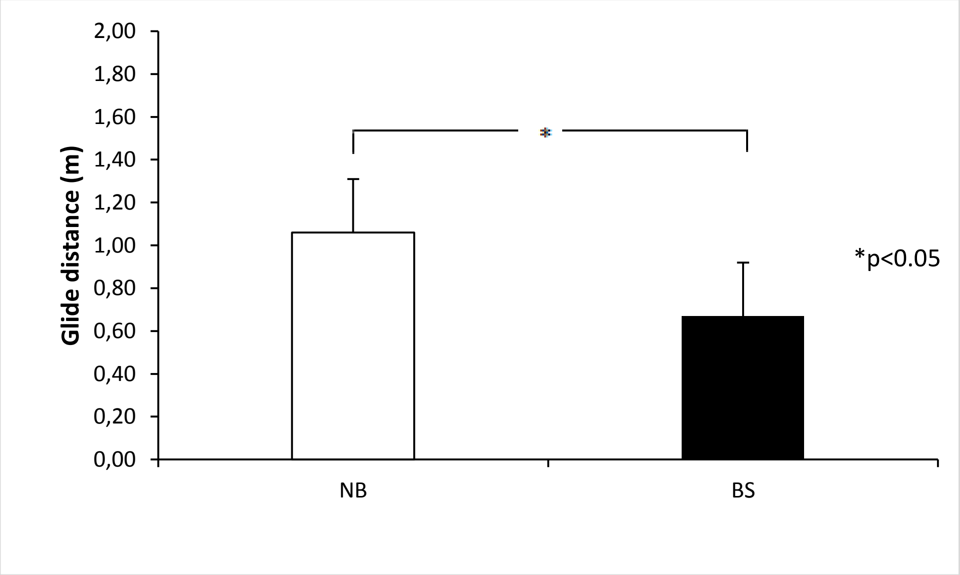


Fig.12 Glide distance in NB group and BS group. Data are expressed as mean ± standard deviation.

DISCUSSION

The results showed that the swimmers beginning the rotation farther from the wall are able to turn faster. In fact, the NB group had a swim-in distance 26 cm higher and a total turn time of almost 1 second lower than the BS group. This result is in accordance with a Puel's study aimed to identify kinematic and dynamic variables related to the best tumble turn times in ten elite male swimmers; the results of the research indicated that the swimmers with the fastest turns initiated their rotation farther from the wall (Puel et al., 2012).

Also Blanksby observed in young swimmers similar results: the place where rotation starts was one of the best indicators of turn performance and the best swimmers initiated their turns farther from the wall than the slower ones (Blanksby et al., 1996).

In the present study the time interval between the moment when the hip reaches the point of 5 meters from the wall before the turn, until the moment in which begins the rotation is lower in the NB group than the BS group.

Starting the turn farther away from the wall and not immediately bringing the head in rotation, lead to an efficient turn. This happens because all the body segments turn simultaneously, the head does not move in advance with respect to the body and feet, pelvis, shoulders and head are lined during the contact period of the feet with the wall. From the biomechanical point of view, this position is advantageous for the pushing phase and moreover, do not breathe during the last stroke allows the athlete to anticipate the start of the rotation.

The NB group shows a significantly higher average speed-in than the BS group, probably because the swimmer, not breathing at the last stroke, doesn't break the turn's performance, keeping the maximum execution speed.

Further evidence that breathing at the last stroke worse the turn performance, is given by the significantly shorter rotation time in the NB group than in the BS group. In fact, the athletes who breathe at the last stroke put their head in a not hydrodynamic position breaking the approach to the wall.

As a consequence of a good swim-in distance, a good rotation time and an optimal malleolus depth, that allowed a quick and correct squatting, the glide distance that follow the push of the feet on the wall was 39 cm longer in the NB group than in the BS group; the same trend was found in the speed-out parameter, even if the data is not statistically significant.

On the basis of the results, it is reasonable to conclude that breathing at the last stroke before turning leads to a wrong approach to the wall and negatively affects all the turning phases, carrying to a worse performance. In this scenario, it is important to train the turn’s technique, starting from the young swimmers. In particular, teaching in young athletes the right breathing technique before turning could be crucial for performance improvements.

PART 2

VIDEO ANALYSIS OF THE BREASTSTROKE UNDERWATER CYCLE: A BIOMECHANICAL COMPARISON BETWEEN TWO TECHNIQUES

Swimming is a constantly evolving sport; starting from the first modern Olympics, held in 1896 in Athens, to the present day, swimming has undergone numerous technical changes, thanks to variations in regulation and insights of athletes and their coaches that have allowed new goals to be achieved.

The introduction of the breaststroke in the Olympic race program dates back to 1908, thanks to the insertion of the 200m breaststroke, where Fredrick Holman wined with the time of 3.09.2 minutes, a time that today can realize a simple beginner.

Holman's technique, however, underwent sudden changes due mainly to regulatory gaps that allowed in 1926 to German Erich Rademacher to swim by recovering his arms out of the water, as if to make a double-armed style and general protests did not lead to any disqualification. In 1928 at the Olympics in Amsterdam, Japanese Yoshiyuki Tsuruta won the gold medal with the time of 2.48.8 minutes, preceding the Philippine Teofilo Ildefonso, who is still remembered for almost all the underwater races.

The first January 1953 was sanctioned by FINA, the authority that promotes and manages swimming practice and coordinates the international agonistic activity of swimming, the division between the "orthodox" breaststroke and the butterfly.

At the end of the 1956 Olympic Games in Melbourne, after attending the 200m gold medal of Japanese Furukawa with the time of 2.34.7 minutes that performed the underwater breaststroke, coming out to breathe only in turn, FINA amended Regulation obliging the athletes to re-emerge at every arm, considering the dangers for competitors due to excessive apnea prolonged.

In 1961, the revolutionary breaststroke technique of the American coach, James Counsilman, that consisted of a tight kick, minimal foot rotation and fast breathing, allowed Chester Jastremky to break down, within a few months, the world record of 200m breaststroke time from 2.36.5 to 2.29.6 minutes and 100m breaststroke time from 1.11.1 to 1.07.5 minutes, upsetting the traditional importance of kicking legs over the arms movement this swimming style.
Only in Mexico City in 1968 the 100m breaststroke race was introduced in the Olympic swimming program.

Another important technical innovation in the breaststroke style could be seen at the Seoul Olympics in 1988 during the 200m breaststroke race won by the Hungarian József Szabó with time of 2.13.5 where for the first time the "new Wave breaststroke", a technique that involves a superficial pelvis movement and a undulatory swim very similar to the dolphin, which reduces friction and increases propulsion surfaces.

Finally, in 2001, the wall of the 60-second was crushed, for the first time in the history of swimming, by the Russian Roman Sloudnov with chrono race of 59.97 seconds in Russian championships.

This brief excursus on the evolution of the breaststroke technique shows how, over the years, new techniques and adjustments to the international rules have led the athletes to better and better performance in shorter times.

The evolution of the underwater breaststroke technique

The execution of this fundamentals of the swim has changed over the years, in parallel with the changes in the regulation.

Before 1960 it was forbidden to overcome the line of the hips with the arms, during the breaststroke swim; so doing the regulation avoided any contamination with the butterfly.

Afterwards this was allowed only and exclusively for the first stroke after the start and after each turn of the race.

Only in 2004, with the help of underwater video cameras at the Athens Olympics, a dolphin legs movement was noticed during the pushing of the arms over the line of the hips in the first underwater stroke of Japanese Kosuke Kitajima, beating the world record holder Brendan Hansen in the 100-breaststroke race.

This fact thwarted the workmen in disarray, because the race judges, placed on the side of the pool, were unable to see these particulars.

FINA abated all the controversy, deciding, on September 21, 2005, to change the regulation and allow a dolphin kick.

An excerpt from the FINA regulation, 2009-2012 edition, reads about diving underwater: "... After the start and after each turn, the swimmer can perform a full arm stroke back to the legs. The head must break the surface of the water before the hands roll inwards at the culmination of the wider part of the second stoke. As long as the competitor is completely immersed, a single dolphin kick is allowed, followed by a breaststroke kick. Next, all leg movements must be simultaneous and in the same horizontal plane, without alternating movements…"

In the next paragraph, the technical regulation continues with these words: "... dolphin kick is not part of the cycle and is allowed only at the start and the turn while the arms are pushed back to the legs or after the stroke is completed during the underwater phase, followed by a breaststroke kick" (FINA Swimming Rules, 2009-2012).

The evolution of underwater breaststroke, however, is not concluded with the above-mentioned regulation. Many athletes, in recent years, just because of the difficulties faced by the judges in seeing the execution of this technical gesture, used the dolphin kick before the movement of the arms and not during or after pushing the arms, as indicated by the Regulation.

This led to a new intervention by FINA, which, following the Doha Congress, in anticipation of the 2014 World Cup Championships, made changes to the technical regulation governing the dolphin kick during the underwater phase swim: "... After the start and after each turn, the swimmer can only carry one full arm back to his legs during which he may remain immersed. After the start and after each turn, at any time before the first breaststroke kick is allowed a single dolphin kick, after which, all leg movements must be simultaneous and in the same horizontal plane without alternating movements ... " (FINA Rule Amendments, 2014).

Analysis of the literature

Analyzing the literature, many studies about the breaststroke technique can be found.

Strzała et al. analyzed the coordination, propulsion and non-propulsion phases in the 100 meter breaststroke race. Twenty-seven male swimmers (15.7 ± 1.98 years old) with the total body length (TBL) of 247.0 ± 10.60 (cm) performed an all-out 100 m breaststroke bout. The bouts were recorded with an underwater camera installed on a portable trolley. The swimming kinematic parameters, stroke rate (SR) and stroke length (SL), as well as the coordination indices based on propulsive or non-propulsive movement phases of the arms and legs were distinguished. Results showed that the swimming speed (V100surface breast) was associated with SL ($R = 0.41$, $p < 0.05$) and with TBL tending towards statistical significance ($R = 0.36$, $p < 0.07$), all relationships between the selected variables in the study were measured using partial correlations with controlled age. SL interplayed negatively with the limbs propulsive phase Overlap indicator ($R = -0.46$, $p < 0.05$), but had no significant relationship to the non-propulsion Glide indicator.

The authors concluded that the propulsion in-sweep (AP3) phase of arms and their non-propulsion partial air recovery (ARair) phase interplayed with V100 surface breast ($R = 0.51$, $p < 0.05$ and 0.48 $p < 0.05$) respectively, displaying the importance of proper execution of this phase (AP3) and in reducing the resistance recovery phases in consecutive ones (Strzała et al., 2014).

Seifert et al. analyzed the kinematics and coordination of the breaststroke start as regards to skill level using a video device. Ten national swimmers were compared with an international swimmer. All swimmers simulated the 100-m pace for 25m after a grab start. The kinematical analysis assessed the durations of leave block, flight, entry and glide, pull-out, and the swim up to the 15-m mark phases.

The coordination analysis assessed the durations of the time spent with the arms close to the thighs after a complete arm pull-push, the time gap between the end of the arm recovery and the beginning of the leg propulsion during the pull-out phase and at the first swim stroke, and the time gap between the end of leg propulsion and the beginning of arm propulsion.

The international swimmer had a shorter 15-m start time than the national swimmers due to shorter times in the swim phase, longer times in the underwater phase, longer times spent with the arms close to the thighs and in glide with the body in extension.

The whole population showed a negative superposition of leg propulsion with arm recovery at the pull-out phase, which disappeared at the first swim stroke (Seifert et al., 2007).

Studying in depth the literature about the breaststroke, some papers specifically focused on the breaststroke underwater cycle can be found.

In 2015, Costa et al. investigated the flow effects around the swimmer and compared the drag and drag coefficient (CD) values obtained from experiments (using cable velocimetry in a swimming pool) with those of Computational Fluid Dynamics simulations for the two ventral gliding positions assumed during the breaststroke underwater cycle (with shoulders flexed and upper limbs extended above the head - GP1; with shoulders in neutral position and upper limbs extended along the trunk - GP2) (Costa et al., 2015). Six well-trained breaststroke male swimmers (with reasonable homogeneity of body characteristics) participated in the experimental tests; afterwards a 3D swimmer model was created to fit within the limits of the sample body size profile. The standard k-ε turbulent model was used to simulate the fluid flow around the swimmer model. Velocity ranged from 1.30 to 1.70 m/s for GP1 and 1.10 to 1.50 m/s for GP2. Values found for GP1 and GP2 were lower for CFD than experimental ones. Nevertheless, both CFD and experimental drag/drag coefficient values displayed a tendency to jointly increase/decrease with velocity, except for GP2 CD where CFD and experimental values display opposite tendencies. Results suggest that CFD values obtained by single model approaches should be considered with caution due to small body shape and dimension differences to real swimmers. For better accuracy of CFD studies, realistic individual 3D models of swimmers are required, and specific kinematics respected.

Vilas-Boas et al. assessed and compared the hydrodynamics of the first and second gliding positions of the breaststroke underwater stroke used after starts and turns, considering drag force (D), drag coefficient (CD) and cross-sectional area (S). Twelve national-level swimmers were tested (6 males and 6 females, respectively 18.2±4.0 and 17.3±3.0 years old). Hydrodynamic parameters were assessed through inverse dynamics from the velocity to time curve characteristic of the underwater arm stroke of the breaststroke technique. The results showed that, for the same gliding velocities (1.37±0.124 m/s), D and the swimmers' S and CD values obtained for the first gliding position are significantly lower than the corresponding values obtained for the second gliding position of the breaststroke underwater stroke (31.67±6.44 N vs. 46.25±7.22 N; 740.42±101.89 cm2 vs. 784.25±99.62 cm2 and 0.458±0.076 vs. 0.664±0.234, respectively). These differences observed for the total sample were not evident for each one of the gender's subgroups (Vilas-Boas et al., 2010).

All the studies above mentioned, focused on the technical characteristics and the time/speed of execution of the breaststroke technique, but no studies, to our knowledge, compared the breaststroke underwater cycle, performed respecting the old regulations and the same gesture, performed following the regulation’s change of 2014.

AIM OF THE STUDY

To evaluate in a sample of agonist swimmers, finalist in regional competitions, the effect of two different types of execution of the breaststroke underwater cycle: by executing the dolphin kick simultaneously with the arms stroke, as permitted by the old FINA regulation; or by performing the dolphin kick before the movement of the arms, as permitted by the new rules since the 2014 regulation's change.

MATERIALS AND METHODS

Participants

Twelve swimmers (4 males, 8 females) were recruited in the study (mean ± SD; age: 16.2 ± 2.9 years, height: 1.71 ± 0.1 m, weight: 61.8 ± 11.3 kg).

At the beginning of the study, all subjects were measured in height (m) and weight (kg) and their anthropometric characteristics were detected.

The measurements of the lengths of the upper and lower limbs were calculated as previously described (see pag. 35).

Inclusion criteria for the study were: BMI between 20 and 24.9 kg/m^2, high level regional athletes (admitted at the final race of the regional championship, for each category).
Exclusion criteria were: trauma or surgery in six previous months, history or clinical signs of cardiovascular or pulmonary diseases

Statistical analysis revealed a normal distribution of the data; all the participants' characteristics are reported in the table 5.

PARAMETERS	**MEAN ± SD**
AGE (years)	16.16 + 2.88
SEX (M, F)	4 M, 8 F
HEIGHT (m)	1.71 ± 0.10
WEIGHT (kg)	61.83 ± 11.33
BMI (kg/m^2)	21.05 ± 2.01
YEARS SWIM (years)	9.17 ± 2.72
HOURS/ WEEK	11.25 ± 2.80
PERSONAL BEST 50 m (s)	33.50 ± 3.28
RIGHT ARM (m)	0.56 ± 0.03
RIGHT ARM + HAND (m)	0.74 ± 0.05
LEFT ARM (m)	0.56 ± 0.03
LEFT ARM + HAND (m)	0.74 ± 0.05
RIGHT LEG (m)	0.96 ± 0.03
LEFT LEG (m)	0.96 ± 0.04
RIGHT FOOT (m)	0.26 ± 0.01
LEFT FOOT (m)	0.26 ± 0.01

Tab.5 Characteristics of the subjects. Data are expressed as mean ± standard deviation.

Materials

These are the materials employed in the study.

- One digital video camera GoPro Hero 5 (GoPro Inc., United States), able to work both in underwater conditions, was used with a resolution of 720 pixel and at a sample frequency of 120 frames per second (fps).

- One suction cup support for the video camera.
- One digital chronometer
- One rigid 5 m measuring tape
- One 1.5 m measuring tape
- One black tape roll
- One plexiglas panel, 1.10 x 0.30 m, with a surface of 0.4 x 0.3 m to fix the underwater camera on the side wall of the pool.
- Six suction caps, fixed on the floor of the swimming pool.

- Three 25 m pool lanes
- Kinovea software v. 0.8.15

Video analysis setting

In order to obtain common reference point useful for video analysis, all subjects wore tape markers.

The markers were placed on: the frontal bone of the cranium, the acromion, the olecranon, the radio-ulnar distal epiphysis, the big trochanter, the peroneal head and the peroneal malleolus.

One digital video camera GoPro Hero 5 (GoPro Inc., United States) was used, at 120 fps and a resolution of 720 pixel, to analyze the breaststroke underwater phase; it was difficult to choose the best position of the camera that allowed to film all the underwater cycle and also to see sharply the markers, positioned on the swimmer's body.

After several attempts, the camera was fixed at a depth of 0.36 m and at a distance of 5.65 m from the start wall (Fig. 13, Fig.14). This positioned allowed to see all the underwater cycle, with a good definition of the images.

The camera was fixed to the plexiglas panel by the suction cup support. The lens of the video camera was positioned in the middle of the panel; the panel was positioned at 5.5 m from the start wall, so that the camera was 5.65 m away from the start wall.

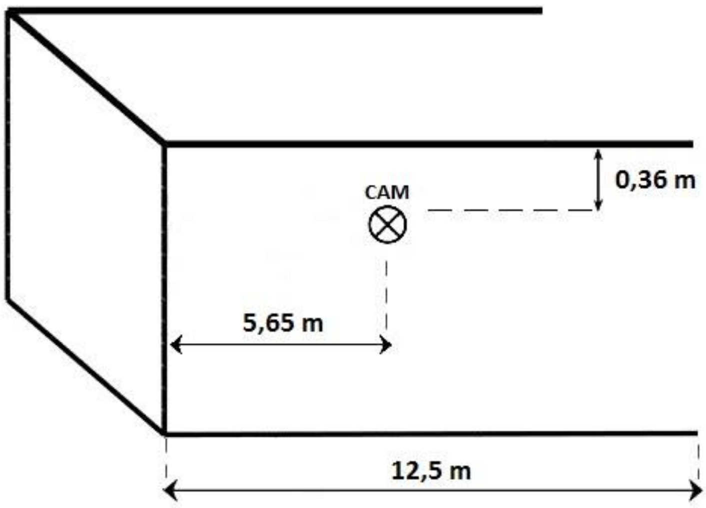


Fig.13 Position of the underwater video camera

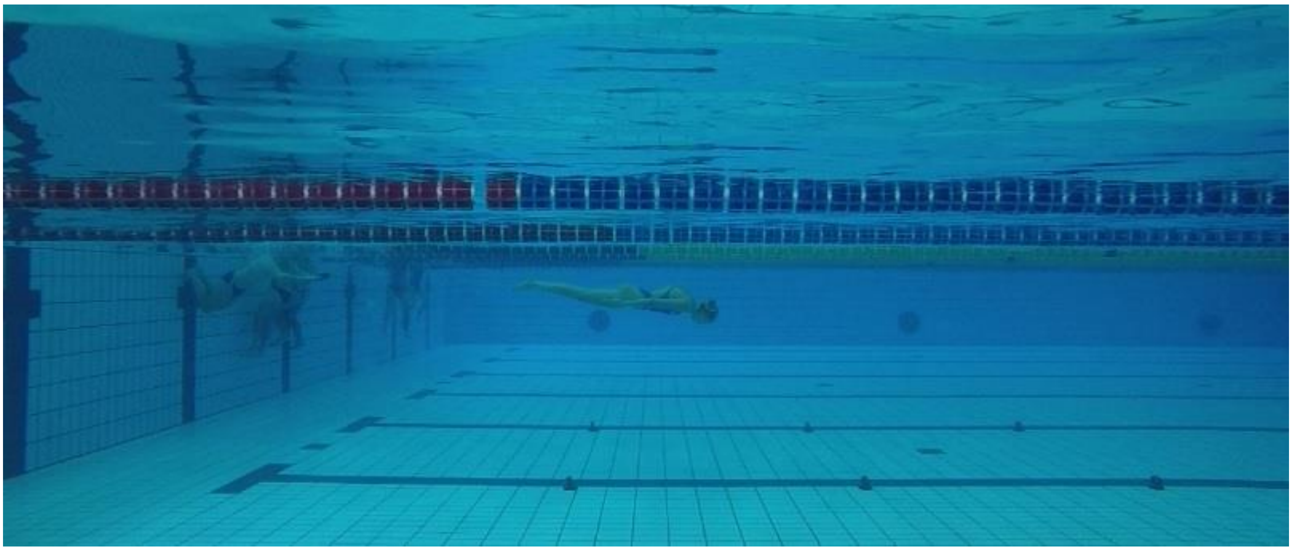


Fig.14 View of the underwater video camera

Six suction caps were positioned, in the third and the fourth lane, on the T designed on the poll floor.

The suction cups were placed in pairs, at 5, 7.5 and 10 m from the start wall.

Thanks to the positioning of the underwater suction cups it was possible to define the reference points to create a grid that Kinovea software employed to make accurate measurements on the swimmer (Fig.15).

All the video were analyzed by two independent operators; a mean of the results of the two operators for each video was considered for the study.

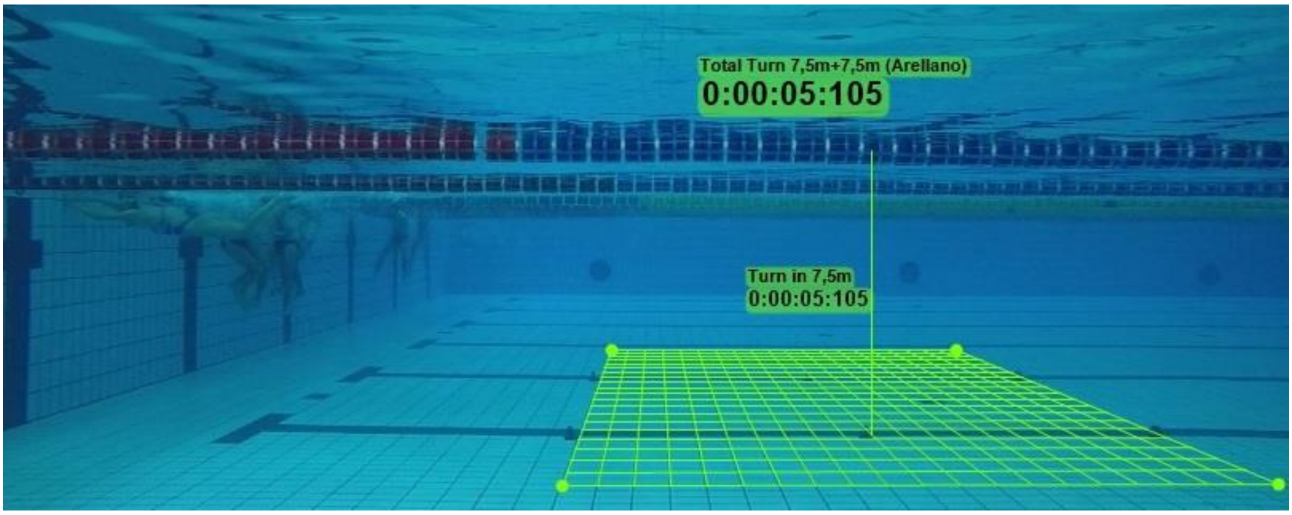


Fig.15 Grid designed by Kinovea software, using the suction caps as reference points.

Experimental protocol

The experimental protocol was inspired by the study of Vilas-Boas et al. (2010).
After a warm up, the subjects performed as fast as possible 50m breaststroke. The test was repeated three times, with 3 minutes of recovery between the repetitions.
Each repetition was composed as follow:

- 25m breaststroke;
- turn and breaststroke underwater phase.
- 25m breaststroke, touching the pool wall with two hands at the end of the swim.

The trial was repeated two times, with a period of a week between the repetitions.
The first time all subjects performed the breaststroke underwater cycle following the regulation previous the 2014 change; in particular they performed the stroke and the dolphin kick simultaneously. The subjects well knew this technique and employed it regularly both during the training and the races.

After this first test, they trained for a week in the execution of the new technique granted by the 2014 change of regulation.
At the end of the week they repeated the test, executing the new breaststroke underwater cycle that consist of a dolphin kick followed by an underwater stroke.

All the test were executed at the same aerial (25°C) and water temperature (26-28 °C), in the same hours of the day (between 6 and 8 am or 2 and 4 pm).
No feedback on the performances was given to the athletes until the end of the study, not to influence the subjects in the execution of the tests.

Parameters recorded

Thanks to the analysis of high-resolution videos (120 fps), it was possible to obtain many parameters, useful for studying the two techniques of execution of the breaststroke underwater cycle.

Time parameters

- Turn in 7.5m time (s): the time period from the moment in which the hip joints swim trough the point placed 7.5 m from the wall and the moment when the hands touch the wall.

- Turn out head time (s): the time period between the moment in which the feet lose contact with the wall and the moment when the head breaks the water surface.
- Turn out 7.5m time (s): the time period between the moment in which the feet lose contact with the wall and the moment of the hip passage at a distance of 7.5m from the wall.
- Turn out 10m time (s): the time period between the moment in which the feet lose contact with the wall and the moment of the hip passage at a distance of 10m from the wall.
- Total Turn 7.5m+7.5m time (s): the time period from the moment when the hip joints swim trough the point placed 7.5m from the wall before turning, till the moment when the hip joints swim trough the point placed 7.5m from the wall after turning.
- Total Turn 5m+10m time (s): the time period from the moment when the hip joints swim trough the point placed 5m from the wall before turning, till the moment when the hip joints swim trough the point placed 10m from the wall after turning.
- Total time 50m (s)*:* time to swim two 25m breaststroke lengths.

Speed parameters

- Turn in 7.5m speed (m*s^{-1}): the swim speed from the moment in which the hip joints swim trough the point placed 7.5 m from the wall and the moment when the hands touch the wall.
- Turn out head speed (m*s^{-1}): swim speed between the moment in which the feet lose contact with the wall and the moment when the head breaks the water surface.
- Turn out 7.5m speed (m*s^{-1}): the swim speed between the moment in which the feet lose contact with the wall and the moment of the hip passage at a distance of 7.5m from the wall.
- Turn out 10m speed (m*s^{-1}): the swim speed between the moment in which the feet lose contact with the wall and the moment of the hip passage at a distance of 10m from the wall.
- Total Turn 7.5m+7.5m speed (m*s^{-1}): the swim speed from the moment when the hip joints swim trough the point placed 7.5m from the wall before turning, till

the moment when the hip joints swim trough the point placed 7.5m from the wall after turning.

- Total Turn 5m+10m speed (m*s^{-1}): the swim speed from the moment when the hip joints swim trough the point placed 5m from the wall before turning, till the moment when the hip joints swim trough the point placed 10m from the wall after turning.

Distance parameter

One distance parameter, important for the analysis of the breaststroke underwater cycle, was recorded.

- Turn out distance (m)*:* the distance between the turning wall and the hip joints when the head breaks the water surface.

The following figures show the analysis of some of the measured parameters.

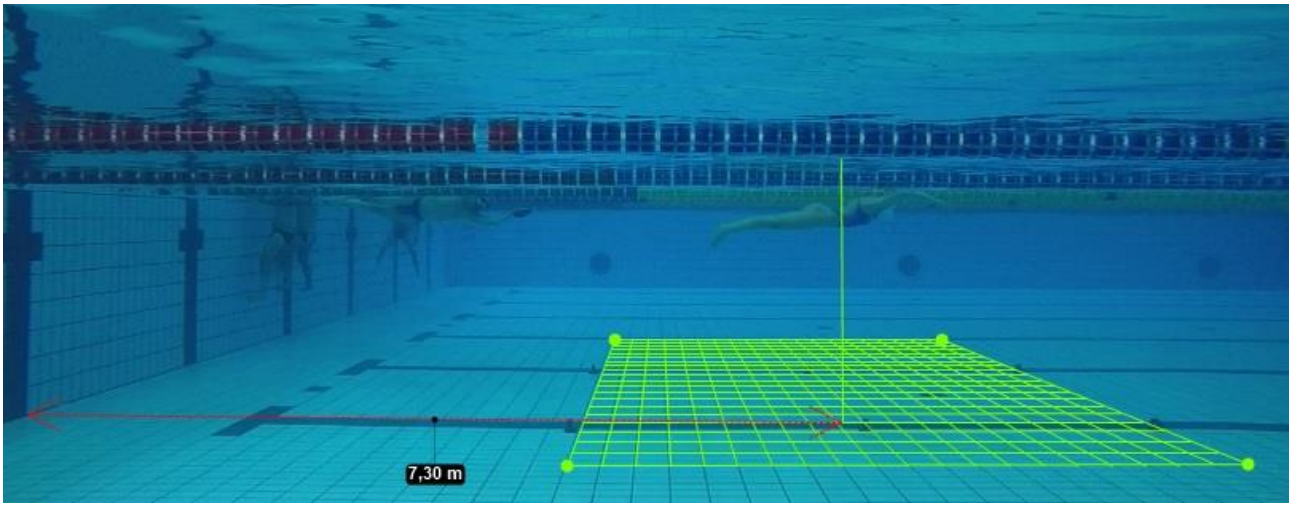


Fig.16 Hip-start wall distance when the head break the surface of the water

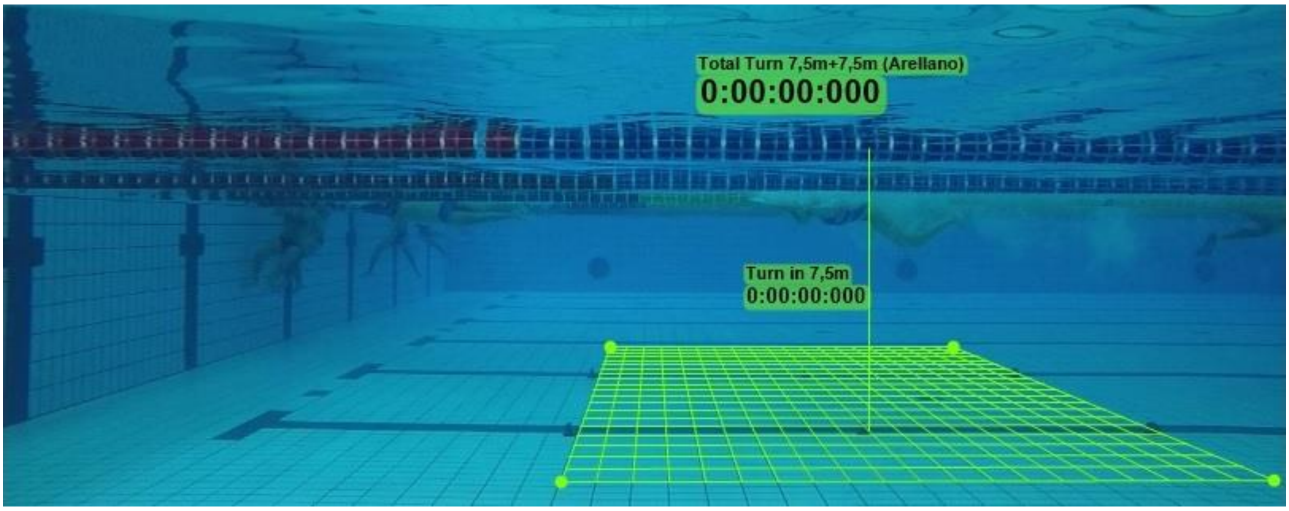


Fig.17 Hip passage on the 7.5m line from the start wall with consequent activation of the Turn in 7.5m and Total Turn 7.5m + 7.5m chronometers.

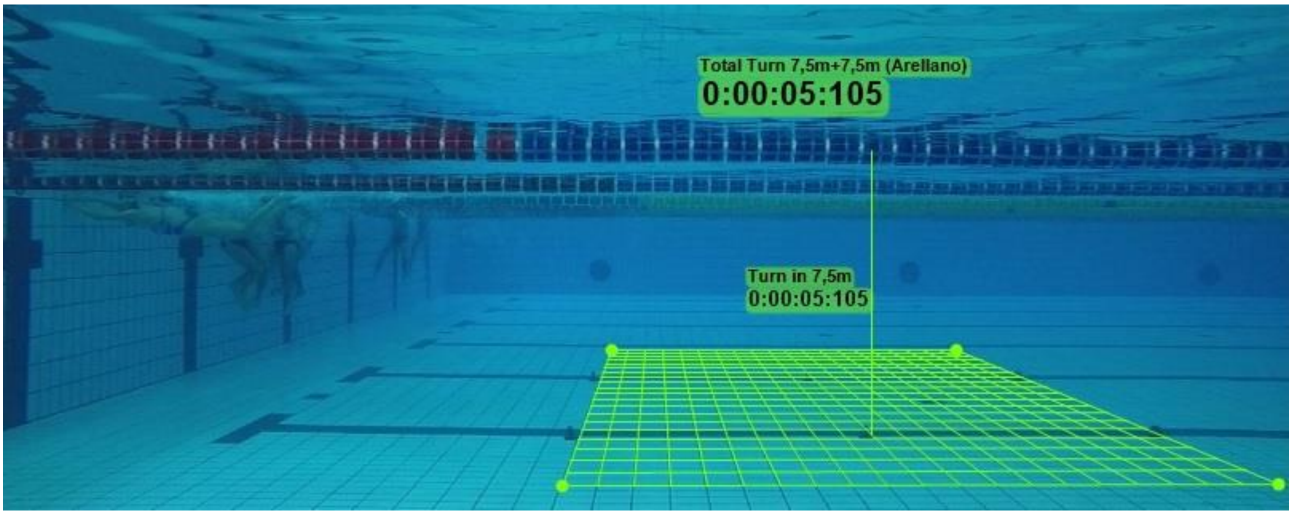


Fig.18 Contact of the hands with the turning wall and consequent stop of the Turn in 7.5m chronometer.

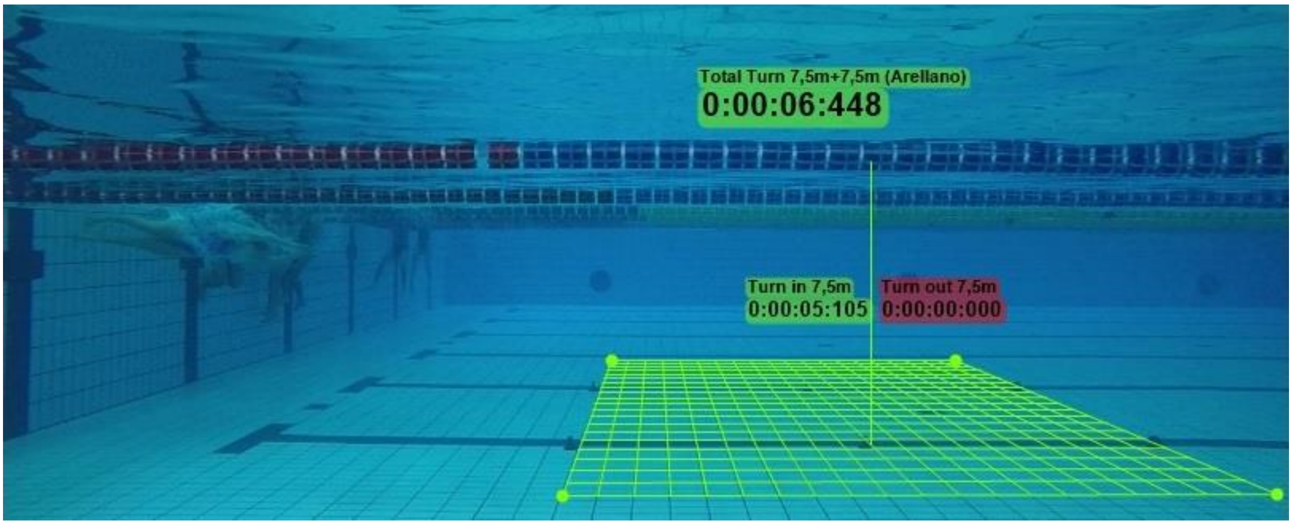


Fig.19 Moment of detachment of the feet from the turning wall and consequent activation of the Turn out 7.5m chronometer.

Statistical analysis

An independent T-test was used to compare the two different techniques of execution of the breaststroke underwater cycle.
All the analysis were performed with STATISTICA, version 12.0 for Windows.
The level of significance was set at p=0.05.

RESULTS

The results are expressed as the average of the three tests performed by each swimmer for both techniques. The results of the two independent examiners were also mediated.

The tables 6 and 7 report the results of the time and speed parameters, while the table 8 shows the results of the distance parameter.

No statistically significant differences between the two techniques were found.

Time (s)							
	Turn in 7,5 m	**Turn out head**	**Turn out 7,5 m**	**Turn out 10 m**	**Total turn 7,5 m + 7,5 m**	**Total turn 5m + 10m**	**Total time 50 m**
OLD TECHNIQUE	5.28±0.53	4.56±0.67	4.74±0.54	7.06±0.70	11.28±1.11	11.57±1.07	37.21±3.13
NEW TECHNIQUE	5.24±0.52	4.74±0.78	4.67±0.56	6.96±0.67	11.16±1.13	11.42±1.03	36.87±2.96

Tab.6 Time parameters expressed as means ± standard deviation

Speed (m*s^{-1})						
	Turn in 7,5 m	**Turn out head**	**Turn out 7,5 m**	**Turn out 10 m**	**Total turn 7,5 m + 7,5 m**	**Total turn 5m + 10m**
OLD TECHNIQUE	1.43±0.14	1.61±0.09	1.60±0.20	1.43±0.15	1.34±0.14	1.31±0.12
NEW TECHNIQUE	1.44±0.14	1.61±0.10	1.63±0.21	1.45±0.14	1.36±0.14	1.32±0.12

Tab.7 Speed parameters expressed as means ± standard deviation

Turn out distance (m)	
OLD TECHNIQUE	7.35 ± 1.16
NEW TECHNIQUE	7.62 ± 1.31

Tab.8 Turn out distance expressed as mean ± standard deviation

DISCUSSION

The results of the study show interesting trends, despite the absence of significant differences between the two techniques of execution in the sample analyzed.

Particularly, a trend in favour of the new technique emerges, both for time and speed parameters. Indeed the time and the speed of execution with the new technique seems to be respectively lower and higher than those obtained with the old technique, for the majority of the parameters.

Considering the *turn out distance* parameter, it is 27 cm higher in the new technique than in the old one; when the swimmer executes the underwater dolphin kick before the complete arm stroke he has an underwater phase longer than the execution with simultaneously arms and legs movement. This means that, with the new technique, the head breaks the surface of the water farer from the turning wall, lengthening the distance covered in underwater condition.

The analysis of the speed parameters allows to note that the *turn out head speed* in the two techniques is identical (1.61 m*s^{-1}).

These two results, higher *turn out distance* in the new technique and equal *turn out head speed*, lead us to think that the swimmer that performed the new technique permitted by the 2014 FINA rules swims for all the underwater phase at an average speed of 1.61 m/s for 27 cm more than the old technique.

Data collected from the video analysis by Haljand et al. during the most important international swimming competitions of the last 40 years (Haljand et al., 1989) and the data collected by Arellano thanks to the videos recorded during entire training seasons of elite athletes (Arellano et al., 2000) led to the conclusion that the speeds maintained by the swimmers during the underwater phases are higher than their own speeds maintained during the complete swim.

These data are also confirmed by the present study in which the speed in the parameter Turn in 7.5, indicating the speed of the swimmer in the last 7.5m before touching the wall and making the turn, is less than the speed in the Turn out head parameter, which measures the speed of the swimmer maintained throughout the underwater phase.

Also in other studies, previously cited, the researchers highlight the importance of the time spent underwater by the swimmers. Vilas-Boas et al. in 2010 said that, after careful analysis during the breaststroke races, the glide time during the swim and during the underwater phases reaches a percentage of 44% in the 200m (Vilas-Boas et al., 2010).

In 2007 Seifert L. et al., comparing international athletes with national level athletes during the start phase followed by the first 15m of a breaststroke race, show how international athletes remain underwater for longer time, making the most of the glide phase to reduce the distance to cover in non-underwater conditions (Seifert et al., 2007).

In the light of the results of the present study, it will be appropriate to evaluate the average speed of the swimmer sample in the first 30 cm after the underwater phase with the old technique (v_1 out), and compare it with the average sample speed in the last 30 cm of the underwater phase performed with the new technique (v_2 in).

In this way it will be possible to compare the two average speeds obtained and check whether a longer underwater phase is really advantageous.

Later, it would be interesting to compare the 30 cm after the underwater in the two techniques of execution (v_1 out, v_3 out) to calculate if the speeds are the same and then verify that emerging from the water further from the edge, thanks to the new technique, does not lead to a drop in underwater speed that leads to a further decrease in the first 30cm after the underwater phase.

Finally, it would be interesting to compare the performance in a breaststroke race, performed by employing the old underwater technique with those of a race carried out by performing the new technique to verify the impact of the two techniques on the whole competition.

Concluding, interesting trends emerged from the work, although not statistically significant, in favor of the new technique that seems to allow times and speed of execution better than the technique adopted before the 2014 change of regulation.

During this study, critical issues related to the recruitment of the subjects were encountered, as it was not easy to find swimmers suitable for inclusion criteria and available to participate in the study.

In addition, athletes and coaches had a week to develop the new technical gesture, a time that may not be enough to elicit statistically significant differences between the two techniques. Unfortunately, the swimmers could not spend more time learning the new technique, as they had to train for the upcoming competition period.

However, the absence of a statistically significant difference between the new technique, which the swimmers had never performed systematically before the study and the old technique, which they performed daily for years, is in itself an interesting result.

If the execution of the new technique for just one week produced results statistically comparable to the performance of the old technique, known for years and well-established, it is reasonable to think that if the athletes and the coaches spent more time learning the new technique, they could obtain increasingly interesting results, in terms of speed and time of execution of the breaststroke underwater phase.

CONCLUSIONS

Video analysis in swimming has been shown to represent an important tool both in the field of scientific research, in order to investigate the factors that influence the execution of a technical gesture or of an entire race, and, for athletes and coaches, in the field of biomechanical analysis, to provide reliable measurements to improve performances.

Already since the end of the 80s, Haljand et al. provided data and information to the coaches thanks to a scrupulous video analysis of every international competition, dividing the race into several parts and identifying for each of them the frequency and number of strokes of the swimmer (Haljand et al.1989).

Mason and Fowlie in a 1997 study wanted to provide coaches and swimmers with an analysis of their opponents with a clear and concise summary for each swimming event in which they participate (Mason and Fowlie, 1997). In this way the coaches of elite swimmers could use the analysis provided to develop a grid of data and define the strengths and weaknesses of the opponents against whom they had to compete, this was possible with a complete biomechanical analysis of each race phase: start, swim, turn, arrival.

Arellano wanted to emphasize the importance of video analysis during the seasonal training period and not only during competitions (Arellano, 2000). Employing the video analysis in training allows you to collect a lot of data and information that help to define in which aspects the athletes need to improve.

In elite swimming, a broad range of methods are used to assess performance, inform coaching practices and monitor athletic progression. Many reasons can lead the coaches to analyze the performance of the athletes. A study of Mooney et al. (Mooney et al., 2016) examined the performance analysis practices of swimming coaches and explored the reasons behind the decisions that coaches take when analyzing performance. Survey data were analyzed from 298 Level 3 competitive swimming coaches (245 male, 53 female) based in the United States. Results were compiled to provide a generalized picture of practices and perceptions and to examine key emerging themes. It was found that a disparity exists between the importance swim coaches place on biomechanical analysis of swimming performance and the types of analyses that are actually conducted. Video-based methods are most frequently employed, with over 70% of coaches using these methods at least monthly, with analyses being mainly qualitative in nature rather than quantitative. Barriers to the more widespread use of quantitative biomechanical analysis in elite swimming environments were explored. Constraints include time, cost and availability of resources, but other factors such as sources of information on swimming performance and analysis and control over service provision are also discussed, with particular emphasis on video-based methods and emerging sensor-based technologies.

In light of the results of the aforementioned study, it is important to give coaches and athletes the opportunity to have the quantitative results of video analysis at low cost.
To this aim, the two experimental studies presented in this dissertation were planned.
Both the first one, concerning the freestyle turn, and the second one, regarding the underwater phase of the breaststroke, were conducted by setting up an economically inexpensive setting, unlike what often happens for other video analysis or movement analysis systems.
The contained costs, however, did not prevent reliable measurements of the parameters examined, providing interesting results on breathing techniques in the approach phase of the freestyle flip turn and on the timing of the execution of the gestures in the underwater phase of the breaststroke.
The limited number of subjects, involved in these studies, don’t permit the generalization of the findings to all the categories of swimmers; however the results provide interesting topics for reflection that must be deepened trough studies on larger samples of elite and amateur athletes.
From the results of the studies described in the present dissertation, athletes and coaches can draw information that can be used and applied in the daily training, in order to increase performance during the race, by improving time and speed of execution.
The realization of these studies has allowed to create a setting consisting of a reduced number of equipment at low costs, reproducible with appropriate adaptations in many swimming pool contexts.
This feature makes it an adoptable system even in amateur contexts, that often have limited economic resources, but that still need to get quantitative data on the performance of the athletes.
It would be desirable, in the future, to apply the setting elaborated in multiple contexts, implementing an ever closer collaboration between swimmers, coaches and movement analysis specialists, in order to guarantee, since the young agonistic age, a careful analysis of the technical gestures that can induce positive effects on performance.

Even considering the limits of the studies, on the whole, the results of the dissertation show that the two-dimensional video analysis in swimming is a low cost and reliable tool for scientific purposes and coaching practices.

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