INVITED CONTRIBUTION

FUNDAMENTAL HYDRODYNAMICS OF SWIMMING PROPULSION.

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The purpose will be to describe the different methods applied in swimming research to visualize and understand water movements around the propulsive limbs and their application to improving swimming technique. A compilation of flow visualization methods applied in human swimming research is presented. Simple propulsive actions will be analyzed combining the kinematic analysis with the flow visualization: underwater undulatory swimming and sculling propulsion. The analysis of vortices generated and 3D analysis of the pulling path seems the most adequate method to develop a new understanding of swimming propulsion. The development of flexible and portable laser systems such as the recently incorporating fiber optics and fiberscopes, will enable the applicability of PIV in real swimming conditions to quantify the wake momentum and vorticity. New and attractive ideas are emerging: the possible use by the swimmer to his advantage of the vorticity if it is produced by an external source, such as the environment, another swimmer or the re-use of his own vortices during the stroke or after the turn will be topics for research in the near future.

Key Words: wake, sculling, undulatory, flow visualization, Strouhal number.

INTRODUCTION

The study of human swimming propulsion is one of the more complex areas of interest in sport biomechanics. Over the past decades, research in swimming biomechanics has evolved from the observation subject's kinematics to a basic flow dynamics approach, following the line of the scientists working on this subject in experimental biology (20, 56). As Dickinson stated (20) "at its most fundamental level, locomotion is deceptively simple, an organism exerts a force on the external environment and through Newton's laws, accelerate in the opposite direction", but the dynamics of force application are not as simple as they might at first appear, specially during swimming or flying where the force is applied to a fluid. In fact, it results from the complex three-dimensional interaction between a stationary fluid and a moving body with soft boundaries. The hydrodynamics of this phenomenon are yet not clear. The muscle contraction flexes or extends a particular joint, moving the limb though the water. The water previously occupied the limb's volume; the subsequent position required the displacement of its particles. At very slow limb displacement, the water particles will occupy steadily and in an orderly way, but at higher limb velocities the water is moving unsteadily, generating a turbulent wake behind. This subject was analyzed by Counsilman (18), who considered that "eddy resistance is more important than frontal resistance and that, at least theoretically, more propulsion is derived from the back of the hand than from the front of it".

In an ideal situation the hand is fixed in the water (no displacement and zero velocity) and the net shoulder muscles contraction produces a full body displacement forward of the swimmer's body (for example using the MAD system); there is no interaction between the hand and the water around it. In a real situation the hand interacts with the water and its velocity is increased. But increasing the backward velocity of the hand alone will not produce the desired forward velocity (similar to a caterpillar paddlewheel); a combination of curvilinear hand movements (up-down, left-right and backward) will produce the desired effect on body velocity (46). The propulsive force is a vector addition of lift (L) and drag (D) forces generated by the hand and they are proportional to velocity squared (see eq. 1,2)

$$L = 1/2\ \rho\ u^2\ C_L\ S \qquad \text{(Eq. 1)}$$

$$D = 1/2\ \rho\ u^2\ C_D\ S \qquad \text{(Eq. 2)}$$

Where u is the relative velocity with respect to the fluid (m/s), S is the hand's surface area (m^2), ρ is the water density (kg/m^3), C_L is the lift coefficient and C_D is the drag coefficient. The values of these coefficients are characteristic of the object tested and are a function of the angle of attack (α) and the sweep-back angle (ψ) as Schleihauf (44, 45) and Berger (7, 37) investigated. Maximum values of C_L (about 0.8-1.0) are obtained between 35° and 45°-attack angle, and maximum values of C_D (about 1.3) are obtained at 90°. The values of C_L and C_D are more similar when all possibilities of sweep-back (different "leading edges" orientations of the hand) angles are considered. This indirect method of propulsive force calculation is based on the proper knowledge of the hand position and its velocity in a three-dimensional reference system (water volume) and in conditions of extreme accuracy the coefficients can be calculated (26, 37) and the water refraction controlled in order to apply adapted DLT methods (25). Considering these limitations some index characteristic have been defined in the 3D pulling path (47):

a) Diagonality index: the average angle of the negative hand line motion and the forward direction at the points of first, second and third maximal resultant force production (57);
b) Scull index or lift-drag index: the average ratio of lift and drag forces (C_L / C_D) at the three greatest occurrences of resultant force (57);
c) Force distribution index: is the average location of the three greatest resultant forces expressed as a percentage of the total duration of the underwater phase of the arm pull (57).

A similar approach was used by Sanders (43) to obtain the propulsive forces alternative vertical breaststroke kicking applied by the water-polo goalkeepers.

Under this methodology four basic hand propulsive movements were defined (31, 32): Downsweep, insweep, upsweep and outsweep. Each stroke was therefore composed of a combination of these movements. For example, breaststroke is composed of outsweep and insweep.

The previous paragraphs based the understanding of swimming propulsion on steady-state flow mechanics that has left many questions unanswered. Some trials observing the flow behaviour around the swimmer's body lead us to try to apply unsteady mechanisms of force production to resolve them. However, such approach needs to analyze the flow behaviour around the propulsive limbs to identify the phenomena, a difficult task in a swimming pool, but quite common in fluid dynamic laboratories.

The traditional semantic classification of the propulsive forces in terms of drag and lift is not relevant when applying a non-

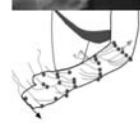
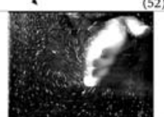
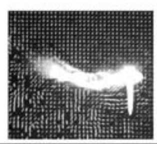
steady hydrodynamic analysis and it is probably more useful to investigate the momentum and the vorticity or their respective scalar indicators the energy and the enstrophy applied by the swimmers limbs on the water.
Our purpose will be to describe the different methods applied in swimming research to visualize and understand water movements around the propulsive limbs and their application to improving swimming technique.

OBSERVING WATER MOVEMENTS
During aquatic locomotion forces are exerted by the body and limbs against the surrounding water, which is not fixed in position but instead yields in response to the action of propulsive surfaces (27). Colwin (12, 13) and Ungerechts (54) suggested new ways of analysing the swimming propulsive movements based on the observation of water around the propulsive limbs. All bodies (including propulsive limbs) displacing water will create vortices (rotating water masses) in their wakes; they carry a fairly high momentum, which can transfer a strong propulsive impulse to the body (55). As Bixler (9) stated when an object accelerates, decelerates, or changes its shape or orientation as it moves through a fluid, the flow will be unsteady. Thus, the resulting pressure field exerted by the fluid on the body's surface, responsible for the propulsion, will be again unsteady, varying differently with both time and position. In this conditions the propulsive drag and lift forces developed by a swimmer's hand at a given time are dependant not only upon the velocity at that time, but also the acceleration at that time and the acceleration history of the hand prior to that time. Under these criteria the calculated ***D*** need to be updated in unsteady flow conditions, for example, through a quasi-steady approach (9):

$$D = 1/2\ \rho\ u^2\ C_D\ S + k\ \rho\ \forall\ a \qquad \text{(Eq. 3)}$$

Where: ***k*** is the added mass coefficient, ∀ is the characteristic volume of the body on which ***k*** is based and ***a*** is the instantaneous acceleration at time ***t.*** The first term is equation 2, which is the drag due to steady state motion. The more water that is "grabbed" by the swimmer's hands the larger the added mass and the larger the propulsive drag. Such quasi-steady model theory is of common practice when investigating fluid forces on structures (49).
Based on the observation of flow movements it is possible to measure the total locomotor force (in fishes). It is calculated by dividing the fluid momentum of the vortex ring (or rings) shed over a fin beat cycle by the duration of the fin beat. The momentum of each vortex ring is itself calculated as the product of the water density, the area of the vortex ring and the mean ring circulation (27). The described procedure, simple in essence but complex in its applicability in human motion, encourages us to apply sophisticated methods of flow measurement such as Particle Image Velocimetry (P.I.V.). This methodology broadly used in fish propulsion studies has been recently applied in human swimming in a very controlled situation (2, 35). Nevertheless, we must improve the methods used to visualize the flow around the swimmer's limbs before applying this advanced methodology.
A compilation of flow visualization methods applied in human swimming research is presented in Table 1. The capabilities and limitations of each method are very different and are adapted to research conditions: laboratory (small water tanks), swimming flume or swimming pool. Under very controlled conditions it is relatively easy to observe and measure water movements; however in real swimming the observations are more complex and less accurate, as it is only possible to analyze the problem in a qualitative and descriptive way at the moment.
The approach developed in Tsukuba University is a first trial to apply PIV in freestyle swimming. A sophisticated swimming flume, a tool similar to that the applied in fish swimming research, is being used. The flume is filled with small close-to-buoyant particles. A laser light sheet within the working area illuminates a horizontal plane, parallel to the water surface. The arm pull action of the swimmer enables his hand to cross the illuminated slice of the flow during the insweep and outsweep. A triggered high-speed camera records the illuminated plane while the hand crosses this specific zone, so that it is possible to observe the hand displacement and water particles movements. Pairs of consecutive images from the video sequences are then input into a cross-correlation processing algorithm, which takes a small, user-defined area of the image and calculates the direction and magnitude of each particle's velocity within that region. This yields a single velocity vector representing the average flow within that small area. Repeating this analysis at each location, a map of velocity vectors can be calculated that provides a snapshot of wake structure and strength (27, 35, 49) [see figure 1.7].

Table 1. Flow visualization methods applied in swimming research (PIV listed bellow is not a flow visualization technique but a mechanism one).

Method	Description	Authors	Sample Picture
1. Natural or spontaneous bubbles	As a result of accidental air entrapment (16)	Colwin (12-16) Ungerescht (54)	
2. Tuft	Observing the direction and motion of the tufts made of thread or lod of an appropriate length and material (36)	Hay (24), Ferrell (22), Toussaint (51), Nakayama (36)	 (52)
3. Reflective particles	Particles of solid tracer are distributed uniformly in the fluid (36)	Arellano (1) Redondo (40)	
4. Injected bubbles and bubbles wall (Path line method)	Fluid tracer (air) is injected continuously into the flow though fine tubes or holes (36)	Arellano (1, 3, 4)	
5. Coloured dye	Fluid tracer (dye) is injected continuously into the flow though fine tubes or holes (36)	Colman (11) Persyn (38)	
6. Sodium Fluoresceinate powder	The flow is visualized using a chemical reaction between the fluid and surface substance (36)	Colman (10)	See figures in this book section (10)
7. PIV	A picture capturing movements of tracer particle is analyzed through some optical and /or mathematical procedure to get velocity information (36)	Arellano (2) Matssuchi (35)	

As Colwin (16) stated "vortices are the muscles and sinews of propulsion, and the activity, seen here in the flow field, represents a history of the swimmer's propulsion". The application of injected bubble enables us to observe the wake produced by a swimmer after the propulsive limb movements; this history tells us about the efficiency of the energy transfer mechanism between the swimmer and the water and his control of propulsive actions. Swimmers of different levels generate very different wakes during simple and complex aquatic movements. In some cases, better swimmers generate bigger vortices that rotate quicker and are kept stationary in the water after the swimmer's stroke or kick, enhancing more efficient energy transfer mechanisms. Simple propulsive actions will be analyzed combining the kinematic analysis with the flow visualization: underwater undulatory swimming and sculling propulsion.

UNDERWATER UNDULATORY SWIMMING

At certain Reynolds numbers, when a wake is generated, a double row of vortices is visualized. Their characteristics depend on the situation of the immersed body, stationary (like a hand following a rectilinear path) or oscillating (like a fish tail). The vortex street shed from stationary bodies produces drag and a staggered Kárman vortex street. An oscillating tail or foil produces a vortex trail shed where the sense of each vortex in the trail is opposite to that of the Kárman 'natural' shedding case (see figure 2); it can be considered as 'thrust-type' trails as the induced momentum produces thrust upon the disturbing body initiating the trail (58).

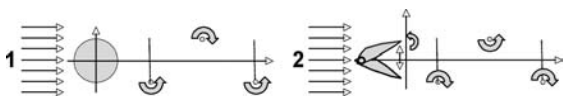


Figure 2. 1. A vortex street shed from a stationary body that produces drag. 2. A vortex trail shed produced by an oscillating foil that produces thrust. Adapted from Weihs (58).

When a fish undulates and propels itself with its tail fin, it produces a water displacement that can be observed: wake vortices. Every vortex generated after each stroke has a different rotation (clockwise or anti-clockwise), producing a jet of water undulating between vortices and flows in the direction opposite to the swimming direction (56). What makes the high efficiency and high thrust of a foil is the manner in which the vortices are arranged behind the foil, the oscillating tail is a more efficient method of propulsion than a classical propeller (42). Before starting to study complex strokes such as the freestyle-pulling path, we decided to begin with underwater undulatory swimming (UUS). The UUS is fully underwater (wave drag can be considered negligible), the body is extended horizontally with the arms stationary, legs and body movements can be considered symmetrical and displacement is obtained with leg and body propulsive undulations or oscillations.

The Strouhal number is a dimensionless number, representing the ratio of unsteady and steady motion (23). Strouhal number (***St***) can be defined by the equation:

$$St = A_{p\text{-}p} f / U \quad \text{(Eq. 4)}$$

Where $A_{p\text{-}p}$ is the tail-beat peak-to-peak amplitude (the distance from the peak of the tail fluke upstroke to the peak of the tail fluke downstroke), f is the tail-beat frequency and U is the mean body velocity. It can be interpreted as well as a reduced frequency, providing a ratio between the momentum caused by the tail oscillation and that due the forward motion of the swimmer. It is then an estimate of the relevance of the unsteadiness in the fluid-body interaction to the overall fluid structure. In our previous studies (4, 5) swimmers with less experience obtained values higher than 1, while top performers obtained values around 0,80. These values are far from the results of efficient water animals (between 0,25 and 0,35 (53)). The practical use of this number is to play with its variables in order to bring its value closer to the more efficient range without decreasing the swimmer's speed, in this case with modifications in frequency and amplitude values. In that sense, it appears to be part of an indicator of the efficiency in the aforementioned energy transfer mechanism. Parameters such as the timing of the change of direction of the tail (acceleration-deceleration), the tail's curvature and its performance in generating circulation or the synchronization between vorticity creation and tail, knees and hip motion appear to be linked to the obtained performance for a given thrust.

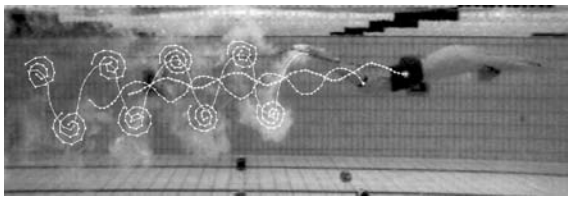


Figure 3. Spiral drawing representing the size and rotation direction of the vortices generated after each change in the kick movement. Some authors have suggested the thrusting impulse is a reaction to the jet stream away from the body, moving between the counter-rotating vortices (28, 53, 59). The trajectories represent hip, knee and big toe. The vortices drawn represented an instant after the change of direction in the big toe trajectory. All the traces were performed with the computer programme GraphClick v2.8.1 (Arizona Software).

The combination of the body landmarks kinematics and flow visualization demonstrated in UUS:

a) A wake of counter-rotation vortices is clearly observed after kick-up and down (see figure 3)

b) The feet leave the vortex behind after each change in their trajectory, maintaining their rotation for several seconds while its size is expanding (see figure 3)

c) The vortex wake pushes a hypothesised jet stream (see figure 3)

To think that the vortex creation *is not related* to the forward displacement of the swimmer's body seems unrealistic considering the controlled circumstances of the UUS displacement studied. The analysis of undulatory displacement of the body land-marks using Fourier analysis demonstrated in UUS a coordinated sequence and increase of amplitude and peak vertical velocities from shoulder to feet. The body landmarks are phases of a simple sinusoid oscillation with very rhythmical motion. The high mean velocities of centre of mass (about 2 m/s) measured in top swimmers are obtained with smaller ranges of c.m. velocities than we expected (about 0,4 m/s) and similar ranges to the most continuous stroke: freestyle (33). In spite of the limits recently imposed by the FINA regulations the applicability of this stroke in the underwater phase of the starts and turns is clear (17, 34).

THE SECRETS OF SCULLING

Another basic propulsive movement is horizontal scull. This short propulsive action of the hand is applied specially in synchro swimming or water-polo (goal-keeper) to keep some part of the body out of the water stationary and high and in the insweep phase (bending the elbow) of all the competitive swimming strokes (6). It is characterised by an important application of hydrodynamic lift force (6, 45). The basic movement is performed using a trajectory similar to an ellipse in the front view and an elliptical-figure eight trajectory in the horizontal plane (see figure 4).

Figure 4: Trajectory and plane position during a cycle of vertical sculling movement (50 Hz). It can be observed the changes in the attack angle, leading edge and trailing edge (sweep back angles) every half stroke (stroke reversal).

The analysis of this movement under the steady or quasy-steady theories would lead us to find that the continuity of propulsive force application could be stopped during the stroke reversal actions. This phenomenon has been analysed by biologists that studied the insects and birds flight finding that the conventional mechanisms (steady) simply do not provide enough lift for a flying insect to stay in the air (8). Delayed stall, rotational lift and wake recapture represent three distinct, yet interactive, mechanisms of unsteady lift generation which are necessary for flying insects to achieve the flight forces needed to support their weight and carry loads (21). An advance in biofoil rotation not only generates circulatory forces at the end of each stroke, it also increases the strength of the wake and ensures that the wing has the proper orientation to use the shed vorticity for generating positive lift at the start of the next stroke (21). It can be hypothesized that sculling actions observed in the figure 4 use the previously mentioned mechanisms. The movement is composed by four kinematic portions: two translational phases (insweep and outsweep), when the hands move through the water with efficient angle of attack (about 40º), and two rotational phases (pronation and supination), when the hands rapidly rotate and reverse direction. The *delayed stall* can be an addition to the forces generated during the hand translation with high angles of attack. Our observations demonstrated that big vortex is generated and de-attached after the start of each translational phase. During the stroke reversal and based in the *rotational circulation* mechanism (a specific application of the Magnus effect) it is necessary an early hand flip, before reversing the direction, then the leading edge rotates backward relative to translation and should produce an upward component of lift. Depending on the timing of the referred stroke reversal one can expect *cumulative Wagner effect* acting in attenuating the generated lift (19). One additional lift force can be obtained with the *wake capture*. The hand benefits from the shed vorticity of the previous stroke. If rotation precedes stroke reversal, the hand intercepts its own wake so as to generate positive lift. It is possible to argue in this case the swimmer's ability to extract energy from its own wake. What is also possible provided a sufficiently high Strouhal number is achieved is to produce wakes consisting on maximum backwards momentum vortices, as is frequent in animal swimming (29, 30). Using particle tracking on the wake of a hand stroke it is possible to delimit the regions of positive (anticlockwise) and negative (clockwise) vorticity on the plane of the laser sheet used. It is also possible to apply unsteady Kutta-Joukovsky theory to relate pressure and velocity measurements as discussed in Redondo et al. (39-42).

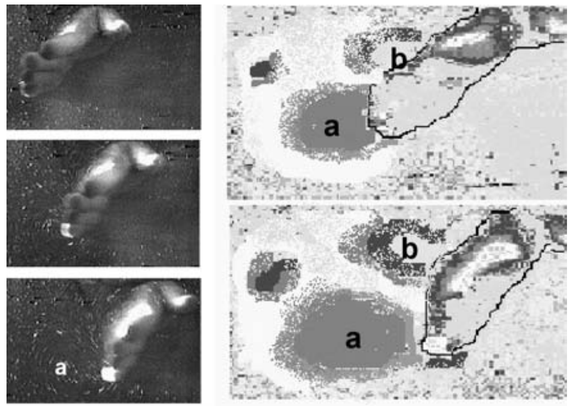


Figure 5: Trajectories of the seeded particles in an experimental tank as a hand stroke is performed. A vertical plane of laser light is used to film the wake at (50 Hz) left. Two maps of the vorticity are shown in the right images showing the shedding of positive (blue-b-) and negative (red-a-) vortices.

Hand drag coefficients obtained experimentally at different water speeds were related to the Reynolds number (Re) and compared with those obtained by Schleihauf, (45, 46), for a wide range of angles and speeds, which included the turbulent wake transition. The drag coefficient decreases when the Reynolds numbers increase near the transition with values of the drag and lift coefficients from 20º to 90º-sweep angle when Re is high [9.4×10^4] (39). The detailed analysis of velocity and vorticity balances in the wakes of swimmers limbs is still at large but figure 5 shows the strong dipole structure produced by a hand stroke (40).

CONCLUSIONS

The analysis of vortices generated and 3D analysis of the pulling path seems the most adequate method to develop a new understanding of swimming propulsion. The development of flexible and portable laser systems such as the recently incorporating fiber optics and fiberscopes, will enable the applicability of PIV in real swimming conditions to quantify the wake momentum and vorticity.

What may be obtained using an integral balance of the momentum and vorticity of swimmers wakes is the feedback necessary to obtain maximum propulsion, irrespectively if it is due to drag or lift projections of the limbs. This is clearly maximized when minimal balances of vorticity, which occur when coherent structures do not spread sideways, are coupled with maximum momentum and minimal energy. This is not an easy balance as demonstrated by a single vertical wake by Linden and Turner (30). For the simpler underwater undulatory swimming analysis on the Strouhal number on swimmers (4) shows that humans are still far from fish and dolphins, that obtain maximum propulsion at about St= 0.2-0.4, (50).

New and attractive ideas are emerging: the possible use by the swimmer to his advantage of the vorticity if it is produced by an external source, such as the environment (48), another swimmer or the re-use of his own vortices during the stroke or after the turn will be topics for research in the near future.

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INVITED CONTRIBUTION

ANALYSIS OF SWIMMING TECHNIQUE: STATE OF THE ART: APPLICATIONS AND IMPLICATIONS.

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INTRODUCTION
Methods of analysing motion have advanced greatly in recent years due to improvement in technology as well as application of scientific approaches. Methods of analysis may involve video based techniques from which kinematics and kinetics can be derived or direct measurement of velocity and force using various velocities and force transducing devices. At the Centre for Aquatics Research and Education (CARE) we have developed methods based predominantly on analysis of video. Analysis based on video ranges from qualitative analysis without quantification of variables, to three-dimensional analysis of kinematics and kinetics from digitised body landmarks from several cameras.
The purpose of this paper is to present video-based methods of collecting data, analysing data, and presenting results for different levels of analysis including qualitative analysis and simple quantitative analysis for immediate feedback, two-dimensional (2D) and three-dimensional (3D) quantitative analysis of kinematics, and deriving forces from the whole body centre of mass. Examples of specific applications and implications are described.

STATE OF THE ART FACILITIES AND EQUIPMENT
In 2000 a six lane 25m swimming pool was planned to accommodate research in aquatics, education and training in aquatics in the Department of Physical Education Sport and Leisure

Studies, and to serve some of the aquatics recreational needs of students and staff of the University of Edinburgh. Fortunately, research was recognised as a priority and considerable flexibility was afforded in designing the facility to accommodate research.

Lighting
The pool room has no windows. This ensures that lighting is consistent and there are no 'shafts' of light affecting the quality of the video recordings. Lighting is supplied by large lights with colour temperature resembling natural white light. Large reflectors are located strategically to disseminate the light evenly to maximise video quality and reduce shadow effects. Three levels of lighting are available with the maximum setting (1000 Lux) used when video recording.

Cameras and camera housings
Up to eight three chip high resolution JVC KY32 CCD 'gen-locked' cameras operating at 50 fields per second record motion simultaneously. Up to three cameras can be used for capturing the motion from above-water perspectives and up to six can be used to capture the below-water motion. Currently three are deployed above water and five below water.
Limitations regarding the dimensions of the building meant that pits or corridors for housing cameras to obtain below-water views were not possible. To overcome this limitation, camera housings were recessed into the walls at six locations – on each of the side walls at 12.5m (for analysis of mid-pool technique) and at 2.5m (for starts and turns) and in the end wall between lanes 1 and 2 and between lanes 5 and 6 (for front views). Although this was a pioneering and problematic exercise it has created some advantages. The cameras are actually in the water and therefore the light rays do not pass through thick glass. This eliminates distortion and the effects of changing angles of the camera axis to the glass when panning and tilting. Kwon (6) has shown that distortion is greater the closer the camera is to the glass. Therefore, depending on the structure of the viewing windows, reduction of distortion when cameras are placed outside the pool is often at the expense of the range through which the camera can pan. The housings at the University of Edinburgh pool have been designed to maximise the angle of pan possible. This means, for example, that the mid pool camera can be panned to track a swimmer through the whole 25m lap. The cameras remain permanently in the water in a constant state of readiness for recording. They can be removed readily for annual servicing which includes replacing the waterproofing 'o rings' of the cameras and pan and tilt motors.
The cables carrying signals to and from the cameras were laid during construction of the pool and are therefore invisible and unobtrusive. In addition to remote electronic control of pan and tilt, camera height can be adjusted readily from the pool deck by a mechanical winding mechanism. Clear perspex covers protect the cameras from swimmers and swimmers from the cameras. These can be removed easily when production quality recordings are required and when distortion free quantitative 2D and 3D analyses are required. It has been found that the quality of the recordings is not affected by the covers for qualitative analysis.
In addition to the six underwater cameras, three above water cameras are supplied by cables that are extendable to any part of the pool deck from three different locations. Camera mountings are located at four elevated positions on the side walls of the swimming hall. A long camera boom provides flexibility in obtaining specific views, for example from directly above a swimmer. The boom runs on rails beside the pool so that a particular perspective of a swimmer can be maintained throughout a swim. The boom is also useful for suspending EMG electrodes for various types of aquatic research including research in hydrotherapy, and for collection of expired air.

Remote control of camera functions and data collection
The nine cables terminate in an air conditioned control room that has a window looking out to the pool. The cables interface to a control system enabling simultaneous 'gen-locked' recording at 50 fields per second. The computer system comprises a control computer and nine storage computers, each of which is dedicated to one camera. The control software (Cameron Communications Ltd) allows any combination of cameras to be used and the recording time to be set. The software allows the user to select any view for display on a control room monitor either in split screen or full screen of a camera selected using the software. The shutter speed, focus, zoom, and gain of each camera are set independently and can be stored to avoid unnecessary repetition and wastage of time between testing sessions. Data are compressed during collection and stored as 'AVI' files.

Playback
Following recording, the AVI files can then be replayed immediately by standard video players such as Windows Media Player, the playback software developed by Cameron Communications, and by qualitative analysis software such as Dartfish. The software by Cameron Communications facilitates quick selection of camera views from a 'playback library' for playback as one camera view, two synchronised views of the same swim, or comparative views of two separate swims. Control features of the software include a slider bar for rapidly locating the section of interest, two speeds of slow motion, single frame advance, pause, and zoom.

Poolside display
The control room is linked by hidden cable to a an air-conditioned poolside compartment housing six 27" monitors for live feedback of any combination of views and two 42" plasma screens for software control and digital playback. Typically, coaches and analysts observe the performance live by watching any of the selected camera views and together with swimmers observe the performance on one of the plasma screens immediately after the swim. With the recent introduction of a remote mouse and keyboard, recording and playback can be controlled on poolside by analysts or coaches.

Concurrent downloading of AVI files to CDROM or DVD and analysis stations
Concurrent with collecting data and providing immediate poolside feedback, recorded AVI files can be downloaded onto CDROM or DVD. The files on the control computer and hard discs for each camera are accessible from a network of five analysis stations in the building. Two of these analysis stations are offices while the others are research laboratories. This means that material for coaches and athletes to take home for further scrutiny can be available very soon after completion of the testing session.

QUALITATIVE ANALYSIS AND SIMPLE QUANTITATIVE ANALYSIS FOR IMMEDIATE FEEDBACK

Various programs provide immediate feedback to swimmers and coaches. Other centres, for example, the Centre for Aquatics Research (CAR) at the University of Granada, and the Katholieke Universiteit Leuven, have developed sophisticated automated reporting systems. Several portable systems for quantifying fractional times of race sections including mid-pool, turns and starts of all swimmers in a competition have been developed, for example, the 'Australian' system by Mason and Cossor at the Australian Institute of Sport, and the system by Arellano developed at The University of Granada. One of the impressive features of these systems is their ability to calibrate distances across all pool lanes so that all swimmers in a race can be analysed.

Rather than analysing the race data of several swimmers in a competition setting, the CARE system specialises in high quality detailed analysis of individual swimmers swimming at coach-selected paces in a single lane. The advantages of the system include:

— Simultaneous synchronised views from several cameras including below-water mid-pool, below-water end-pool (turn) at 2m from the wall, front/rear view, and three above views including one directly above the swimmer using the boom camera.

— Zooming to maximise the image size to increase the ease and effectiveness of qualitative analysis and to increase the accuracy of measurements. This also facilitates high quality stills ('snapshots') with text or graphic overlays for qualitative analysis.

— The underwater views enable qualitative analysis of stroking technique and postures in both mid-pool and starts and turns, streamlining and glide trajectories.

— Panning on any one camera. When swimming continuous laps the mid-pool below-water camera is usually panned. When analysing turns and starts the end-pool below-water camera is often panned.

— The ability to measure kinematics associated with particular events not observable from above views. These include time and distance from the end wall at the instant of commencing kicking following turns and starts, speeds at wall exit, commencement of kicking, and surfacing.

— The ability to measure 2D angles with camera axes perpendicular to reference planes including the vertical plane along the line of the swimming direction from the below-water mid-pool and end-pool cameras and above-water boom camera; the vertical plane perpendicular to the direction of motion using the front/rear view underwater camera and above-water boom camera; and the horizontal plane using the above-water boom camera.

Variables routinely measured in the service programs, for example, for the swimmers of the Scottish Institute of Sport are shown in Table 1.

Table 1. Variables routinely measured for quick feedback.

Phase	Variable	View
	***Race parameters*:** stroke length; stroke frequency; speed,	mid U/W
	stroke index:	
	Times	
Mid-Pool	pull time	mid U-W
	recovery time	mid U-W
	***Angles at events (hand entry, hand exit, max, min)*:**	
	trunk to horizontal	
	hip in vertical plane	mid U-W
	knee in vertical plane	mid U-W
	shoulder roll to horizontal	mid U-W
	arm angle to line of travel	front U-W
	Trunk angle to line of travel	boom A-W
	Thigh angle to line of travel	boom A-W
	Hip angle in horizontal plane	boom A-W
		boom A-W
	Times	
	time in (from 7.5m to fist wall contact)	end U-W
	hand contact time	end U-W
	foot contact time	end U-W
Turns	time out (from last wall contact to 15m)	mid U-W or boom
	time commence kick (from last contact)	A-W
	time surface (from last contact to head breaking surface)	end/mid U-W
	total time	
	Angles	
	hip, knee, and trunk to horizontal at first contact	
	hip, knee, and trunk to horizontal at max knee flexion	end U-W
	hip, knee, and trunk to horizontal at max last contact	end U-W
	hip, knee, thigh and trunk to horizontal at surfacing	
	Distances	end U-W
	distance from wall at commence kick	
	distance from wall at surfacing	end/mid U-W
		end U-W
		end/mid U-W
	Times	
	block time (from gun to last contact)	boom
Starts	flight time (from last contact to head entry	boom
	glide time (from head entry to fist kick)	end U-W
	kick time (from first kick to head surface)	end U-W
	swim time (from head surface to 15m)	boom
	total time (gun to 15m)	
	Angles	
	hip, knee, and trunk to horizontal at gun	boom
	hip, knee, and trunk to horizontal at max knee flexion	boom
	hip, knee, and trunk to horizontal at last contact	
	hip, knee, thigh and trunk to horizontal at head entry	boom
	hip, knee, thigh and trunk to horizontal at foot entry	boom
	Distances	
	distance from wall at head entry	end U-W
	distance from wall at commence kick	
	distance from wall at surfacing	end U-W
		end U-W
		end/mid U-W

TWO-DIMENSIONAL (2D) AND THREE-DIMENSIONAL (3D) QUANTITATIVE ANALYSIS FOR RESEARCH

Staff and postgraduate students at CARE regularly conduct 2D and 3D data collection and analysis. 2D approaches include quantification of passive drag and added mass from digitised video data of subjects performing inclined glides, and quantification of movement rhythms and inter-joint coordination in various modes of swimming. 3D approaches are being used to quantify body roll and changes in temporal and spatial movement patterns across conditions such as swim speeds, stages of a simulated race, and preferred race distance.

Most studies in swimming have been limited to 2D analysis techniques. However, except in the case of distinctly planar

swimming skills such as dolphin kicking and flutter kicking without body roll, 2D analysis does not enable accurate quantification of swimming skills because the motion of body parts is not confined to planes perpendicular to the camera axes. In previous 2D studies bilateral symmetry has been assumed. It is preferable not to assume bilateral symmetry as it has been shown that swimmers' techniques are not symmetrical (1). Also, there are asymmetries in the anthropometric characteristics (12). For this reason, most of the quantitiative research conducted at CARE employs 3D data collection and analysis methods.
A three dimensional calibration frame (Figure 1, 2) 1.5 m in length, 1.5 m high and 1 m wide as described in detail by Psycharakis et al. (2005) was constructed to accurately calibrate the 3D space using the direct linear transformation (DLT) method.

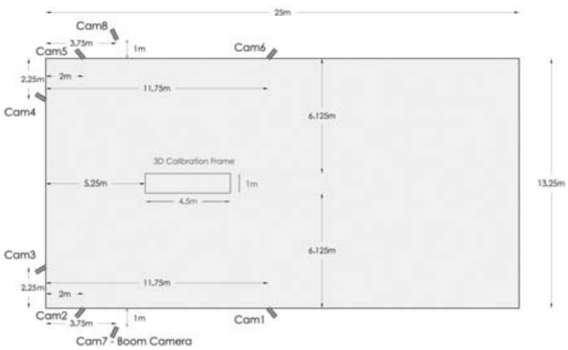

Figure 1. Position of the calibration frame relative to the cameras.

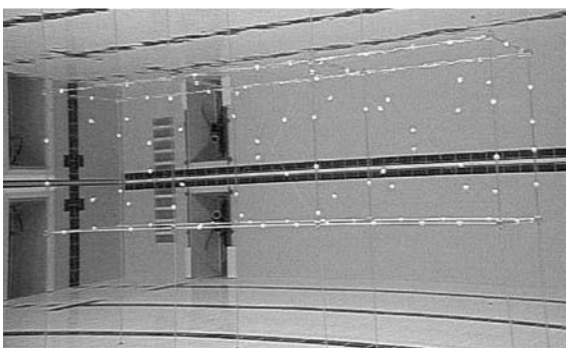

Figure 2. Underwater view of the calibration frame.

Flexural stiffness and orthogonal axes were ensured by using 12mm aluminium tubing and triangulation by wires. The locations of the centres of the 92 (46 above and 46 below water) 3cm diameter polystyrene spheres were then determined to within 1mm using surveying techniques.
Tests of the calibration procedures for a set of 30 digitised points yielded mean RMS errors of 3.9mm, 3.8mm and 4.8mm for the X, Y and Z axes respectively. Considering the volume of the calibrated space (6.75m^3), the errors in this study were similar or lower than those reported in studies by Payton et al (8) and Coleman and Rankin (2). The reliabilities indicated by repeated digitisations of one marker were ±0.4mm, ±0.5mm and ±0.4 mm, for the X, Y and Z axes respectively.
The APAS system is used for digitising the landmarks in each camera view and determing the 3D locations using the DLT algebraic equations arising from the digitised coordinates of the calibration markers. Above and below water 3D coordinates resulting from separate DLT transformations of above and below-water landmarks are then merged using a MATLAB program to produce continuous time series for each landmark. Variables of interest for each study are then determined using bespoke MATLAB programs and sub-routines. These typically include linear and angular kinematics with respect to inertial and internal frames of reference.

DERIVING FORCES FROM THE WHOLE BODY CENTRE OF MASS

It is well established that the accuracy of kinematics and kinetics derived from position-time data using a rigid-link human body model is dependent on the accuracy of estimating the segment masses, segment centre of mass locations relative to the segment endpoints and, in the case of angular momentum and angular kinetics, segment moments of inertia. These are collectively referred to as body segment parameter (BSP) data. The accuracy of segment centre of mass position also affects the accuracy of angular momentum and whole body angular kinetics due to its influence on the remote terms.
BSP data may be obtained from various sources that may be categorized as cadaver studies, immersion studies, direct measurement techniques, and mathematical models (11). The methods vary in the extent to which they take into account individual characteristics and therefore vary in the accuracy of the BSP data and consequent calculated values of kinematics and kinetics. For example, Miller and Nissinen (7) found large discrepancies between ground reaction forces derived from whole body centres of mass digitized from cine film and ground reaction forces measured directly from a force platform. BSP data were identified as contributing to those errors.
The Elliptical Zone method developed by Jenson (5) is a mathematical modeling technique to determine BSP data of each body segment of individual subjects. The method applies the assumption of Weinbach (13) that cross sections of the body segments can be modeled accurately as ellipses. Dempster (4) found that this assumption yielded very small errors with the exception of the shoulders. Using BSP data obtained by the elliptical zone method Sanders et al. (1991) found that the low frequency parts of the ground reaction forces of drop jumps derived from digitized high speed video were within 3% of those obtained directly from a force platform. Wicke and Lopers (14) found that the volumes of several body segments and the whole body can be measured accurately using the elliptical zone method. Although the elliptical zone method appears to offer the advantage of providing accurate BSP data for any individual, its use has not become common. Proponents of the method typically project photographic slides of the front and side views of the subject onto a large digitizing table such as a PCD Model ZAE 3B (5) and Calcomp 9100 (10). A cursor is moved along the edges of body segments to obtain the diameters of the ellipses required for input to the ZONE program that then calculates the BSP data. Therefore, application of the method has been limited by the availability of digitizing tables and data collection programs compatible with the digitizing device.

Recently, researchers at CARE (3) have developed a PC version of Jensen's 'elliptical zone' digitising program to yield accurate body segment parameter data. The software has several features designed to maximise the accuracy of the BSP data and its ease of use. Images of the calibration rods and body segments can be zoomed prior to digitising or tracing. A user can 'undo' mistakes and continue from the last correct entry. The body segments can be outlined easily using a laser mouse with the segment zoomed. If the outline is not as desired it can be redone. The elliptical cylinders are generated and displayed automatically. Figure 3 illustrates examples of the traced outlines from which the diameters of the elliptical zones are determined.

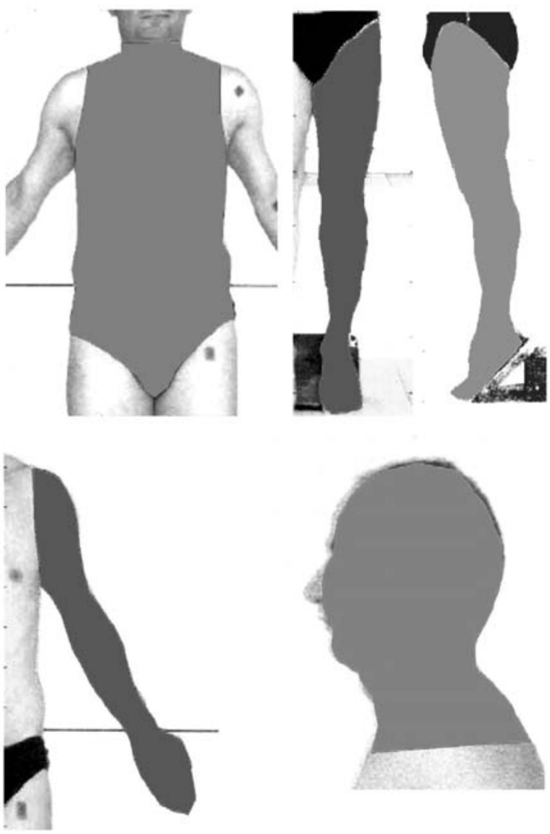

Figure 3. Examples of the outlines of body segments obtained by tracing the image with the mouse.

CONCLUSION

This paper described how 'state of the art' video equipment and video-based methods are being applied to assist analysis and research in swimming at the Centre for Aquatics Research and Education. Applications ranging from qualitative analysis for immediate feedback to 3D analysis to advance knowledge of how performance is optimized were presented.

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EFFECTS OF FATIGUE ON THE KINEMATIC HANDS SYMMETRY IN FREESTYLE.

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The purpose of this study was to investigate the effects of an exhaustive test on the symmetry of right and left hands trajectories. Eight male international swimmers performed 25 m in

1/2 tethered swimming at maximal velocity to calculate power before and after an exhaustive test of 4*50m freestyle. Right and left fingertips were digitised frame by frame from underwater views (50Hz). The trajectories were characterised by different points in the frontal plane (O), (I) and the sagittal plane (F),(D) et (B) to calculate the symmetry index (SI) based on the differences right-left coordinates. The spatial symmetry and the temporal asymmetry observed for all the points was maintained after the exhaustive test. The stable spatial symmetry with fatigue could be related to the high level of the population. The temporal asymmetry was not associated to the breathing side or to the dominant hand and could reflect the individual force-time patterns within the stroke.

Key Words: freestyle, fatigue, kinematic, symmetry.

INTRODUCTION

Symmetry can be defined as an exact correspondence between opposite halves of a figure or a form, whereas asymmetry is any deviation from this "ideal" structure (5). During walking, Robinson *et al*. (1987) determined a symmetry index (SI) to evaluate the gait symmetry before and after chiropractic manipulation on patients. For Herzog *et al*. (1989) acceptable symmetry in walking corresponded to SI lower to ± 10%. Goble *et al*. (2003) observed a decrease of kinematic and forces asymmetry with the increase of walking velocity. In running, Karamanidis *et al*. (2003) confirmed the symmetry of the gait. All these studies involved the lower limbs movements during terrestrial locomotion.. During swimming, the propulsion were principally generated by the upper limbs. Front crawl is characterised by alternative right and left arms strokes associated to a varying number of kicks (11). Symmetry in swimming was recently investigated by Haffner and Cappaert (1999) who reported symmetry on angular values of the upper limb for international swimmers. Cappaert and Van Heest (1999) concluded that the symmetry of the studied parameters reflected the most efficient stroke and thus characterised the best swimmers.

Other studies underlined right and left differences for the body roll angle (2), (4), (10), stroke duration with greater values for the breathing side (1), (16) when Goldfuss and Nelson (1971) and Potts *et al.* (2002) have reported strength and power imbalance between both arms in competitive swimmers.

In regard to these previous results obtained in fresh conditions, the aim of the study was to investigate the effects of an exhaustive test on the symmetry of the right-left hand trajectories.

METHODS

Eight voluntary male international swimmers participated in this study (age: 22.5 ± 2.3 yr, height 1.87 ± 0.07 m and weight 79.0 ± 6.5 kg). Five swimmers were characterised by a unilateral breathing pattern (right-sided) whereas the three other presented bilateral breathing pattern. After a standardised 1200 m swim warm-up, each swimmer performed 25 m in semi-tethered swimming at maximal velocity to obtain maximal swimming power (P) before (pre) and after (post) an exhaustive test of 4*50m in freestyle.

A swimming ergometer, fixed on the start area of the pool, was used to collect instantaneous force (f) and instantaneous velocity (v) in semi-tethered swimming, the swimmer being attached by a cable-pulley system to a powder brake (Lenz). Two digital video cameras (Panasonic WV-CP454E, 50hz) were used to record the underwater frontal and sagittal views.

The right and left fingertips, were digitised frame-by-frame according to Schleihauf's software (Kinematic Analysis) over a stabilised portion of 5s in the middle part of the 25 m power test. The smoothed 3-D trajectories were characterised by different points in the frontal and sagittal plane (Figure 1). Each point was characterised by its temporal and spatial coordinates. To avoid any cumulative effect of the temporal parameters, the temporal coordinate for each point was calculated by subtracting the temporal coordinate of the previous point on the same axis ($t_n = T_n - T_{n-1}$ (s))

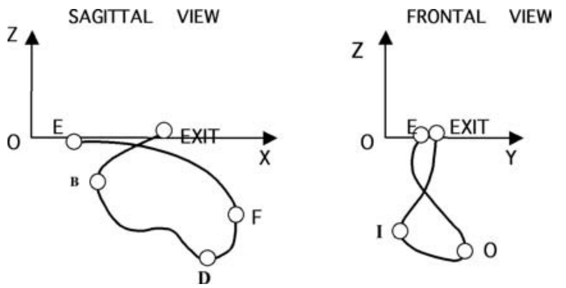

Figure 1. Characteristic points of the fingertip trajectory on the x-antero-posterior axis: F (maximal forward coordinate), B (maximal backward coordinate), on y-transversal axis: O (maximal outward), I (maximal inward), and on z-vertical axis: D (maximal depth).

According to Robinson et *al.* (1987), the symmetry index (SI) was calculated for each point

$$SI = \frac{X_R - X_L}{\frac{1}{2}(X_R + X_L)} \times 100$$

where X_R and X_L corresponded to the right and left coordinates. A negative SI indicated a right dominant side and a positive value a left one. Acceptable symmetry corresponded to SI lower to ± 10% (8).

The mean absolute SI, standard deviation (*s*) were calculated. Data from the left and right sides were compared through a non-parametric Wilcoxon test ($p<0.05$).

RESULTS

Results indicated that the maintain of the spatial symmetry (SI<10%) after the exhaustive test (figure 2A) with a temporal asymmetry (2B) was not significantly modified. Great individual variations were observed for the temporal asymmetry with right or left dominance depending on the subject and the point (figure 3).

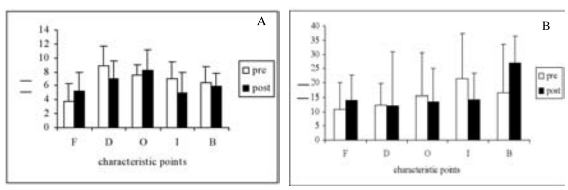

Figure 2. Mean absolute spatial SI (A) and temporal SI (B) of the characteristic points.

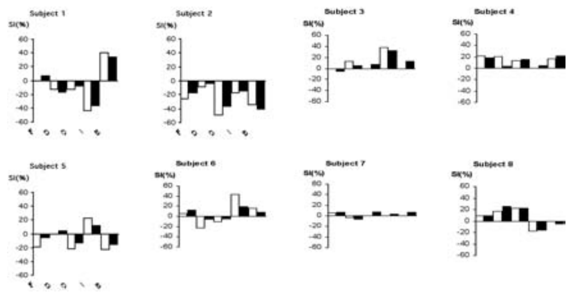

Figure 3. Individual temporal SI (%) for all the characteristic points.

Each subject presented a left or right dominance depending on the point excepted for subject 2 for which a left dominance was observed for all the points (figure 3). Whatever the subject and the point, the left or right dominance remained unchanged in fatigue condition.

DISCUSSION

The swimmers presented a spatial symmetry either in pre or post conditions. This was in the same way of the symmetry on angular values of the upper limb observed by Haffner and Cappaert (1999) in eight international swimmers. The stable symmetry reflected a strong pattern not affected by the fatigue condition as mentioned by Rodacki et al (2001). The present results on spatial symmetry highlighted the top level of the studied swimmers. Conversely, hands trajectories presented strong temporal asymmetry not modified with fatigue. This stable asymmetry appeared to be not related to the dominant hand and/or to the side breathing contrary to several authors who concluded that breathing have an influence on stroke duration and body roll angle (1), (4), (16) and on strength and power imbalance between arms (6), (12). The temporal asymmetry could reflect the individual intra-cycle force-time pattern in regard to previous results indicating differences among subjects in force-time pattern during the arm stroke (11), (15). These authors suggested that swimming propulsion is rather produced by impulse (force by time) than by high average force. Thus, it seems plausible that the observed temporal variability could reflect the variability of impulse distribution during the arm stroke.

CONCLUSIONS

The stable spatial symmetry and temporal asymmetry characterised the top level studied swimmers. The intra-cycle temporal variations suggested to study the force-time pattern to detect a possible effect of fatigue on impulse production within the stroke.

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FRONT CRAWL KINEMATIC: BREATHING AND PACE ACUTE EFFECTS

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The aim of this study was to verify the effects of breathing and no breathing and pace on stroke length (SL) and rate (SR) and swimming velocity (SV). Ten sprinter males performed 6 front crawl trials of 25 m (rest interval: 1min30s). SL, SR and SV were measured under two breathing conditions: breathing to the preferred side every cycle (B) and no breathing (NB), and three paces representatives of: warm up pace, 1500 m freestyle race pace, and 50 m freestyle race pace. Each trial was filmed

with a motion analysis system (60 Hz) from sagital view. A reflective marker was fixed to the swimmer's right wrist to quantify SL and SR. SV was obtained by the SL and SR product. Under NB conditions, SR and SV increased independent of the pace. The increase of pace was related to decrease of SL and increase of SR and of SV, whatever the breathing condition.

Key Words: breathing, stroke length, stroke rate, swimming velocity.

INTRODUCTION

Mean stroke length (SL) and rate (SR) and mean stroke velocity (SV) are objectives criteria and useful performance evaluation factors which are used by coaches and swimmers. It is recognized that SL is a good propulsive efficiency indicator and can be used to evaluate progress in the technique level (8). SR is dependent of the spent time in each stroke phase: propulsion and recovery. Product of SL and SR is the SV, in a given distance (7), not considering propulsive affects of push-off from the start and turnings. It has been demonstrated that increased SV is achieved by a combination of increasing SR and decreasing SL (4, 5, 7) and that a given swimmer swims faster in short term by increasing SR and that the same swimmer improves the maximum swimming speed in long term by increasing the SL (11). This negative relation between SR and SL seems to be an ability to adjust SV learned as part of training for competition (5). Swimmer body position is a very important factor when drag and propulsive forces are well thought-out (2). Alterations in body position could reflect in SL, SR and SV. To decrease possible negatives effects of the breathing motion, swimmers are oriented to keep head aligned with the longitudinal body axes, even during breathing motion (1). Although a correlation between the breathing movement and the performance has not been previously found (9), competitive swimmers usually breathe less frequently in short term events (e.g. 50 m freestyle).

Considering that swimming kinematics can be modified under different swimming condition (e.g. breathing and different paces) (5), the aims of this study were to verify (a) breathing and no breathing effect and (b) different paces on SL, SR and SV among 50 m freestyle swimmers.

METHODS

Ten 50 m front crawl male specialists (age: 20.7 ± 2.4 yr.; total body mass: 77.4 ± 5.1 kg; height: 184.5 ± 7.8 cm; upper limbs span: 193.5 ± 5.2 cm; 50 m freestyle mean best time: 23.5 ± 0.66 s) participated in this study. Subjects performed 6 front crawl trials of 25 m with a rest interval of 1min30s, in a 25 meters pool. SL, SR and SV were measured under two breathing conditions: breathing to the preferred side every cycle (B) and no breathing (NB), and three paces representatives of: warm up pace (P1), 1500 m freestyle race pace (P2), and 50 m freestyle race pace (P3). Each trial was filmed with a motion analysis system (60 Hz) from sagital view. A reflective marker was fixed to the swimmer's right wrist to quantify SL and SR, after digitalizing (only the first frame, when the wrist appeared in the surface of the water was used, in three consecutives cycles). A 2 m frame was used to calibrate linear distance in the beginning, in the center and in the end of the screen field (12 m) (there was a variation of 2.2% in the number of pixels corresponding to 2 m from the center to the extremes of the screen). SV was obtained by the SL and SR product. Statistical analysis was made with repeated measures ANOVA in a mixed 2x3 model (breathing and pace conditions). To verify main effects a Bonferroni post-hoc test was used (significant level of 0.05). Software SPSS 12.0 was used.

RESULTS

Table 1 presents mean and standard deviation of SV.

Table 1. Mean ± standard deviation of SV; n = 10. B = breathing; NB = no breathing; P1 = warm up pace; P2 =1500 m freestyle race pace; P3 = 50 m freestyle race pace.

	BP1	BP2	BP3	NBP1	NBP2	NBP3
SV ($m \cdot s^{-1}$)	1.21 ± 0.07	1.45 ± 0.06	1.86 ± 0.08	1.32 ± 0.10	1.60 ± 0,08	1.91 ± 0.07

No-breathing, independent of the pace, could increase SV [$F(2, 18) = 41.8$; $p < 0.001$; $\eta^2 = 0.823$]. As expected, increased pacing has caused an increased SV values, independent of the breathing condition, [$F(2, 18) = 250.4$; $p < 0.001$; $\eta^2 = 0.965$]. Approximately 96% of the SV variance can be explained by the different paces. No significant interaction between breathing condition and pacing was found [$F(2, 18) = 1.44$; $p = 0.263$; $\eta^2 = 0.138$].

Figure 1 presents mean and standard deviation of stroke rate by trials.

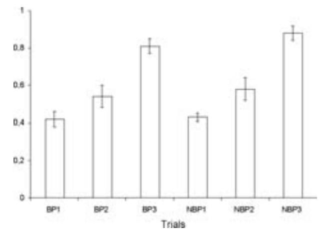

Figure 1. Mean ± standard deviation of stroke rate n = 10. B = breathing; NB = no breathing; P1 = warm up pace; P2 =1500 m freestyle race pace; P3 = 50 m freestyle race pace.

No breathing, independent of the pace, has caused increased SR values [$F(1, 90) = 13.03$; $p = 0.006$; $\eta^2 = 0.592$]. Under both, breathing and no-breathing, conditions, SR increased with the increasing pace [$F(2, 18) = 366.9$; $p < 0.001$; $\eta^2 = 0.976$]. Interaction between breathing and pace was significant [$F(2, 18) = 14.6$; $p < 0.001$; $\eta^2 = 0.619$]. Approximately 97% of the SR variance can be explained by the different paces.

Figure 2 presents mean and standard deviation of stroke length by trials.

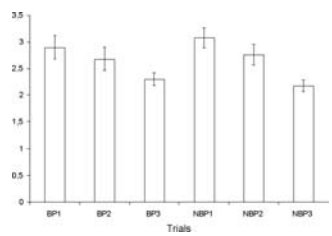

Figure 2. Mean ± standard deviation of stroke length n = 10. B = breathing; NB = no breathing; P1 = warm up pace; P2 =1500 m freestyle race pace; P3 = 50 m freestyle race pace.

Breathing condition did not cause any change in SL [$F(1, 9) = 0.045$; $p = 0.836$; $\eta^2 = 0.005$]. Under both, breathing and no-breathing, conditions, SL increased with the increasing pace [$F(2, 18) = 178.8$; $p < 0.001$; $\eta^2 = 0.952$]. Approximately 95% of the SR variance can be explained by the different paces. Interaction between breathing and pace was significant [$F(2, 18) = 8.698$; $p = 0.002$; $\eta^2 = 0.491$].

DISCUSSION
This study was planned in a way to verify different breathing and pace effects on front crawl stroke linear kinematics parameters. Increases of SV (Table 1), related to the increased pacing, were obtained by the negative relation of increased SR and decreased SL, as previously described (5, 7).
The breathing effects were observed in higher SR values found in no-breathing trials when compared to the breathing trials (Figure 1), but breathing could not change SL values (Figure 2), which were similar under both, breathing and no-breathing condition. Previous study (9) has showed that front crawl swimmers can perform the breathing action without it interfering with their basic stroke parameters. This cited study (9) has analyzed kinematics of the trunk and upper extremity in six male swimmers under a 200 m freestyle race pace, differently of the present study, which has analyzed SR and SL under three different paces (warm up pace, 1500 m freestyle race pace, and 50 m freestyle race pace). Perhaps, under only one pace, these differences would not be visible.
In response to the increasing pace, the adopted strategy to increase SV was to increase SR, as SL decreased. Such acute adaptations have been described in literature (4, 7, 8). When swimming intensity increases from an aerobic to an anaerobic level, swimmer increases SR and decreases SL (8). It is not considered most economical strategy, but the most used (3).
It must be considered the high variance of SV, SR and SL which can be explained by the increased pace: respectively, 96%, 97% and 95%. It means that kinematics parameters are, in a strong manner, influenced by intensity of the swimming. So, when a coach evaluates the kinematics parameters of the swimmers, it must be done under different pace conditions, including training exercises and competition events. In this way, the evaluation would be more objective and complete.

CONCLUSION
Breathing, among sprinters swimmers, could increase, stroke rate and, consequently, stroking velocity. To increase stroking velocity, in an acute way, swimmers increased stroke rate and decreased stroke length. Assessment of the kinematic parameters should be performed under different paces and breathing condition.

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TIME-FREQUENCY PARAMETERS OF WRIST MUSCLES EMG AFTER AN EXHAUSTIVE FREESTYLE TEST

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The purpose of this study was to investigate the effects of an exhaustive test on the EMG frequencies of 2 wrist muscles. Seven male international swimmers (22.6 ± 2.7 years, height 191 ± 4 cm, weight 82,7 ± 5,3 kg, 1.92 ± 0.09m/s for the velocity on 100m) performed an exhaustive test of 4*50m freestyle. An EMG system was used to record the electrical activity of 2 wrist muscles: the M. flexor carpi ulnaris (FCU) and the M. extensor carpi ulnaris (ECU). The time-frequency treatment was done according to the Knaflitz'method. The instantaneous mean frequency (IMNF) was obtained for each stroke of each 50m. The mean IMNF was calculated for each 25m of each 50m. Results indicated for both muscles, a decrease of IMNF at the end of the intensive test indicating the attempt of fatigue and the high recruitments within the crawl stroke. Subjects' differences were observed which could support the individualization of the training process.

Key Words: freestyle, fatigue, EMG, frequency, forearm.

INTRODUCTION
The swimmers propulsion is determined by the ability to generate propulsive force while reducing the resistance to forward motion. Propulsive force is mainly generated by the arms, which provide more than 85 % of the total force of the crawl stroke (1, 7, 13). Richardson (11) suggested that the most forward propulsion was related to the ability to maintain a given hand angle during the swimming stroke which was directly affected by the ability of the forearm muscles to maintain this position. Different studies on elementary movements under-

lined the role of forearm coactivations in the wrist stabilisation (10). In a single-joint study with unstable loads, Milner (10) found that the extensor carpi ulnaris (ECU) and the flexor carpi ulnaris (FCU) cocontractions increased the mechanical stability of the hand by increasing the stiffness of the wrist joint. In fatigue conditions, different studies indicated a shift of the power density of the signal towards lower frequencies in isometric conditions (3).
In swimming, previous results underlined the high activation of the (ECU) and of the (FCU) (2). Few studies focused on the effect of fatigue on the EMG in swimming (12). Because of the complexity of the movements, the studies were based only on the amplitude signal process. Recently, new development allowed to assess muscle fatigue from spectral parameters of EMG during cyclic dynamic conditions (9). In regard to these previous results, the aim of this study was to evaluate the effects of an exhaustive exercise on time-frequency parameters of the ECU-FCU forearm muscles in freestyle swimming.

METHODS
Seven male international swimmers participated in this study (22.6 ± 2.7 years, height 191 ± 4 cm, weight 82,7 ± 5,3 kg, 1.92 ± 0.09m/s for the velocity on 100m). After a 1200m standardised warm up, each subject performed an exhaustive test of 4*50m freestyle with 10s rest between them. An EMG system (ME 3000 P8, Mega Electronics Ltd, Kuopio, Finland) was used to record the electrical activity of 2 right muscles: the M. flexor carpi ulnaris (FCU) and the M. extensor carpi ulnaris (ECU). Electrodes were waterproof fixed on the midpoint of the contracted muscle belly as suggested by Clarys and Cabri (1993). The gain of the amplifier was set at 1000 with a common mode rejection ratio of 92 dB and high and low passes filters respectively of 8 and 500 Hz. The EMG signals were stored on-line on an acquisition card (Flash memory 32 MB) with a sampling frequency of 1000 Hz. After validate the quasi-cyclostationarity of the EMG for successive crawl strokes, the time-frequency treatment has been using A Choi-Williams transform according to the Knaflitz'method (9). The instantaneous mean frequency (IMNF) was obtained for each stroke of each 50m. The mean IMNF was calculated for each 25m of each 50m.

RESULTS
Results indicated a significant decrease of the IMNF between the 1st 25m of the 1st 50m and the last 25m of the 4th 50m with of percentage of decrease (PR) of 11.41% for the ECU and 8.55% for the FCU (figure 1). The regular decrease of the ECU was statistically similar to the decrease of the FCU.

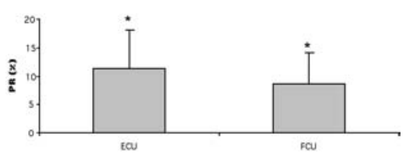

Figure 1. Percentage of decrease (PR) of IMNF between the 1st 25m of the 1st 50m and the last 25m of the last 50m.

Individual differences were observed in the decrease of IMNF from one 25m to another both for the ECU and FCU (figure 2).

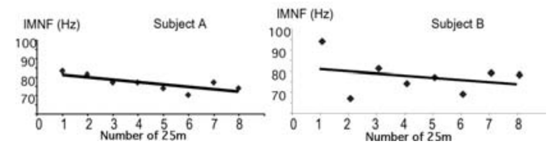

*Figure 2: ECU- IMNF decreases during the eight 25m of the 4*50m for 2 subjects.*

DISCUSSION
The decrease of IMNF at the end of the intensive test indicated the attempt of muscular fatigue of the wrist muscles as observed in elementary movements (3) or dynamic contractions (7). The lower frequencies at the end of the 4*50m reflected a decrease of muscle fibber conduction velocity (3) and/or a modification in the motor units recruitments (6) and/or an accumulation of chemical products (3).
The similar decreases for the ECU and the FCU indicated that both antagonist muscles are strong involved during the crawl stroke and reached similar statement of fatigue a the end of the 4*50m. The high recruitment of the antagonist ECU could be linked to the high water load supported by the swimmer's hand as De Luca (1987) showed that the higher the load that the subject supported was, the higher the "reciprocal activities" of the muscles were. In regard to previous results on elementary movements (5), ECU and FCU appeared as strong fatigable muscles in swimming as indicated by the magnitude of the frequencies decrease. Subjects' differences could reflect the individual variability in motor unit recruitments and /or the subject capacity to restore the muscle during the 10s rest between each 50m.

CONCLUSIONS
The decrease of EMG frequencies of both ECU and FCU muscles attempted the fatigue at the end of 4*50 m test. The magnitude of the decrease reflected the strong involvement of these 2 muscles in the crawl stroke. Individual results could be useful to adapt the training muscular exercises to each subject.

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EFFECT OF TECHNICAL MISTAKES ON ARM COORDINATION IN BACKSTROKE

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This study quantified the influence of two technical mistakes, the hand entry outside of the shoulder axis and head flexion on the thorax, on arm coordination in backstroke, with increases in velocity. Sixteen national level swimmers simulated these two mistakes, often observed in non-expert swimmers, individually and in combination at four race paces. They also swam with a traditional technique at the four paces. An adaptation of the Index of Coordination (IdC) (3) allowed the inter-arm coordination to be quantified in backstroke. In each swim condition, the negative values of IdC confirmed a catch-up coordination. This coordination was influenced by the mistakes adopted by the swimmers because, when the two mistakes were associated, the arm coordination was most disturbed.

Key Words: backstroke, non-expert swimmers, technical mistakes, coordination.

INTRODUCTION
The backstroke and front crawl are alternating strokes that allow a relative continuity of propulsive arm actions to overcome forward resistance as velocity increases (5). In backstroke, an increase in velocity is associated with an increase in stroke rate, and a decrease in stroke length (2, 4). In front crawl, Seifert, Chollet and Bardy (9) demonstrated a preferential arm coordination mode in relation to pace: for slow paces (from 3000-m to 200-m) swimmers adopted the catch-up coordination mode, during which they tended to glide with the arm extended forward, whereas they switched to a relative superposition coordination in sprint (from 100-m to maximal velocity). In backstroke, the alternating body roll, which may lead to a 90° abduction of the shoulder during the mid-pull (8), and limited shoulder flexibility (8) require an additional arm stroke phase and particular arm coordination. Lerda and Cardelli (6) showed that the clearing phase (after the push and before the recovery) does not allow continuity between the propulsive actions of the two arms. The swimmers, therefore, adopt catch-up as their preferential coordination mode whatever the skill level or velocity (6). Common technical mistakes observed in non-expert backstroke swimmers could disturb this coordination. The aim of the study was to quantify the influence of two mistakes (entry of the hand outside of the shoulder axis and head flexion on the thorax) and their combination on the arm coordination in backstroke with velocity increases.

METHODS
Sixteen national swimmers simulated two mistakes observed in non-expert swimmers and performed swim trials in four conditions: with the entry of the hand outside of the shoulder axis (OS), with head flexion on the thorax (FT), and with a combination of these two mistakes (2M); performance parameters in these three conditions were compared with those using their traditional (T) coordination. Moreover, they swam in all four conditions at four race paces (400, 200, 100 and 50-m). Two underwater video cameras (Sony compact FCB-EX10L) videotaped from frontal and side views (50Hz). They were connected to a double-entry audio-visual mixer, a video timer, a video recorder and a monitoring screen to mix and genlock the frontal and lateral views on the same screen, from which the mean stroke rate was calculated. A third camera, mixed with the side view for time synchronisation, videotaped all trials with a profile view from above the pool. This camera measured the time over a 12.5-m distance (from 10-m to 22.5-m) to obtain velocity. Stroke length was calculated from the mean velocity and stroke rate values. From the video device, three operators analysed the key points of each arm phase with a blind technique, i.e. without knowing the analyses of the other two operators. Thus, the arm stroke was divided into six phases (fig. 1): entry and catch (A), pull (B), push (C), hand lag time at the thigh (D), clearing (E) and recovery (F). The index of coordination used in crawl (1) was adapted for the backstroke so that arm coordination could be quantified.

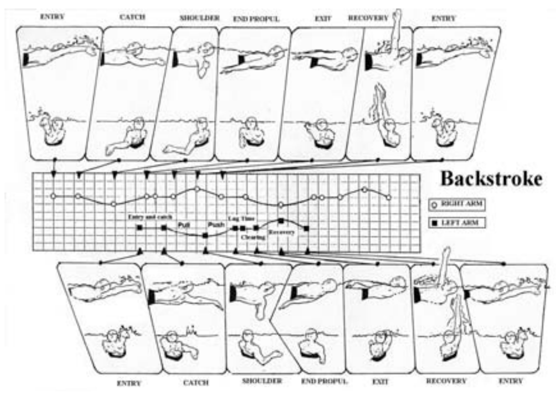

Figure 1. Modelling of arm stroke phases in backstroke between left and right arms.

Two-way ANOVAs (technical mistakes: 4 levels * race paces: 4 levels) analysed the effect of technical mistakes and race paces on the spatial-temporal parameters, the arm stroke phases and the inter-arm coordination with a level of significance set at 0.05.

RESULTS
With the increase in race pace, velocity and stroke rate significantly increased, while stroke length significantly decreased. Table 1 shows that velocity and stroke length were higher while stroke rate was lower for T than for the other conditions; the opposite was observed for 2M.

Table 1. Comparison of spatial-temporal parameters in the conditions with technical mistakes and the traditional coordination condition.

Conditions	Velocity ($m.s^{-1}$) ($m.s^{-1}$)	Stroke Rate ($stroke.min^{-1}$)	Stroke Length ($m.stroke^{-1}$)
T	1.28±0.16	36.2±6.5	2.15±0.2
FT	1.23±0.14	37.3±6.1	2.01±0.2 a
OS	1.15±0.18 a, b	39.9±7.3 a, b	1.76±0.3 a, b
2M	1.12±0.18 a, b	40.1±6.9 a, b	1.71±0.3 a, b

a: significant difference with T; b: significant difference with FT at P<0.05

With the increase in race paces, the propulsive phases (B and C) increased while the non-propulsive phases (A, D, E, and F) decreased. In the traditional coordination condition, the relative durations of the propulsive phases were significantly smaller (T: 35.6±4.4%, FT: 37.6±4.2%, OS: 39.4±3.5%, 2M: 40.9±3.9%) than in the conditions simulating technical mistakes. Table 2 indicates that only the entry and catch (A), push (C) and clearing (E) phases showed significant difference between reference condition.

Table 2. Comparison of the arm phases in the conditions with technical mistakes and the traditional coordination condition.

Conditions	A : Entry and catch phase (%)	C: Push phase (%)	E : Clearing phase (%)
T	16.1±5.2	16.2±3.5	15.6±2.5
FT	13.7±4.5 a	16.9±3.7	15.9±2.4
OS	8.5±1.2 a, b	18.9±4.1 a, b	17.8±2.9 a, b
2M	7.7±3.9 a, b	20.3±4.9 a, b	18.5±3.1 a, b

a: significant difference with T; b: significant difference with FT at P<0.05

Whatever the condition, the IdC tended to decrease with increases in race pace. The IdC was significantly more negative for traditional coordination (T) (-14.3±4.5%) than for OS (-10.6±3.6%) or 2M (-9.9±9.1%) (P<0.05), showing that the association of the two mistakes (FT + OS = 2M) led to less marked catch-up coordination.

DISCUSSION
In the four conditions, the increases in race pace were associated with an increase in stroke rate and a decrease in stroke length, showing that whatever the technical mistake adopted (and consequently whatever the skill level), the management of spatial-temporal parameters was similar (2, 4). In line with previous studies (2, 4), our study confirmed that higher velocity and higher expertise are related to greater stroke length. These spatial-temporal parameters changed according to the distribution of the arm stroke phases. Notably, the head flexion on the thorax (FT) and, more particularly, the entry of the hand outside of the shoulder axis (OS) led to a decrease in the relative duration of the entry and catch phase. These mistakes prevented the deep hand-sweep that prepares the propulsion and were regularly associated with a dorsal position without shoulder roll (8). Beginners are often not aware that having an entry of the hand outside of the shoulder axis is a mistake; they thus shorten the entry and catch phase to rest on the water (i.e. to maintain the upper body and the head on the surface) instead of plunging their hand deeper to find a resistive mass of water. Using the OS and 2M mistakes led to longer push and clearing phases and consequently to less marked catch-up coordination (less negative IdC), which did not indicate better propulsion, as commonly assumed. Indeed, a high IdC reveals good technique only if it is associated with high velocity and great stroke length. In the OS and 2M cases, the higher IdC and the longer push and clearing phases indicated a problem of hand-sweep rhythm. In particular, the premature entry of the hand in the water meant that the hand was in the water too long and had an upward path during the push phase, instead of a backward and downward path with acceleration. Even though the push phase was longer for the conditions with technical mistakes, a high average force may not be as effective as a high maximal force (3, 7). These authors (3, 7) showed that the hand undergoes a constant change in direction and alternating acceleration and deceleration during the underwater stroke phases, which does not enable it to apply high continuous force. Hence, although a relatively long propulsive phase is needed to apply high peak forces, a long push phase could be used by swimmers to compensate their mistakes and to balance the body.

CONCLUSION
The entry of the hand outside of the shoulder axis seems to be the non-expert behaviour that most influences inter-arm coordination, and even more so if this technical error is associated with a head flexion on the thorax. Coaches could use the index of coordination and the assessment of arm stroke phase durations to quantify the inter-arm relationships coordination. This information in association with the spatial-temporal parameters (velocity, stroke rate and stroke length) could then be used to correct non-expert swimmers.

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SIMULTANEOUS RECORDINGS OF VELOCITY AND VIDEO DURING SWIMMING

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A method is described for the recording a swimmer's velocity and synchronizing these records with the underwater video. Examples of these records during pushing off from the side of the pool, breaststroke, butterflystroke, backstroke, and crawlstroke are presented. These records demonstrate to swimmers and coach the biomechanics of swimming, and they are useful for immediate feedback.

Key Words: swimming, biomechanics, breaststroke, butterflystroke, backstroke, crawlstroke.

INTRODUCTION
There have been many pictures of swimmers from above or below the surface of the water (1, 4). Patterns of motion have been analyzed in detail, and many coaches form definite opinions about the best stroke techniques. As the arms and legs are moving about the center of mass of the body, it is difficult to judge the velocity, and incorrect conclusions about stroke mechanics are often made. Recordings of swimmers' velocities have also been reported (2). The current work involves underwater videos of swimmers synchronized with recordings of instantaneous velocity displayed on the computer screen. The videos and the recordings are stored, and the data are available for detailed analysis immediately or at a later time.

METHODS
Velocity is measured by attaching a fine (0.2 mm diameter) non-stretchable line to the back of a belt around the swimmer's waist. The line passes through a series of pulleys and over the wheel of a DC generator positioned at the side of the pool. The voltage output of the generator is converted to digital format at a sampling rate of 400/s. Underwater video cameras are spaced along the side and one at the end of the pool. The cameras along the side are spaced so that as the swimmer moves out of view from one camera the image appears in the next one. The videos are recorded sequentially, and the pictures are synchronized with the tracings of the velocity. The computer screen showing the velocity and the underwater picture can be viewed during the swim and is available for immediate review and analysis.

RESULTS AND DISCUSSION
Pushoffs
The simplest recording is obtained by asking the swimmer to push off from the side of the pool in a streamlined position and to remain motionless in a horizontal position for the rest of the glide. As shown in Figure 1, the velocity during this gliding motion decreases exponentially due to the swimmer's drag. The computer program calculates the characteristics of the velocity curve (Figure 2). From the point of view of competitive swimming, these curves reveal important considerations. First, it is noted that due to drag the swimmer's velocity immediately decreases upon loss of contact with the side of the pool. In addition the time spent gliding underwater after a start or turn is specific to the swimmer's mean swimming speed on the surface. (5). For example, if the swimmer's mean velocity on the surface is 1.8 m/s, swimming must be resumed by 0.8s after leaving the wall. It is possible to calculate that at this time the swimmer's waist would be 3.3 m from the side of the pool. The coach can know if the swimmer is making the optimal transition from the pushoff to swimming.

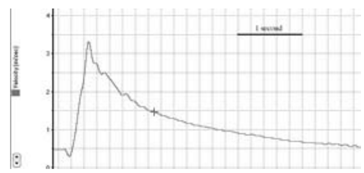

Figure 1. Tracing of velocity after pushoff.

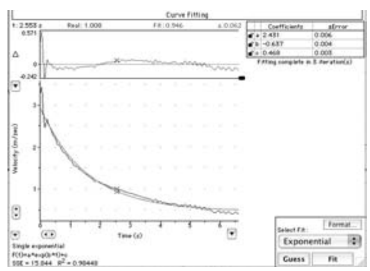

Figure 2. Analysis of velocity after pushoff.

In breaststroke races the swimmers are allowed one arm stroke and one leg stroke before coming to the surface and resuming swimming (Figure 3). It has been found that the mean velocity of this underwater swimming may be slower than swimming on the surface (5).

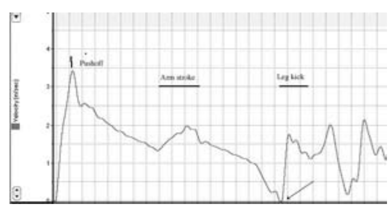

Figure 3. Recording of velocity after pushoff in breaststroke.

In figure 3 the swimmers average velocity from pushing off the wall to surfacing just before the first complete stroke cycle on the surface was 1.52 m/s, and he traveled 7.0 m. His average velocity during the remainder of the lap was 1.58 m/s. This difference indicated a need to complete the underwater phase in a shorter time so the average velocity would be greater or at least equal to his surface velocity. Figure 3 also shows that after the arm stroke the velocity decreased to zero as the swimmer brought the arms under the thorax and the legs were flexed in preparation of the kick (see arrow). Although this preparation for returning to the surface increases drag, zero velocity can be avoided by abbreviating the time underwater (5).

Breaststroke

This style of competitive swimming is the most definable of the four stroke patterns, and the one that is most amenable to analysis. It has the greatest oscillations of velocity. Figures 4 and 5 show stroke cycles of two breaststroke swimmers.

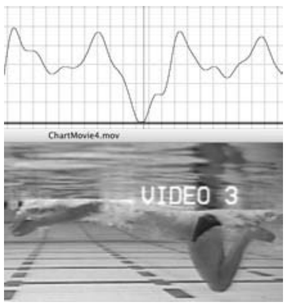

Fig 4. Breaststroke. Picture at minimal velocity.

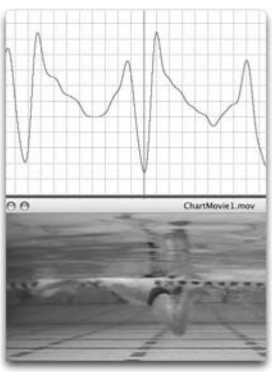

Fig 5. Breaststroke. Picture at minimal velocity.
Note: in all of the pictures of swimmers, the vertical dashed lines on the velocity recordings indicate the speed at the time of the video frame and are part of the computer program.

Although these recordings were made at slightly different swimming speeds, it is apparent that the swimmer in Figure 4 has a period of zero velocity when the legs are flexed in preparation for the propulsive kicking action. During the same part of the stroke cycle the velocity for the swimmer in figure 5 is significantly greater than zero. The cause of this difference can be explained by the differences in the angles of the thighs to the torso. The resistance to forward movement or drag is much greater for the subject in figure 4 than in figure 5. This increase of drag is related to the frontal surface caused by the position of the swimmer's thighs.
The pattern of breaststroke swimming can be characterized by defined phases.

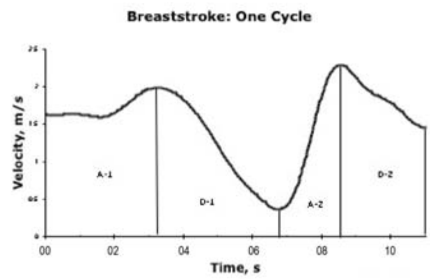

Figure 6. Phases of the breaststroke stroke cycle.

At the beginning of the stroke cycle the action of the arms produces an initial acceleration, A-1.This followed by a period of deceleration, D-1, as the legs are flexed in preparation for the kick. The acceleration due to the legs, A-2 is much greater than A-1. The glide after the kick is associated with the second period of deceleration, D-2.

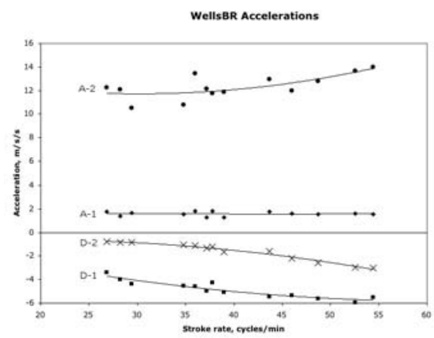

Figure 7. Accelerations during stroke cycle.

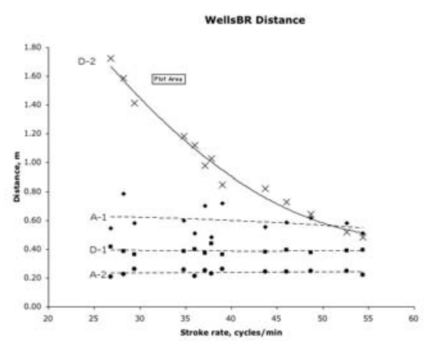

Figure 8. Distances of stroke phases.

Figures 7 & 8 show the results of the analysis of 13 one-length swims of a swimmer doing the breaststroke and going from slow to fast speeds. The accelerations of the kick phase (A-2) increased slightly, but the accelerations of the arm stroke (A-1) were independent of stroke rate and velocity. In the non-propulsive phases the decelerations were greater when the swimmer was going faster. These patterns were probably related to the increased body drag with increased velocity. As reported before (3), the distance traveled each stroke during the breaststroke is dependent on the time spent in the glide after the leg action (D-2) During all the other phases the distance traveled is independent of stroke rate. Another way of looking at breaststroke swimming is to say, "it's all about timing." These observation suggest that the breaststroke swimmer can practice the skills related to arm and leg action at slow stroke rates. Improvements should transfer to faster stroke rates. Practice at the faster speeds should focus on minimizing drag during the glide after the kick (D-2).

Butterflystroke

The butterflystroke is swum with greater variation of the pattern than the breaststroke. Figure 9 shows the velocity profile of three swimmers who were using the same stroke rate and were going at about the same speed.

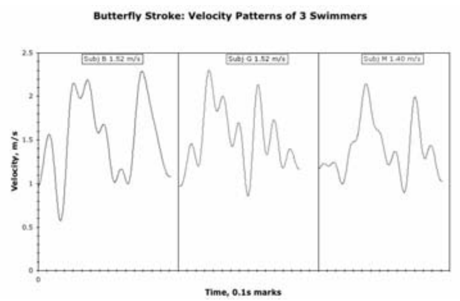

Figure 9. Butterflystroke velocity profile 3 different swimmers.

The first peak in each panel is the result of the arm and leg action. There is then a decrease of the velocity until the second leg action. Variations in the pattern can also be observed in the same swimmer.

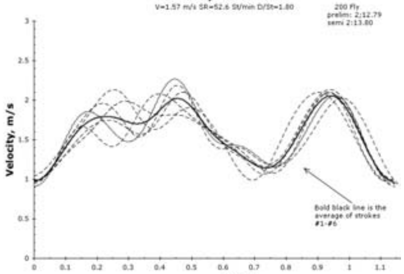

Figure 10. The velocity profiles of six sequential strokes are indicated by the dotted lines. The solid line is the average of the six stroke cycles.

In Figure 10 the variations occur in the timing of the arm and leg actions at the first part of the stroke. In some instances the arm flexion occurs before the leg flexion, and there is a decrease of the velocity between the two motions. At the other extreme the initial leg and arm actions are so closely related that the velocity shows just one maximal peak. The second peak of velocity is due to the legs acting alone, and is very reproducible.

Backstroke

Although fluctuations of the velocity during the stroke cycle may be apparent at slow stroke rates, they become very small at greater stroke rates swimming the backstroke.

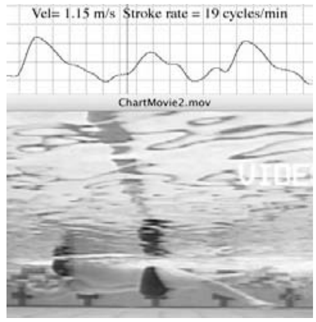

Figure 11. Backstroke at slow speed.

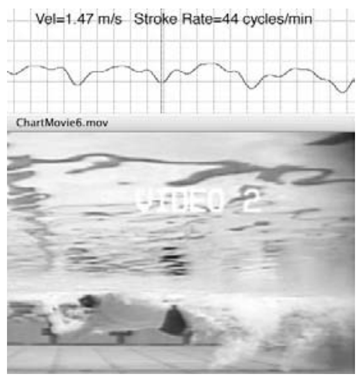

Figure 12. Backstroke at greater speed.

As shown in Figure 11 the velocity increases with each arm action and at this slow stroke rate there is a non-propulsive or glide phase. At greater stroke rates the glide phase almost disappears. The recovery of arm after its propulsive motion is fast, and on it's next entry is immediately used for propulsion without a gliding phase. The decelerations noted in Figure 12 are quite common for this stroke style. Although we initially attributed this to the increased flexion of the leg, other views suggested that it might be related to the swimmer's poor alignment at this phase in the stroke cycle.

Crawlstroke

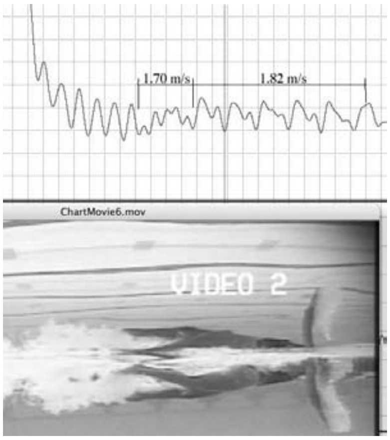

Figure 13. Female-swimming crawlstroke (freestyle).

After the swimmer entered the water from a diving start the velocity decreased rapidly and then showed fluctuations related to the repeated leg flexions and extensions known as dolphining (Figure 13). In this section the mean velocity of was 1.70 m/s. During swimming the crawlstroke the velocity was 1.82 m/s. It is apparent that this swimmer should limit dolphining to three cycles and then begin swimming. It is important for swimmers to learn when to begin and when to stop dolphining after a start or after a push-off from a turn. Such decisions can only be made from recorded data.

CONCLUSION

Swimming in all competitive stroke styles involves accelerations and decelerations. The simultaneous recording of the swimmer's velocity and the synchronized underwater video enables the viewer to see the effects of motion in different parts of the stroke. Additional calculations such as mean, maximal, and minimal velocities, time of a chosen segment, distance traveled are incorporated into the program and are useful in understanding the effects of different stroke patterns. Swimming involves major accelerations and decelerations. The patterns of movement and the resulting velocities are very different in the competitive stroke styles. In each there are variations among swimmers, and even during a single swim the patterns may change. Starts and turns can also be analyzed. These approaches are limited only by the imaginations of the swimmers and their coaches.

ACKNOWLEDGEMENT

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UNDERWATER UNDULATORY SWIMMING: STUDY OF FREQUENCY, AMPLITUDE AND PHASE CHARACTERISTICS OF THE 'BODY WAVE'

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The purpose of this study was to analyze wave motions of underwater undulatory swimming (UUS) and to compare these whip-like actions with previous studies developed in butterfly and breaststroke. UUS is characterized by vertical displacements of the body parts such that a wave progresses along the body with most of its power contained in a single sinusoidal harmonic (H1). Progression of the H1 wave from hip to ankle raises the possibility that energy is transmitted along the whole body in butterfly swimming and from the hips in USS. In UUS upper body segment movements were not part of the body wave and would be used to stabilize position. Increasing values of vertical velocities caudally from hip to knees to ankles appears to be related to maximising horizontal velocity of the CM in UUS. A future analysis of the wake structure generated by UUS and its relationship to wave characteristics seems a logical step for further understanding propulsive mechanisms in UUS.

Key Words: Fourier transform, harmonic, technique, hydrodynamics.

INTRODUCTION

When swimming underwater undulatory swimming (UUS) the swimmer's body parts are displaced horizontally and vertically through the kick cycle. These motions have been likened to oscillations or wave-like motions (2, 3, 5). When dolphins and butterfly swimmers were compared, based on body wave (BW) velocity and duration of the up beat, BW velocities were similar while the duration of the up beat was different (5). Harmonic or Fourier analysis[1] was applied by Sanders et al. (2, 3) to determine the frequency, amplitude and phase characteristics of the vertical undulations of the swimmer's body parts. They found differences in phase between body parts in butterfly swimming such that a body wave travelled caudally and suggesting that energy gained by raising the CM was transmitted caudally and contributed to a propulsive whip-like action, while in breaststroke the range of vertical motion of the hips was large relative to the vertical motion of the CM. It was proposed that these vertical motion differences reduced the need to do work to raise the CM and the transmission of a body wave enabled energy accrued by the upper body to be reused to raise

the caudal half of the body to a streamlined position in which drag is reduced.
The purpose of this study was to analyze wave motions of UUS and to compare these whip-like actions with previous studies developed in butterfly and breaststroke.

METHODS

Subjects

Twenty international and national ranked swimmers, ten male and ten female, were videotaped performing UUS for a 15m sprint after a water start. The distance was covered in the horizontal direction and at approximately one meter in depth to avoid wave resistance.

Instrumentation

One camera (S-VHS sampling at 50 Hz) with its optical axis perpendicular to the line of motion of the swimmer recorded each trial through an underwater window. To avoid the influence of impulse from pushing off the wall, the camera recorded the movement from 7.5 to 12 m from the wall. As this study was two-dimensional, a symmetrical 13 points model was digitized after each video-capture using Kinematical Analysis System developed by R. Schleihauf at San Francisco State University (www.kavideo.sfsu.edu). Coordinates of the CM were determined. The digitised coordinates of the body landmarks were exported to a set of MatLab routines (developed by R. Sanders). The program steps were: 1) Raw data was smoothed and interpolated to 100 samples per second. 2) Stick figures of the kick cycles were produced. 3) A kick cycle was selected based on the vertical displacement of the ankle 4) The cycle time was normalised to percentiles of the total cycle time. 5) Data and graphs of vertical displacement, vertical velocity and vertical acceleration versus % of kick cycle were obtained. 6) Fundamental harmonic (H1, H2, …Hn) velocity of body segment were calculated and graphically displayed. 7) A graph of wave amplitude of first five harmonics and their power contribution was displayed. 8) Phase analysis of the two first harmonics (H1 and H2) was performed. 9) Joint angles, angle velocity and angle acceleration evolution of hip, knee and ankle were determined for the kick cycle.

Variables

Distance of the body per kick (KL, m(cyc^{-1}), kick frequency (KF, Hz) and mean CM horizontal velocity (CMHV, m(s^{-1}) were the basic variables to describe the UUS technique (see table 1). Vertical position data were input to the Fourier analysis software to obtain the fundamental frequency and its harmonics. Amplitude of each frequency was calculated by $C_n=(A_n^2+B_n^2)^{0.5}$, were A_n and B_n are cosine and sine coefficients for the nth frequency (harmonic). The contribution of each harmonic to the power of the signal, that allows us to know its influence in the movement, was given by $2C_n^2$. Average velocity of the travel of the wave along the body was determined for the fundamental harmonic (n=1) for the vertex to shoulders, shoulders to hips, hips to knees and knees to ankles (m/s) by $u=d/t$ where u is the velocity of travel along the body, d is the displacement between adjacent landmarks and t the time taken to achieve the same phase as the previous landmark.

RESULTS AND DISCUSSION

Table 1 shows mean swimmers UUS kick characteristics. On average the group took approximately 0.46 s to complete a kick cycle. This was less than half of the that obtained in the studies of the butterfly stroke (2) and breaststroke (3).

Table 1. Means and SD for the displacement of the body per kick (KL), kick frequency (KF), kick index (KI) and CM velocity (v).

	KL (m·cyc^{-1})	KF (Hz)	CM v (ms^{-1})
Mean	0.76 (±0,14)	2.17 (±0,324)	1.63 (±0,17)

Figure 1 shows the vertical velocity (VV) of each body landmark and CMHV. Upper values of absolute VV were found in the downward kick compared with the upward kick in the knee and ankle. This produces a small increment in the CMHV at the end of the downward kick. Peak values of VV increase progressively from shoulder to hip to knee to ankle. CMHV showed a small range of variation during the cycle, this low variability demonstrates a likely contribution of different kind of propulsive mechanisms appropriately combined in a period of body oscillation. A wave transmitted in a cephalo-caudal direction along the body can contribute to conservation of mechanical energy. The vertical movement of the body parts was almost entirely comprised of one low-frequency waveform (Table 2) and it suggests a truly harmonic or wave-like pattern, as Ungerechts (6) and Sanders (2) suggested. This means that vertical movements of the body landmarks are phases of a simple sinusoid oscillation with very rhythmical motion. Upper body segment results were more variable. Our H1 results of the vertex and shoulder were similar than the obtained in butterfly (2) and breaststroke (3) however, hip, knee and ankle showed values about 100% of power contribution different than the previously obtained (2, 3) where the H1 and H2 harmonics contribution was very differently distributed in butterfly (about 50%) and breaststroke (about 70% for H1). The arm strokes performed during these strokes explained the differences found in UUS, where the arms are stretched and fixed forward in horizontal position.
The increasing amplitude of oscillation from hip to ankle suggested a 'whip-like' action. It can be hypothesized that there is a relation between this action and the production of a wake with rotating vortices that can be propulsive, as UUS visualized wakes suggested (1). Each time the tip of the feet change direction, it sheds a stop/start vortex. As the feet move to the other side, a low-pressure region develops in the posterior half of the legs, sucking a bolus of fluid laterally (as Tytell and Lauder (4) proposed in eel propulsion).

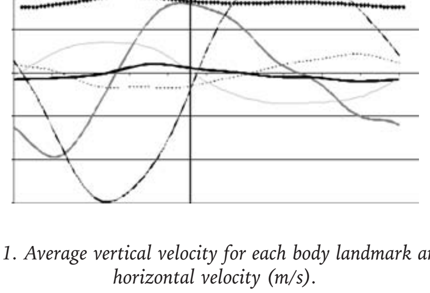

Figure 1. Average vertical velocity for each body landmark and CM horizontal velocity (m/s).

Table 2. Mean Percentage Power Contributions of H1 and H2 to waveform power.

Body Landmark	H1		H2	
	Mean	SD	Mean	SD
Vertex	91,28	9,02	6,29	8,50
Shoulder	94,34	5,63	3,15	3,41
Hip	96,89	3,15	2,43	2,91
Knee	96,77	1,84	2,77	1,82
Ankle	98,94	0,60	0,93	0,66

Table 3. Mean and SD for Fourier amplitude H1 wave and range of vertical motion (m).

	Amplitude	Range
Vertex	0,013 (±0,005)	0,102 (±0,04)
Shoulder	0,015 (±0,003)	0,066 (±0,02)
Hip	0,029 (±0,007)	0,068 (±0,016)
Knee	0,059 (±0,013)	0,136 (±0,031)
Ankle	0,099 (±0,02)	0,239 (±0,056)
CM	0,007 (±0,004)	0,041 (±0,021)

The range of vertical motion produced by the calculated waveforms was about four times that of the Fourier amplitudes presented. Mean Fourier amplitudes for H1 and range of vertical motion are presented in Table 3. Mean Fourier amplitudes of H1 and range, increased progressively from vertex to ankle showing the lowest vertical movement in CM. The obtained results were similar to those obtained in studies of butterfly (2) and breaststroke (3) in hip, knee, ankles and CM.

CONCLUSIONS

UUS is characterized by sequential vertical displacements of the body parts such that a fundamental sinusoidal wave harmonic (H1) dominates the waveform power and travels caudally from hip to ankle. This raises the possibility that energy is transmitted mainly from the hips in USS rather than along the whole body as in butterfly swimming. Upper body segment movements appear to be used only to stabilize the body and to maintain a horizontal position. Increasing values of vertical velocities of hip, knees and ankles appears to be associated with horizontal velocity of the CM in UUS. A future analysis of the wake structure generated by the underwater undulatory swimmer and its relationship to wave characteristics seems a logical step for further understanding propulsive mechanisms in UUS.

NOTES

[1] Any periodic signal can be broken down into its harmonic components. The sum of the proper amplitudes of these harmonics is called Fourier series (7).

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EMG-MODEL OF THE BACKSTROKE START TECHNIQUE

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This study researched in more depth a 6-phase model that describes the time pattern and the activity level of the muscles while executing the backstroke start. Five male backstroke sprinters of the German national swim team performed four backstroke starts over a distance of 7.5 m. EMG-data were recorded by a water protected 8-channel EMG from eight arm, shoulder, trunk and leg muscles. To compare the quality of muscular activity patterns, the IDANCO-system served as a quantitative method. The EMG recordings in the 5 swimmers indicated a medium repetition consistency and reproducibility of the identified patterns of muscle activity. In the initial hang phase, and the final glide phase the EMG recordings of the first dolphin kick demonstrated an identical and analogue movement behaviour. During the flight phase, and especially during the water entry the number of different muscle activation patterns grew significantly.

Key Words: swimming, backstroke start, EMG, reproducibility-system.

INTRODUCTION

Cossor and Mason (3) proved that the underwater speed during the glide phase of the start had a great impact on the position within the starter field, and in addition, influenced the total race time in the 100m backstroke swimming.
Furthermore, it was assumed that the out of the water phase plays a key factor in the sprint performance. For this reason, this study researched a 6-phase model that contains not only kinematic and dynamic parameters [Krueger et al., in this volume], but also describes the time pattern and the activity level of the muscles that generate and transmit the forces and stabilize the body while executing the different movements during the backstroke start.
EMG studies of the start movement in crawl swimming showed that in the out of the water and underwater phase the

grab start is characterized by lower interindividual differences in muscle activity when compared to the track start (4). The greater interindividual reproducibility of the muscle activity patterns in the grab start might be caused by the more standardized movement behavior of this technique. Since the backstroke start out of the water is characterized by small interindividual variations in the technical execution versus the start movements from the top of the block, it is hypothesized that in elite backstroke sprinters the EMG patterns of the most important propulsion and stabilization muscles are almost identical.

METHODS

Five male backstroke sprinters of the German national swim team performed four backstroke starts over a distance of 7.5 m. The comparably short start distance of 7.5 m had to be used due to the limited length of the cable of the EMG measuring device. The over all start time was recorded by high speed video analysis (Redlake Inc., 125 Hz). Kinematic parameters (block time, flight time, and overall start time, angles at take off and water entry, take off velocity) were calculated by motion analysis (SIMI-Motion, Ger). Dynamic data were measured as 3-dimensional ground reaction forces by a mobile water proof force plate (Kistler Inc., Ger) mounted to the pool wall. The EMG provides information about muscle activation and the specific temporal pattern of the coordinative interplay between the propulsive and stabilizing muscles. In the present study surface electromyography was used, which is a) more adaptable to global studies on athletes and b) was better accepted by the subjects (5). The skin was shaved, rubbed and cleaned, and the electrodes were fixed with adhesive tapes and plastic films (Tegaderm, 3M Inc.). EMG-data were recorded (sample frequency 1000Hz) by a water protected 8-channel EMG (Biovision Inc., Ger) from eight arm, shoulder, trunk and leg muscles located on the right side of the swimmers body (see Table 1). These muscles represent the most important kinetors for stabilizing the initial hang phase, the take off, flight and water entry movement, and also the undulating whole body movement when executing the dolphin kicks during the underwater phase. It is assumed that the investigated muscles produce most of the explosive power needed for an effective start of the swimmer.

Table 1. The eight muscles of the right side of the body chosen for the EMG in the backstroke start.

Upper body	Lower body
m. deltoideus	m. rectus femoris
m. biceps brachii	m. gluteus maximus
m. triceps brachii	m. semitendinosus
m. erector spinae	m. gastrocnemius medialis

Raw EMGs were corrected to obtain the full wave rectified signals. The data were band-pass filtered (butterworth 2nd-order, cut-off frequencies 10.0 Hz and 400.0 Hz) and averaged by Butterworth at 8.0 Hz, 2nd-order. The amplitude of the linear envelope was normalized with respect to the maximum muscle activity during the whole start movement up to the 7.5m limit. Each muscle of each subject was used as its own reference (5). The time durations of the four phases of the out of the water phase (reaction phase from signal to the first movement; pressure phase from first movement to hands off; jump phase from hands off to feet off; flight phase from feet off to hip entry), and of the first two phases of the underwater phase (entry phase from hip entry to the maximum depth of the feet, which is regarded as the starting point of the first dolphin kick, and glide phase I with the first dolphin kick that ends at the second maximum depth of the feet) were all normed separately in order to allow intra- individual and inter-individual comparisons of the patterns of the muscle activities during the different movements of the backstroke start.

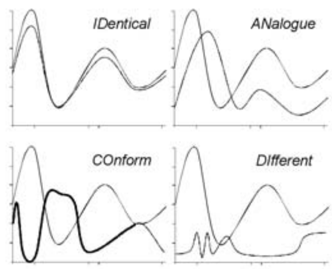

Figure 1. The IDANCO-system with four criteria for EMG pattern similarity (Bollens et al., 1988).

The IDANCO-system as used by Bollens et al. (1) served as a quantitative method to compare the quality of muscular activity patterns. The comparisons are based on the linear envelope of the raw EMG-signal. The term IDANCO stands for *IDentical*, *ANalogue*, *COnform*, and *different* muscle activity patterns (see fig. 1). Since the swim start is an acyclic movement, Conform patterns that are characterized by a reverse activation of agonists and antagonists could not be found. Because such phenomena primarily occur in cyclic movements, this category was dropped. The remaining three criteria (IDentical, ANalogue, DIfferent) led to a modified "IDANDI"-system indicating three different levels of muscular specificity. Furthermore, in contrast to Bollens et al. (1) the 3 point-score within each category that quantifies the degree of the differences in the time duration on the one hand and the amplitude of the muscle activation on the other hand, or in both modalities was not used. Differences in one of these or both modalities were all summarized in the category "analogue" patterns in the respective phase of the start movement.

RESULTS

Although 7.5 m is a very short distance to measure the swim start performance, the athletes exhibited remarkable differences in the overall start times (table 2).

Table 2. Kinematic parameters of the 5 athletes in the backstroke start.

	BW [kg]	F_{RMax2} [N]	Hands off [s]	Take off [s]	Hip entry[s]	Start time time 7,5 m	$v_{take off}$ [$m \cdot s^{-1}$]	PB 50B [s]
T.E.	71.0	742.3	0.48	0.82	1.10	3.69	3.75	26.89
T.R.	75.0	922.1	0.47	0.77	1.10	3.59	2.95	24.80
H.M.	73.0	1,055.6	0.53	0.76	1.17	2.72	2.92	26.16
M.C.	80.0	984.0	0.45	0.67	1.04	3.23	3.56	25.53
S.D.	90.0	1,243.9	0.49	0.78	1.08	2.77	3.50	25.14
Mean	77.80	989.56	0.486	0.761	1.097	3.200	3.34	25.70
SD	±7.60	±183.54	±0.029	±0.055	±0.047	±0.449	±0.38	±0.83

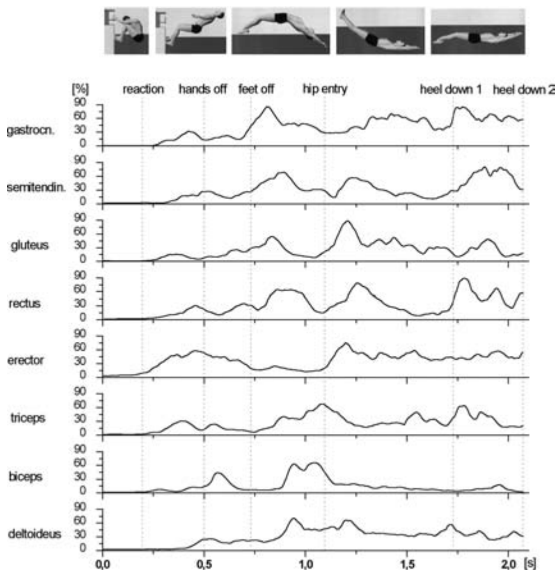

Figure 2. The normalized and averaged (3 trials) muscle activity pattern of the backstroke start movement of the athlete SD.

The EMG data of the 8 investigated muscles of one participant (100m backstroke finalist) of the Olympic Games in Athens 2004 (see Figure 2) form a representative model of the muscle activity pattern of the backstroke start. The start movement during the out of the water phase is initiated in the static reaction phase by the M. erector spinae (54.0±40.7%) that was active to move the upper body backward towards the jump off position. In the jump phase, after pushing the hands off the wall, the M. deltoideus (21.3±7.9%) helped to bring the shoulder backward. In addition, all four leg muscles showed very high activity during the explosive extension of the legs at the take off. In the flight phase Mm. biceps brachii (33.9±3.1%), triceps brachii (34.4±15.2%), and deltoideus (39.5±0.6%) contributed a lot to stabilize the body shortly before and during the water entry. After the hip entry M. gluteus maximus showed maximum activity (88.2%) to accelerate the body by sweeping the legs downward. In the underwater glide phase the cyclic propulsion movement of the dolphin kick was characterized by maximum muscle activities of the Mm. rectus femoris (89.2%) and gastrocnemius (84.7%) during the upward sweep, and by time lagged activities of the M. semitendinosus (79.9%) during the downward sweep (see fig. 2). The EMG recordings in the 5 swimmers indicated a medium repetition consistency and reproducibility of the identified patterns of muscle activity (see Fig. 3). 13.0% of all patterns proved to be identical, and 57.2% were at least analogue. Thus, 70.2% showed a form of *intra-individual stability*, and only 29.8 % could not be held constant in the repeated trials of each athlete. Most of the identical patterns (85.2%) were found in the static hang phases I and II and in the following jump phase (11.1%). During the flight phase and especially during the water entry all investigated individuals exhibited a less specific activation. Since the swimmers performed different flight distances and showed a great variety in the way they adapted their movement behavior to the conditions of the water entry situation, the muscle activation was different or analogue from trial to trial. During the first dolphin kick 54.2% of the EMG recordings indicated analogue patterns which meant that in the glide phase the movement behavior of each individual was becoming more constant again.

The *inter-individual comparison* (dark circles in fig. 3) supported the growing variability of the muscle activation along the different phases of the backstroke start. Only in the initial hang phase did the swimmers exhibit more or less identical EMG patterns. During the flight phase and the water entry the number of different muscle activation patterns grew significantly. In the final glide phase the EMG recordings of the first dolphin kick demonstrated a more analogue movement behavior again.

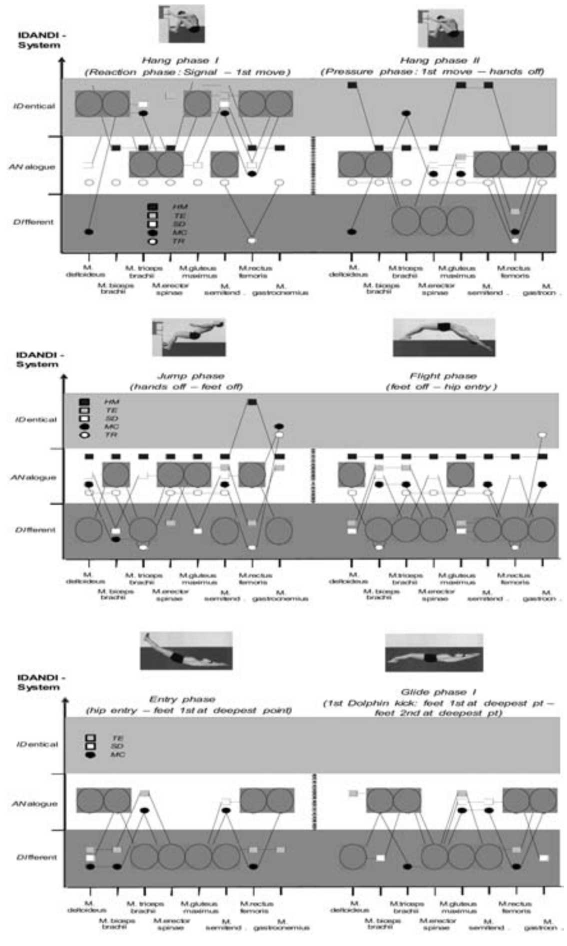

Figure 3. Comparison of the muscle activity patterns of five elite swimmers in the backstroke start (in the underwater phase two swimmers were excluded due to technical reasons).

DISCUSSION

In contrast to former EMG studies on the grab and track start technique (4), the EMG recordings of five male top swimmers

gave a very distinct indication of both a high repetition consistency and a high reproducibility of the identified patterns of muscle activity "during the initial hang phase and the final glide phase". In the middle part of the start movement, i.e. during the flight phase and the water entry, the dynamic involvement of the propulsion and equilibrium muscles showed greater intra- and inter -individual variability. This may be caused by the necessity to adapt the specific movement behavior to the varying situational conditions of the transition from out of the water to underwater environment, like e.g. flight height and distance, angle and depth of water entry. Therefore, the electromyographic results are in line with former findings by Cabri et al (2) showing that the water entry movement required more activity from the stabilisation apparatus of the back and the arms, rather than from the propulsion muscles of the legs probably because of the higher resistance during water entry of the body. After the swimmer is fully immersed, the more standardized propulsive up and down sweeps of the dolphin kicks lead to more constant muscle activity patterns again.
In conclusion, the overall image of muscle contraction allowed the formation of a representative 6-phase model of the investigated muscles participation in the backstroke start.

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THREE-DIMENSIONAL ANALYSIS OF THE EGGBEATER KICK IN SYNCHRONIZED SWIMMING

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One of the fundamental techniques in synchronized swimming is the eggbeater kick. The purpose of this study was to examine the kind of kinematic parameters that are reflected in an excellent eggbeater motion and, in particular, to evaluate the rotational angle of the hip. Nine Japanese elite synchronized swimmers served as subjects. The kinematics of the lower limbs and the hip rotational angle of each subject were quantified using three-dimensional video analysis. The hip almost rotated internally during the eggbeater kick. It was considered that the internal and external rotation movements of the hip were reflected in the foot abduction and adduction movements. This was because the phase of the angle curve between the hip rotation and foot abduction was almost identical in the reverse direction.

Key Words: eggbeater kick, synchronized swimming, video analysis, hip rotational angle.

INTRODUCTION

The vertical eggbeater kick is the most fundamental and important technique in synchronized swimming, water polo, water rescues, and so on. A few researches have focused on the eggbeater kick. The foot speed was the most important factor contributing to the performance of the eggbeater kick, and the swimmers were required to learn sculling motions emphasizing horizontal rather than vertical motion (2, 3). In our previous study of the eggbeater kick (1), the rotational movement of the hip was considered to be important to control the strength and direction of the movement. The purpose of this study was to examine the type of kinematic parameters that are required to perform an excellent eggbeater motion and, in particular, to evaluate the rotational angle of the hip during the eggbeater kick. The rotational angle of the hip and other kinematic parameters were calculated by original programs using Mathematica (Wolfram Research, USA).

METHODS

Nine female synchronized swimmers (height: 1.60 ± 0.05 m, weight: 53.2 ± 4.16 kg) served as subjects for this study. All the subjects were Japan national A team members, four of whom were silver medalists in the 2004 Athens Olympic Games. All the subjects provided written informed consent. The eggbeater kick motion was recorded using three video cameras (60 fps), including two underwater cameras. One underwater camera was set on the bottom of the pool almost beneath the subject, and another underwater camera was also set on the bottom of the pool, but at the left side of the subject. The third camera was set in front of the subject through an underwater viewing window. All the subjects attached an additional landmark on their left thigh to facilitate the evaluation of the rotational angle of the hip (fig. 1). The semi-spherical landmark made of Styrofoam was attached to the middle of the left thigh with Velcro tape.

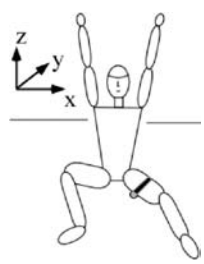

Figure 1. The coordinate system in this study and the additional landmark on the left thigh.

The subjects performed stationary eggbeater motion with maximum effort and extended both arms in the air; they maintained this elevated position for a duration of over 5 sec. The videotapes were manually digitized using Frame DIAS II (DKH Co., Japan). The Direct Linear Transformation (DLT) method was used to obtain the three-dimensional space coordinates of the lower limbs. The three-dimensional calibration frame was a rectangular parallelepiped (1.0 m*1.0 m*1.2 m), which had 160 control points. The errors in its reconstructed coordinates were 0.008 m (x-axis), 0.007 m (y-axis), and 0.006 m (z-axis). The coordinate system in this study is shown in Fig.1; the x, y-, and z-axes are the frontal, sagittal, and vertical axes, respectively. The three-dimensional data were smoothed using a low-pass digital filter with a cutoff frequency of 6 Hz.

RESULTS AND DISCUSSIONS
The left hip rotational angle

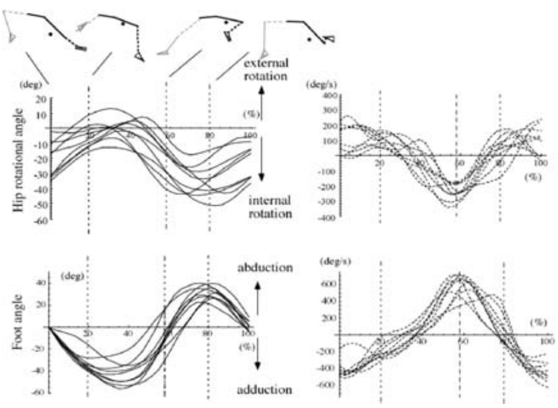

Figure 2. The time-angle curves (left) and the time-angular velocity curve (right) of the left hip (upper) and the left foot (lower) of all the subjects during one cycle of the eggbeater kick. A hip angle of zero implies that the toe is pointed anteriorly. The foot angle is the relative angle from its initial position.

Figure 2 shows the left hip rotational angle, the foot abduction and adduction angle, and each angular velocity that is influencing propulsive force in water, of all the subjects during one cycle of the eggbeater kick. The horizontal axes indicate the ratio when one cycle is assumed to be 100%. The rotational angle of zero implies that the toe is pointed anteriorly. The maximum internal rotation angle of the hip during the eggbeater kick ranged between –20° to –50°, which occurs just before the swimmer kicks outside after his foot was swept inside. In our previous study on the breaststroke kick of competitive swimmers (not published), the internal rotation of the hip was about –10°. In general, the range of internal rotation of the hip is considered to range from 0.0° to 45.0°; therefore, it was assumed that during the eggbeater kick, the internal rotation of the hip is very large. These rotational movements of the hip were connected to which the movements in the eggbeater kick? It was clarified as shown in Figure 2 that the phase between the hip rotational angle and the foot abduction angle was almost identical in the reverse direction. In addition, the peak values of the hip rotational angular velocity and the foot abduction angular velocity appeared almost at the same time. The eggbeater kick is a movement where the foot is abducted kicking water downward at the inside of foot; this is followed by adduction and inversion for generating a lift force due to the sculling effect. The foot movement is considered very important during the eggbeater kick for elevating the body. The results in this study indicated that the hip rotational movement is reflected in the foot abduction and adduction movement in the eggbeater kick.

Two movement types of the eggbeater kick

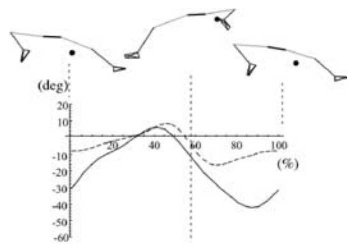

Figure 3. The left hip rotational angle of Sub. A (broken line) and Sub. B (solid line).

All the subjects were Japanese elite synchronized swimmers; however, different patterns of the hip rotational angle were noted in two subjects who were especially proficient performing the eggbeater kick. Fig. 3 shows the hip rotational angles of Sub. A and Sub. B, who had the highest and 2nd highest trochanter height in this experiment. Both Sub. A and Sub. B also got the higher scores of the eggbeater kick test in the Japanese National Team Trials. It must be clarified that the hip rotational angle of Sub. B was much larger than Sub. A in the latter phase of motion in which the knee joint was extended. Figure 4 shows the planes formed by the ankles through the eggbeater kick of Sub. A and Sub. B; ankle planes were calculated using the least square method on the supposition that an orbit drawn by the ankle is assumed to be on almost the same plane (1).

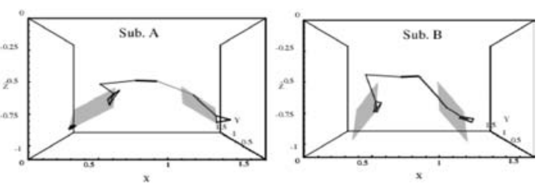

Figure 4. The planes formed by the ankles through the eggbeater kick of Sub. A and B.

There was a significant difference in the angles to the horizontal plane (water surface); the angles were 41.2° and 55.3°, respectively. However, as shown in fig. 5, the abduction angle of Sub. A was larger rather than that of Sub. B and there was negligible difference in the foot abduction angular velocity; therefore, it was considered that Sub. A performed the eggbeater kick using the hip rotation movement in addition to the high flexibility indexes of knee and foot joints. It would appear that Sub. A performed the eggbeater kick in a manner consistent with the results of Sanders's report (3), emphasizing horizontal motion, rather than vertical motion. In other words, Sub. A generated the upward propulsive force through the lift force generated the foot sculling motion. In contrast, Sub. B performed the eggbeater kick emphasizing the vertical motion, and generating the propulsive force mainly using the drag force. Almost half of the subjects in this study performed the eggbeater motion similar to Sub. B. This study did not clarify which motion was better for large propulsive force generations during eggbeater kick; however, it was suggested that there were two variants for the eggbeater kick—one emphasized the horizontal motion for the lift force and the other the vertical motion for the drag force.

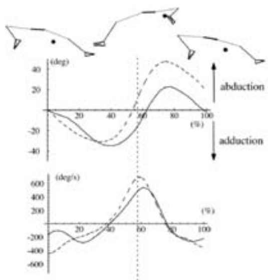

Figure 5. The left foot angle of abduction and adduction (upper) and the angular velocity (lower) of Sub. A (broken line) and Sub. B (solid line).

CONCLUSIONS

In this study, the magnitude of the rotational angle of the hip in the eggbeater kick was clarified performed by elite synchronized swimmers. The hip almost rotated internally during the eggbeater kick. In this study, the maximum internal angle ranged from 20.0° to 50.0°. It was considered that this internal rotation movement of the hip was reflected in the foot abduction and adduction movement that is expected to be very important for the generation of propulsive force to elevate the body. From the results of the analysis of the subjects who attains higher positions with regard the eggbeater kick, it was suggested that there are two variants of eggbeater kicks - one emphasizing the horizontal motion and the other emphasizing the vertical motion.

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INVERSE DYNAMIC MODELLING OF SWIMMERS IMPULSE DURING A GRAB START.

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Under race conditions, the start directly influences an athlete's performance. Taking into account the difficulties coming from the specific parameters relative to the start, comparing the swimmer's movement with the kinematic data stays the best approach to understand the motion. The model of the present work was developed through this approach allowing us to predict the swimmer's performance (trajectory, velocity) and the joint moment of each articulation during the impulse phase of the grab start. This model defines kinematical and dynamical data with the following mean dispersions: 9 % for horizontal and total speed at the instant of take off, 1 % for the swimmer's internal joint power. By means of this model, it becomes possible to analyze and understand the joint moment of each articulation and the segmental coordination for each swimmer performing a grab start.

Key Words: swimming, grab start, model, performance, joint moment, energy cost.

INTRODUCTION

Regardless of the discipline, whether 100 m Freestyle, 200 m 4 strokes (medley), or other, the study of the swimmers' performances involves the identification of three technical phases: start, turns and strokes phases. An analysis of the temporal distribution of the races showed that the start phase accounts for 15 % and 7.7 % of total time, respectively for 50 m and 100 m freestyle events (1). In short distance races (50m and 100m) the start represents a particularly important factor. For instance, at the Athens Olympic Games (2004), the time separating the eight finalists in the men's 50m freestyle finals was 0.44 s, which represents 2% of the winner's total race time (21.93 s). This difference in performance among the finalists may result from the time lost during the start phase.
Several studies carried out since the 1970's have shown that the start depends primarily on the quality of the swimmer's impulse on the starting platform and also on the water glide (7). However, the studies carried out to date are often contradictory when it comes to defining the most efficient movement required to optimize the athlete's performance impulse. This may lie partly in the fact that there are no objective tools currently available to provide a precise and quantitative evaluation of the movements in situ. Although recent studies have been undertaken, using both dynamic and kinematic approaches, they do not yield additional information concerning the relationship between the swimmers' movements and their actual performance (7). Few studies have addressed the modelling (dynamic and/or kinematic) of the parameters that determine the performance according to the swimmers' movements during start phases (4). Thus, the modelling method used for the study of movements in others sports (skiing, etc.) seems the most effective approach as far as understanding movements and predicting performance is concerned (5). A model based on inverse dynamic was developed in order to predict the impulse parameters during grab starts. The study presented here aimed the evaluation of the precision of this model by comparing the predicted speed and power values with experimental data collected in situ.

METHODS
Four national level swimmers were instructed to perform a grab start. Subjects' average height and mass were respectively 183.5 cm (± 3.41) and 75.77 kg (± 3.89). Swimmers were equipped with passive markers fixed on each articulation. For each start, a high speed camera (125 frames.s^{-1}) was placed at the edge of the swimming pool, at a perpendicular angle to the athlete's trajectory. The camera recorded the swimmers' profile movements. At the same time, ground reaction forces were recorded using a force platform fixed on the starting platform in order to simulate real competition starts (figure 1). The sampling frequency was 1000 Hz. Speed of the swimmer's centre of mass was obtained by integration of its acceleration. For each start, the kinematical (camera) and dynamical (platform) data were synchronised (0.008 s accuracy).

Figure 1. Image of recording a swimmer's impulse on the force platform by the high speed camera. In gray lines, segment's modelling using passive markers.

While the athletes were on the platform, a two-dimensional cinematography analysis was carried out during the impulse phase, in order to determine the angle between the subjects' segments (right side) and the horizontal axis. These data have been fitted using a polynomial method (6, 8). Morphological properties of the subjects are defined using their height, mass and the anthropometric tables of Dempster et al. (3). The sum of segment energies was obtained using the equations of sum of segment energies as defined in Winter (8).
During the impulse phase, subjects were represented using an open tree structure composed of eight straight segments connected with frictionless joints. Input data for the model consisted of the fitting angles calculated at each joint, and the subjects' morphological properties. For each joint, the dynamic torque, force and power were determined using the inverse dynamic equations (8, 5). Based on an analysis of the swimmers' forces and joint moments exerted during the impulse, the model predicts the total power of the subject during the impulse phase, as well as the speed, angle and position of the subjects' centre of mass at the instant of takeoff.

RESULTS
The model presented in this study was able to predict parameters that have also been collected from the force platform, with the following mean dispersions: underestimation of 9% (0.4 ± 0.1 m.s^{-1}) for horizontal and total speed, overestimation of 0.3 m.s^{-1} (± 0.15) for the vertical speed and overestimation of 4 degrees (± 3) for the angle between the vector tangent to the trajectory of subjects' centre of mass at takeoff and the horizontal axis (figure 2). The model was able to predict the swimmer's internal joint power observable using the video image and the time derivative of the sum of segment energies (8), with the mean dispersions of 1% (figure 3).

Subject	$V_{XGtakeoff}$		$V_{Zgtakeoff}$		$V_{Gtakeoff}$		$\alpha_{takeoff}$	
	a)	b)	a)	b)	a)	b)	a)	b)
1	3.56	4.09	0.38	-0.09	3.58	4.09	6.20	-1.35
2	3.92	4.25	-0.16	-0.35	3.92	4.26	-2.34	-4.82
3	3.75	4.14	-0.54	-0.66	3.79	4.20	-8.16	-9.16
4	4.10	4.44	-0.13	-0.44	4.10	4.47	-1.92	-5.73
mean	3.83	4.23	-0.11	-0.38	3.84	4.25	-1.55	-5.26
Sd	0.23	0.15	0.37	0.23	0.21	0.15	5.90	3.21

Figure 2. Swimmer's performance parameters: a) using the model; b) using force platform.
With: $V_{XGtakeoff}$: horizontal speed of the swimmer's centre of mass at take off (m.s^{-1}), $V_{ZGtakeoff}$: vertical speed of the swimmer's centre of mass at take off (m.s^{-1}), $V_{Gtakeoff}$: total speed of the swimmer's centre of mass at take off (m.s^{-1}), $\alpha_{takeoff}$: angle between the vector tangent to the trajectory of subject's centre of mass at takeoff and the horizontal axis (degree).

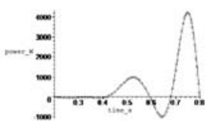

Figure 3. Swimmer's power: a) using the model (point); b) using the energies approach (line) of Winter (8).

DISCUSSION
This model makes it possible to consider joint moments resulting from the muscle activation during the movement (figure 4). These joint moments reflect the muscular activities of the subject (8). The main interest of this model lies in the possibility of analysing the individualised coordination of each segment of the swimmer.

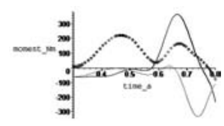

Figure 4. Joint moment of the hip (point), the knee (black line) and the ankle (gray line) during the impulse of a grab start.

The model still remains limited by the lack of the precision of the kinematics data and the lack of knowledge related to the morphological properties of the subject. The specificity of the measurement "in situ" imposes the use of passive skin fixed markers. The shifting of these markers during the subject's movement can differ from the anatomical centre of giration of each articulation and create a major source of error in the inverse dynamic estimations (2). This phenomenon is amplified by variations between the morphological properties of the segments resulting from the studies of Dempters et al. (3), and those specific to each swimmer. Using the same kinematical (video) and anthropometric data as input parameters, the estimations of the power developed by the swimmer resulting from the model and that resulting from the energy calculations (8) present a weak mean dispersion. This dispersion between the results of these two methods confirms the hypothesis that small errors in kinematic measurements will lead in mistakes in results obtained by the model.

CONCLUSION

The impulse model developed for a grab start is able to predict the swimmers' performance parameters using easy to install tools (only one camera). In the short term, this model should be able to provide more precise informations regarding the role played by joints in achieving the most effective grab start and to determine the swimmers' joint moments during the impulse phase. Future developments will increase the accuracy of the model and will contribute to the modelling and optimization of the most efficient movement strategies.

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SPEED VARIATION ANALYSIS BEFORE AND AFTER THE BEGINNING OF THE STROKE IN SWIMMING STARTS

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Currently, few biomechanics studies have been conducted to examine the transition from the underwater phase to the stroke phase in swimming starts. The objective of this study was to evaluate the speed before and after the beginning of the stroke in front crawl and its relationship to the time to 15 meters in order to determine the importance of the underwater phase and transition phase in the entire performance of the swimmer. The transition speed of four athletes was recorded with video cameras and signal synchronizer. According to the results, the majority of swimmers reduced speed after the beginning of the stroke. There was a negative correlation between the difference in speed before and after commencing the stroke and the time at 15 meters. Therefore, attention should be paid to the underwater phase of starts to improve performance in front crawl.

Key Words: stroke, performance, transition phase.

INTRODUCTION

In the beginning of the 1980s, the right point of the start of front crawl was intensely discussed (1). Hay (4) contributed the information about the position of the swimmer. His comments suggested that the swimmer had to be as horizontal as possible until the speed forward was less than the speed of the stroke. Only a few studies involving the swimming starts have been conducted to examine the transition from underwater to stroke in the swimming starts.
According to Hay (4), the swimmer's performance is measured by the time to cover a certain distance, being able to divide it in three partial times: the time between the start signal until the feet leaving the block is called 'start time'. 'Block time' refers to the period between the feet leaving the block until the first contact with the water. 'Time of glide' (underwater phase) is from the first contact with the water until the swimmer commences stroking.
Guimarães & Hay (3) found that the most important phase in swimming is the underwater phase. However, the transitions phases and turns are also related to performance. As well as the phases, the speed in each one of these suggests independent evaluations. Karpovich found that the speed of swimmer in front crawl comes 70% from arm and 30% of the legs (1). Counsilman (1) suggested that the upper limbs are the principal, and in some cases, the only propulsion source during the front crawl swimming.
To understand the time of a swimming competition it is necessary to evaluate the starting time, glide time, turn time and arrival time. The proportion of starts, turns and arrival times increases when the distance of the test decreases (7). Hay (5) verified that starts represents 11% of the total time of a 50 meters in front Crawl swimming, and suggested an intensification in studies of the techniques starts to reduce the time expense at this phase. Navarro (8) and Pereira et al. (9) recommended focusing on the start as one of the main factors for improving competition times.
The objective of this study was to evaluate the speed before and after the beginning of the stroke in national and state level swimmers, as well as relating them with the performance to 15 meters.

METHODS

Six starts of four male swimmers state and national level have been evaluated in accordance with the methods of Hubert (6). All participants were required to perform 6. The data were collected in the Doze de Agosto Club´s swimming pool and analyzed in the Aquatic Biomechanics Research Laboratory of CEFID/UDESC. The following variables were measured: speed before the beginning of the stroke (Sb), measured in the underwater phase, in the interval of 1 second before the first movement for beginning of the stroke; speed after the beginning of the stroke (Sa), measured in the interval of 1 second after the beginning of the stroke and time in 15 meters (T15m). The performance of the 15 meters corresponds to the time that the swimmer takes to cover this distance. Time to 15 meters was determined in accordance with the methods of La Fuente et al. (2). Four video cameras, one miniDV and three VHS type (30 Hz) were used to collect kinetic variables. For the underwater images, cameras had been connected to waterproof boxes and fixed each one to a tripod setting in deep of the swimming pool and an electronic trigger with a light bulb, composed of one led, a bell and two boxes of sound synchronized the video camera to the instant of the start signal. Data was analyzed using Intervideo 3 WinProducer and CorelDRAW 10 software. Statistical programs SPSS was used for Windows 11,0 and GraphPad InStat version 2.04 were used to obtain Spearman correlations to establish the relationship between the variation of speed and the time to 15 meters.

RESULTS AND DISCUSSION

The Sb and Sa and the time to 15 meters of each athlete in the six starts are presented in table 1. It was observed that only athlete 4 had a greater Sa than Sb. Consequently, his time to 15 meters was large.

Table 1. Sb(m/s) and Sa the beginning of the stroke and time to 15 meters.

	Athlete 1			Athlete 2			Athlete 3			Athlete 4		
Starts	Sb	Sa	T15m	Sb	Sa	T15m	Sb	Sa	T15m	Sb	Sa	T15m
1	1,78	1,61	7,199	1,58	1,54	6,799	1,78	1,71	6,766	1,30	1,52	7,133
2	1,66	1,57	7,233	1,65	1,66	6,866	1,94	1,57	6,633	1,36	1,67	7,199
3	1,66	1,56	7,266	1,52	1,61	6,866	2,01	1,55	6,699	1,91	1,76	7,000
4	1,89	1,52	7,099	1,67	1,54	6,832	1,99	1,55	6,666	1,44	1,75	7,233
5	1,60	1,52	7,399	1,80	1,56	6,899	2,14	1,62	6,533	1,94	1,74	7,199
6	1,91	1,52	7,199	1,69	1,62	6,832	2,08	1,58	6,566	1,32	1,64	7,233
Avg.	1,75	1,55	7,233	1,65	1,59	6,849	1,99	1,59	6,644	1,54	1,68	7,166
sd	0,13	0,04	0,099	0,10	0,05	0,035	0,12	0,06	0,086	0,30	0,09	0,089
cv	7,36	2,49	1,368	5,83	3,03	0,512	6,21	3,96	1,293	19,22	5,43	1,245

The speed before the beginning of the stroke varied from 1.3m/s to 2.14m/s, and the speed after the beginning of the stroke from 1.52m/s to 1.76m/s. Time to 15 meters varied from 6.53s to 7.4s. The standard deviation and the coefficient of variation were always smaller in the Sa than the Sb. There was negative correlation (-0.473) between the variation of the speed and the time to 15 meters when the speed decreased after the beginning of the stroke (Sa). The athletes 1, 2 and 3 had similar behavior in the underwater phases for the beginning of the stroke, whereas athlete 4 was different. This difference suggests that athlete 4 did not perform the underwater phase satisfactorily, since his Sa had been greater then Sb. The images of swimmer 4 had shown an incorrect position of the underwater phase considering the desirable positions described by Hay (4). For Guimarães and Hay (3) the best performances occur when the Sb is greater then Sa, what we could verify for swimmers 1, 2 and 3 (table 1).

CONCLUSION

It was verified that performance is better when Sb was greater than Sa, resulting with decrease time to 15 meters. That indicates that beyond the importance of the underwater phase, the transition phase must have special attention; therefore, to begin the stroke at the correct instant is an important factor for the performance in the starts.

Reevaluation of each swimmer individually is suggested, as well as the basis of trainings of underwater phase. The swimmer must be qualitatively evaluated through underwater images searching to verify the entrance angle in the water and the depth reached during the underwater phase. Therefore, it is necessary to continue studies and also increase the number of evaluated athletes.

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FUNDAMENTAL FLUID DYNAMIC RESEARCH ON CONFIGURATION OF THE HAND PALM IN SYNCHRONIZED SWIMMING

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In synchronized swimming, the hands usually describe a “figure 8” or an egg-shaped oval during sculling motion. Various types of sculling movements are employed depending upon the actions and purposes, although the function of all sculling motions is to produce lift force through reciprocating motion. Optimal hand configurations for sculling are not standardized among athletes and are instead determined empirically by coaches and athletes. In this research, the hydrodynamic characteristics of five hand configurations are investigated in a basic study in a steady-state flow field to determine the configuration that produces maximum resultant force.

Key Words: hand, synchronized swimming, maximal resultant force, steady-state.

INTRODUCTION

Synchronized swimming is a highly artistic sport in which points are awarded separately for technical merit and artistic expression, both of which demand high levels of skill and artistry. A stable lift force is desirable for artistry in competitions. The stronger this force is the better.

A continuous sculling motion with the hands and an eggbeater kicking motion with the legs produce the lift needed to create buoyancy. Sculling is a hand motion that describes a "figure 8" path or an egg-shaped oval path. Kartashov (1) classified sculling motions into many types according to their various operations and purposes, although fundamentally speaking these motions are virtually the same in that they all develop lift force using reciprocating motion. However, the configuration of the palm of the hands has not been standardized in principle among athletes. Instead, coaches and athletes determine the optimal configuration based on experience.

This study measures the aerodynamic characteristics of five different hand configurations to determine the configuration that provides maximum lift force for the best performance. In addition, the characteristics of hand configurations used by athletes are compared. Although sculling is a reciprocal and unsteady motion, especially when the hand changes orientation at the point where the direction of movement changes, the lift-drag force is investigated in this preliminary study under stable conditions.

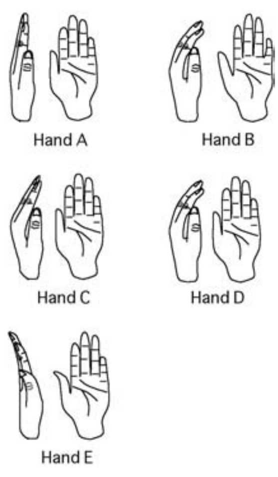


Figure 1. Configurations of hand model.

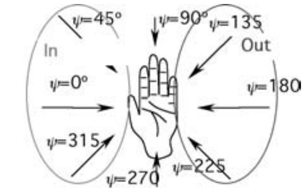


Figure 2. Sweepback angle y entering the palm, defined by Shleihauf (2).

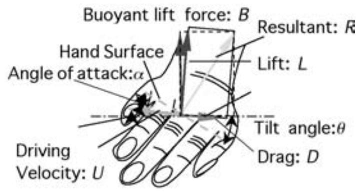
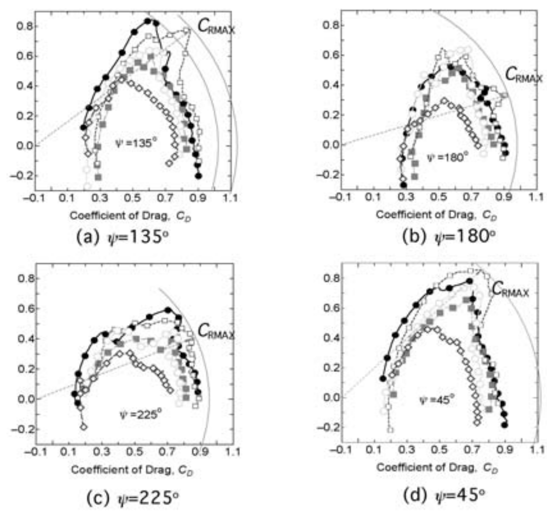


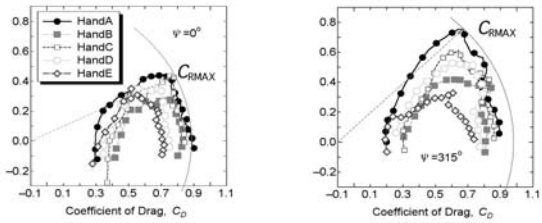
Figure 3. Forces and velocities acting on hand paddle.

METHODS

The aerodynamic characteristics of hand replicas are measured in a wind tunnel using a three-component load cell. Plaster models are made into the same size and shape taken from the hand of a female swimmer and molded into five different hand configurations as shown in Fig. 1 (A: A flat palm with no gaps between fingers, B: a cupped palm with gaps between fingers, C: a cupped palm with no gaps between straightened fingers, D: a cupped palm with no gaps between fingers, E: an inversely bent palm with no gaps between fingers).

The lift, drag and moment on each of the plaster models are measured with a three-component load cell at one-degree intervals from -5° to 95° for each angle of attack α. Each angle of attack α has seven types of sweepback angles ψ (0°, 45°, 90°, 135°, 180°, 225°, 315°) based on the Schleihauf (2) definitions shown in Fig. 2.





(e) ψ=0° (f) ψ=315°

Figure 4. Differences in polar curves during sculling between in out-sweep movement (ψ =135o, 180o, 225o) and in in-sweep movement (ψ = 45o, 0o, 225o) on different hand configurations.

Experiments are performed at a wind speed of 20 m/s, which corresponds to the Reynolds numbers (3.4x10^5). This speed is almost equivalent to actual swimming speed.

Figure 3 shows the flow aspects and fluid forces on the palm of the hand. The palm is tilted at an angle θ, and it moves in still water with a driving velocity *U* and at a driving angle *d*. The water hits the hand at an angle of attack α. If the hand were a wing, lift force *L* occurs at a right angle to the driving velocity *U,* and drag force *D* occurs at a right angle to lift force *L,* as shown in Fig. 3. The resultant force $R = \sqrt{L^2 + D^2}$ builds up on the back of the hand and its vertical component is buoyancy lift force *B*. Furthermore, the authors (2003) previously calculated the maximal buoyancy lift force based on these equations of motion, taking into consideration the relation between velocity and the fluid forces. The results showed that the highest buoyant lift was obtained at the highest resultant force of the lift-drag force; in other words, $\sqrt{C_L^2 + C_D^2}$ occurred at the point farthest from the origin in the polar curve or the lift-drag curve.

Sculling motion is a combination of in-sweep and out-sweep movements with the elbows bent at a right angles while swimming in a standing orientation. During the out-sweep movement, the forearm performs supination and during the in-sweep motion it performs pronation. When translated into changes in sweepback angles, these motions are equivalent to ψ =135°, 180°, 225° (out-sweep) and ψ = 45°, 0°, 315° (in-sweep), respectively.

RESULTS AND DISCUSSION

Figure 4 (a) to (f) are polar curves showing changes in the drag coefficient C_D and the lift coefficient C_L corresponding to changes in the angle of attack in which α = 0° to 90° based on differences in the hand configurations. Each figure represents a different sweepback angle ψ. Markers are placed every 5° for each attack angle α in these figures. It is assumed that the degree of buoyancy lift force developed by each hand can be expressed with respect to the distance from the origin of the polar curve. The circular arc C_{RMAX}, which is the maximum length from the point of origin along the polar curve, is indicated in each graph. The angle of attack α for C_{RMAX} is also shown in Table 1. Because the sculling movement utilizes mainly lift force, the farthest point from the origin when the angle of attack α <60° is determined to be the best hand configuration in each sweepback angle ψ.

Table 1. The maximum lift-drag force point in sculling motion.

Figure	ψ [deg]	C_{RMAX}	Hand Model with C_{RMAX}	Ratio against Hand A	α [deg]
Fig. 4 (a)	135	1.23	C	1.10	51
Fig. 4 (b)	180	1.07	C	1.11	55
Fig. 4 (c)	225	1.04	C	1.01	53
Fig. 4 (d)	45	1.21	C	1.08	47
Fig. 4 (e)	0	0.99	C, A	1.03	60
Fig. 4 (f)	315	1.08	A	1.00	47

Regarding the out-sweep ψ =135° in Fig. 4 (a), the polar curves for Hand C and Hand A have a big lump near at the point where the angle of attack α =50° and 45°. C_{RMAX}=1.23 is obtained with Hand C. Regarding the out-sweep ψ =180° in Fig. 4 (b), C_{RMAX} is 1.07 when Hand C and Hand D are α =55° and 45°, and in out-sweep ψ =225° in Fig. 4 (c), C_{RMAX} is 1.04 when Hand C and Hand A are α =50° and 60°, respectively. Similarly, regarding the in-sweep ψ =45° in Fig. 4 (d), significant lumps appears near the angle of attack α =50° and 45° on the polar curves of Hand C and Hand A. C_{RMAX} is 1.21 with Hand C. For the in-sweep ψ =0° in Fig. 4 (e), C_{RMAX}=0.99 is obtained when Hand C and Hand A are both α =60°, and for in-sweep ψ =315° in Fig. 4 (e), C_{RMAX}=1.08 when Hand A is α =50°. Hand C constantly produces the largest thrust during out-sweep. Since it is impossible to change the hand configuration during the in sweep/out sweep cycle, it is evident that Hand C consistently develops the largest buoyancy lift force.

Next, Hand B, which is a cupped palm with gaps between the fingers, is compared with Hand D, a cupped palm with no gaps between the fingers. It is interesting to note that competitive swimmers and water polo players often have gaps between their fingers whereas synchronized swimmers in general do not. Only in Fig. 4(e) is C_{RMAX} of Hand B with gaps about 3% greater than C_{RMAX} of Hand D without gaps. Thus, Hand D without gaps is relatively advantageous.

Hand configurations can be largely divided into three types: cupped, flat, and inversely bent as shown in Fig. 1. The results of hand E with an inversely bent shape shows the worst performance in every graph of Fig. 4. This is due to large detachment of water flow on the backside of the hand because the palm is bent inversely. Also, the inversely bent palm cannot grasp the water the water in the way the other hand configurations can. Thus, this configuration cannot develop a large resultant force. Comparing the two cupped hand shapes, Hand C with flat fingertips and Hand D with curved fingertips, in every sweepback angle ψ, Table 1 show that Hand C develops the largest resultant force C_{RMAX} compared to the other hand models. Hand A with a flat palm displays larger results than Hand C only when the sweepback angle is ψ=315°, but otherwise Hand C displays the largest C_{RMAX} values among all the configurations. Based on these results, it is found that Hand C, a cupped hand with no gaps between straightened fingers, provides the largest resultant force.

CONCLUSION

To find the best hand configuration for generating the largest lift-drag resultant force in synchronized swimming, five different models were constructed and their stable-state fluid characteristics investigated.

The following results concerning good buoyant lifting performance were obtained:
1. A cupped hand is better than a flat hand.
2. On a cupped hand, straight fingers are better than naturally bent fingers.
3. A configuration without gaps between the fingers is better than one with gaps.
4. Hand C, which is a cupped hand with straight fingers, develops the most buoyant lift force in sculling motion.

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BIOMECHANICS OF TOWING IN SKILLED AND LESS-SKILLED LIFESAVERS

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Successful and safe lifesaving operation depends on the effectiveness and skill of the lifesaver. The objective was to study lifesaving towing and to identify biomechanical differences in the performances. Eight lifesavers towed an unconsciously acting victim in a swimming pool. Skilled lifesavers towed the victim faster and with longer strokes than the less-skilled. Less-skilled lifesavers had a more upright body position leading to higher drag force. They also had difficulties in keeping the victim's head above the water surface. The victim also travelled considerably low in relation to the water surface with less-skilled lifesavers.

Key Words: lifesaving, technique analysis, towing grip.

INTRODUCTION
Lifesaving using body contact technique is physically demanding and even a dangerous manoeuvre both for the victim and the lifesaver. Therefore, as a general rule body contact should be avoided with a conscious victim (3). It is recommended to use some technical aid between the lifesaver and the victim (7). To avoid further hazards, it is very important that the lifesaver has adequate skills to be able to act effectively. An unconscious victim is more in life threatening danger than a conscious victim. So the speed and effectiveness is vital to both start the first aid and further actions for securing survival.
Lifesaving manoeuvre is anaerobic and exhaustive for the performer (8, 5, 4). The towing technique is optimal, when an effective survivor back stroke kick or a scissor kick will be used allowing streamlined body position in water. Ineffective kicking and hence poor towing performance aggravates drag forces in the same mechanism as during ordinary swimming (6). On the other hand, propelling and buoyant forces give additional help to a lifesaver with an optimal technique (2). In lifesaving towing drag forces increase especially due to the victim and his/her clothes (9). The aim of the present study was to compare two different towing grips during lifesaving manoeuvre between skilled (SLS) and less-skilled lifesavers (LSL).

METHODS
The subjects of the study were three female (20.0 ± 1 y) and five male (25.2 ± 8 y) lifesavers. They were voluntary university students or staff members, who had at least one qualification from level 1 - 4 of Royal Lifesaving Society Australia (RLSSA) or a valid international life guard certificate. Written informed consent was obtained from each subject. Ethical approval was obtained from the Human research Ethics Committee of the University of Ballarat, Australia.
The task was to tow a living victim acting unconscious (height 174 cm, body mass 62 kg, BMI 20 kg/m^2) for 50 m in a 25-m long swimming pool. Water temperature was 27° C. The participants used two different towing grips on the victim: cross-chest (CC) and head-neck (HN) in randomised order. They chose kicking style by themselves and used it similarly in both trials. The instruction for the performances was: "Swim as fast as you would in a real rescue situation. Do your best. Keep the victim's head above water all the times. Use your preferred towing kick. Use one hand to hold the victim. The other arm may be used to assist with towing." Instruction for an alive victim was: "Be as relaxed as you can. Act as an unconscious person. Do not move any parts of your body during the tow."
The division of the subjects into two groups, skilled and less-skilled, was based on the evaluation of their skills during the lifesaving tasks. The skills were evaluated by the researcher based on visual observation from video pictures, and subjects' 50 m towing time, and number of used strokes. The time for each 50 m towing lap was measured and the strokes were counted by an assistant. Selected strokes during the towing task were analyzed based on video recordings using Peak Motus movement analysis system. The performances were recorded by two Panasonic S-VHS cameras, which were placed on the pool side, one of them underwater. The cameras were synchronized with the timer on the accuracy of 0.02 s. The recordings were made at a frame rate of 50 Hz. Because of the limitations in camera locations only a two-dimensional movement analysis could be made. Markers on selected anatomical landmarks were placed by texture on both the participant and the victim (shoulder, elbow, wrist, hip, knee, ankle). From video recordings the locations of the markers were digitized frame by frame from the body side, which was closer to the pool bottom. The calibration frame was a 10 m long "seasnake" with nine floating balls. The calibration frame was 4 m long and 0.801 m high (Picture 1). The stroke analysis started and stopped at the beginning of kick on the maximal flexion of legs. Absolute coordinates were low pass filtered with Butterworth cut-off frequency 3 Hz. To characterize the differences in the towing technique, the angle of the shoulder-hip-line from horizontal ("Body angle"), the depth of the victim's ankle from the surface and the travel distance per stroke were calculated. Average values for one stroke were calculated for statistical comparison.

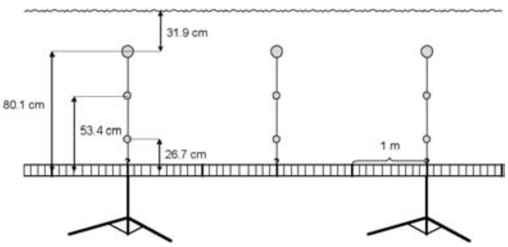

Figure 1. The calibration frame under water: 4 meter long "seasnake" and nine floating balls (design by Peter Clothier.)

RESULTS

Table 1 presents the main findings of the performances with two different towing grips. Mean towing time for 50-m with CC grip was 78 s for SLS and 147 s for LLS; and with HN grip 83 s and 126 s, respectively. The average number of strokes for 50-m using CC was 71 for SLS and 144 for LLS; and using HN 74 and 111, respectively. The average distance per analysed stroke using CC was 68 cm for SLS, and 30 cm for LSL, and using HN 63 cm, 44 cm, respectively. The average body angle from horizontal using CC was 24° for SLS, and 50° for the LSL, and using HN 32°, and 35°, respectively. The victim's mean ankle depth from the water surface during CC towing was 68 cm with the SLS, and 104 cm with the LSL, and during HN 80 cm, and 101 cm, respectively.

Skilled lifesavers towed the victim very close to their own bodies. They also acted closer to the water surface than their less-skilled colleagues (Fig. 2). They could keep the victim' s head well above the water during all efforts.

Contrarily, less-skilled lifesavers had their bodies deep in water and consequently, the lower part of the victim's body was noticed to sink down. Some lifesavers in the LSL group could not keep the victims' head constantly above the water surface during towing. The angle of the LSL's body was steeper than the SLS's. Some of LSL's body position resembled standing position.

Table 1. Towing time (s), stroke count, distance per stroke (cm), average body angle of the life saver (degrees from horizontal), average ankle depth of the victim (cm).

	Head and neck towing (HN)					Cross-chest (CC)				
Subjects	**Time 50 m**	**Strokes 50 m**	**Travel distance / stroke**	**Max body angle°**	**Victim's ankle depth**	**Time 50 m**	**Strokes 50 m**	**Travel distance/ stroke**	**Max body angle°**	**Victim's ankle depth**
Skilled lifesavers										
CC						71	59	88	25	47
BB	90	82	61	30	96	94	84	44	18	90
AA	68	63	74	23	84	70	69	72	30	67
RR	90	78	54	43	60					
Mean	**83**	**74**	**63**	**32**	**80**	**78**	**71**	**68**	**24**	**68**
SD	**12**	**10**	**10**	**10**	**18**	**13**	**12**	**22**	**6**	**22**
Less-skilled lifesavers										
VV	123	113	37	31	98	170	163	19	54	130
MM						138	144	35	36	78
SS	132	119	46	30	87					
PP	119	102	49	45	117	134	126	35	59	103
Mean	**126**	**111**	**44**	**35**	**101**	**147**	**144**	**30**	**50**	**104**
SD	**9**	**9**	**6**	**8**	**15**	**20**	**19**	**9**	**12**	**26**

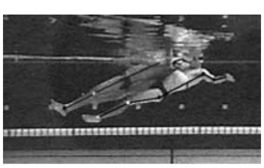

Figure 2. Typical examples of towing using cross-chest grip by a skilled lifesaver (first panel) and a less-skilled lifesaver (second panel).

DISCUSSION

The major finding of the study was that the skilled lifesavers as compared to their less-skilled counterparts could obtain higher speed by doing fewer and more effective strokes throughout the towing. Consequently they were able to keep the victim's body closer to the water surface. This helped to keep the victim streamlined and his face constantly out of water. According to Pia (7) it is impossible to keep the victim's body position horizontal during CC grip, because the rescuers' arm is crossing the victim's chest, which in turn causes the victim's head and body to sink lower in water. In this study the main reason why both the victim and the rescuer were drafting deep was due to the lack of skill to perform the manoeuvre. LSL typically had a low towing speed leading to more upright body position in relation to water surface and hence to difficulties in keeping the victim's face above the water. If each individual kick was ineffective, LSL needed to kick more frequently to travel forward, which increased physiological strain even to an exhaustive level (8). The lack of towing skill means also that even though the limb movements produce a lot of kinetic energy it will not transform correctly to result in effective movement forward (1).

HN grip was noticed to be superior for the LSL to use. Versatile lifesaving skills need to be frequently practised in water (5). The SLS subjects, who actually were competitive swimmers as well, had a reasonably good kicking technique. Other lifesaving qualifications seemed less important indicators in this case. We conclude that less-skilled or inexperienced lifesavers should not use CC towing grip as the principal technique especially when towing an unconscious victim. HN grip can be substituted by gripping on the victims's collar behind neck.

ACKNOWLEDGEMENTS

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gestions can be given to swimmers because the flow field is easily understood visually through analysis of mechanisms using PIV method.
Theoretical and experimental values were almost identical. It was suggested that a pair of vortices observed by the shift phase might be a vortex ring. In addition, from the comparison of both values, a swimmer with an efficient stroke can form a large vortex because swimmers propel themselves using the reaction force of the jet flow. Therefore, they might note the value of a large jet flow. It was also suggested that these values might serve as an index for propulsion force evaluation of swimmers in future. Moreover, by measuring the flow field around swimmers of different levels, strokes that produce greater propulsive force might be clarified. Suggestions for more efficient stroke skills can be given.

CONCLUSION
In conclusion, we confirmed that swimmers form vortices and use jet flow as a propulsion mechanism of sculling motion. Suggestions offered in this study are a first attempt at clarifying propulsion mechanisms; further study is intended. Future studies should examine the provision of feedback to facilitate coaching.

ACKNOWLEDGEMENTS
The authors gratefully acknowledge the members of the Swim Laboratory and Matsuuchi Laboratory at University of Tsukuba. We also thank all participants in this study, which was supported by Grant-in-Aid for Scientific Research ((B) (2)16300202), ((B) (2)15300216)) from the Japan Society for the Promotion of Science, Japan.

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STROKE FREQUENCY STRATEGIES OF INTERNATIONAL AND NATIONAL SWIMMERS IN 100M RACES

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The purpose of this study was to examine stroke rate strategies of elite international and national junior level swimmers. Norwegian junior national (NOR) and European Short course championships (EUR) race analysis was performed by videography. Clean swimming velocity (v_{clean}) stroke rate (SR) and stroke length (SL) were analyzed for each lap. The frequency of use of five models for SR strategies during a race were identified for finalists (rank 4th – 6th/8th) and the top 3 performers for all 100m races. The most common strategy was model D for the top 3 performers (decreasing SR at the beginning, and increasing SR in the end of the race) and model B (decreasing SR throughout the race) for the finalists. It seems that the strategies most often used by the best performers in 100m short course races are decreasing during the first part of the race, and increasing at the end, and is a compensatory mechanism for a decrease in SL.

Key Words: Race analysis, swimming performance, stroke rate.

INTRODUCTION
It is documented that swimming race performance is, among other factors, affected by the strategies swimmers use to control the clean swimming velocity (v_{clean}), stroke length (SL) and stroke rate (SR) during the various phases of the race (e.g. 2). These authors found that for distances of 200m and longer the SL decrease with fatigue, and that faster swimmers compensate by increasing SR at the end of the race. In other studies it was found that for 200m races the decline in velocity at the end of the race was due to a decrease in SL (4), and that SL, and v_{clean} decrease throughout the race (9). Furthermore in the latter study mean SR increased for the last lap. For 100m races in long course it has also been reported that SL is a success factor for performance (6) and for breaststroke SR increased and SL decreased in the last part of the race (9). The SR strategies successful swimmers use during a short course 100m race is however rarely investigated, nor is there any information on differences in SR strategies between medal winners and other finalists. The purpose of this study was to examine successful SR strategies of elite international and national junior level swimmers, and furthermore to test the hypothesis that top 3 performers use a different race strategy than other finalists.

METHODS
Races from the finals at the Norwegian short course junior national championships (NOR, n=24) and from the finals at the European short course championships (3) (EUR, n=32) were studied. The races were all male 100m events. Mean (±SD) international point scores for the two groups were 626 (±59) and 911 (±31) respectively ($p<0.05$).
For all races, race analysis was performed by videography. Three or four cameras (50 Hz) were mounted perpendicular to the pool, making it possible to record all lanes at positions 0,

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ANALYSIS OF SCULLING PROPULSION MECHANISM USING TWO-COMPONENTS PARTICLE IMAGE VELOCIMETRY

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The flow field around a human body during swimming presents a very unsteady condition. This study analyzed the flow field around the hand using particle image velocimetry method. A male subject participated in this study, and the flow field around the hand during the sculling motion was visualized. The results indicate that a pair of vortices and the jet flow occurs around hand during sculling motion. The swimmer generated a great propulsive force as a reaction force of the jet flow. The theoretical value of the jet flow of a vortex ring and the experimental value were indicated as nearly equal. This measurement is expected to become an index for evaluating propulsive force in unsteady conditions.

Key Words: unsteady, PIV method, sculling, propulsion mechanism.

INTRODUCTION
Lately, many swimmers use an S-shaped pattern as a stroke pattern during swimming. This stroke pattern was advocated by Counsilman (1), who reported that it is used as a propulsive force that uses lift force effects. During the S-shaped pattern, there is sculling movement to increase the lift. Therefore, it is interesting to analyse the sculling propulsion mechanism, which is a basal motion of the S-shaped stroke pattern. Numerous studies have estimated propulsive forces during human swimming. However, most have been based on quasi-steady analyses. The actual flow field around the swimming human body is in a perpetually unsteady condition. Unsteady effects must therefore be considered (8).
Recently, a method to analyse an unsteady flow field around a human body has been established in the field of engineering: Particle Image Velocimetry (PIV). Measurements taken near the bodies of fish and insects have been reported using PIV (2, 6). The flow field around moving fish and insect are in an unsteady condition. We therefore inferred that it is appropriate to use this method to analyse the flow field around a human swimmer. Some researchers have visualised the flow field around the human body by applying PIV to the swimmer's environment (4, 5, 7). Nevertheless, no studies have applied PIV to swimming humans.
This study was intended to analyse the propulsion mechanism of sculling motion in human swimming using two-components PIV (2C-PIV).

METHOD
A male subject participated in this study. His body height was 1.72 m; his body weight was 67 kg, with 141.1 cm^2 hand area. The subject had swum competitively before; he was sufficiently accustomed to sculling skills. The subject was informed of the experiments and their associated risks before giving his informed consent to the study.

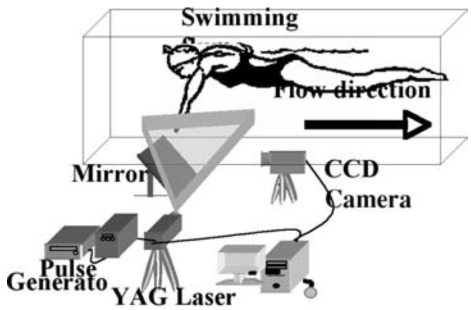

Fig. 1. The experimental situation.

This study used a swimming flume (4.6 x 2.0 x 1.5 m; Igarashi Industrial Inc., Japan). Figure 1 shows the device used for PIV measurement. Tracer particles (50 μm) were mixed in water. To illuminate the particles of the test section, the beam of an Nd-YAG laser (New Wave Research, USA) was spread to resemble a plane of light, thereby horizontally illuminating around the left hand from the side of the swimming flume. The subject was instructed to maintain a position against the flow (0.5 m/s) using a sculling motion in a prone position. Two hundreds time sequential images of the unsteady flow field around the left hand were captured using a CCD camera (15 Hz) from the lower side through a mirror. They were subsequently stored in a personal computer. The subject wore goggles during PIV measurements for protection from the laser light. Moreover, to reduce the influence of halation, the subject wore a black glove on the left hand. They did not influence the subject's skill. Positional data and the particle velocity data were output from the image data obtained during the experiment. The velocity vector-vorticity distribution data were calculated from the output data using software (MATLAB; The MathWorks Inc., USA). In this study, the rotational direction of vortex was defined with counterclockwise as positive; clockwise was negative.
In addition, the force generated by the hand was evaluated. A pair of vortices was inferred to form because of the sculling motion in sections of the vortex ring. The circulation value when assuming that a pair of vortices observed in the flow field is a vortex ring was calculated using the following equation.

$$\Gamma = \int \omega ds \quad \text{(Eq. 1)}$$

Therein, ω represents vorticity and *ds* indicates the unit area. Moreover, the induced velocity by the vortex ring was calculated using the formula and applying the law of Biot-Savart:

$$V_0 = \frac{\Gamma}{2R} \quad \text{(Eq. 2)}$$

where V_0 represents the induced velocity, Γ was circulation of vortex ring, and R was radius of vortex ring. The forecast value of the jet flow by the theory (the theoretical value) was calculated using these formulae. Those calculated values were compared with experimental values of the jet flow of an actual flow field.

RESULTS

The time sequential velocity vector-vorticity map and image picture during sculling are shown in Fig. 2 and Fig. 3.

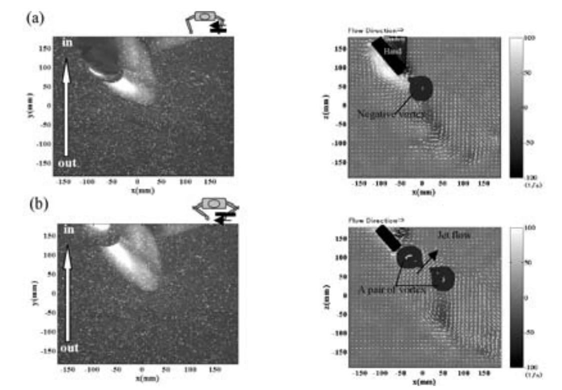

Fig. 2. Velocity vector-vorticity map at the shift phase from out-scull to in-scull. (Image picture: left, velocity vector-vorticity map: right)

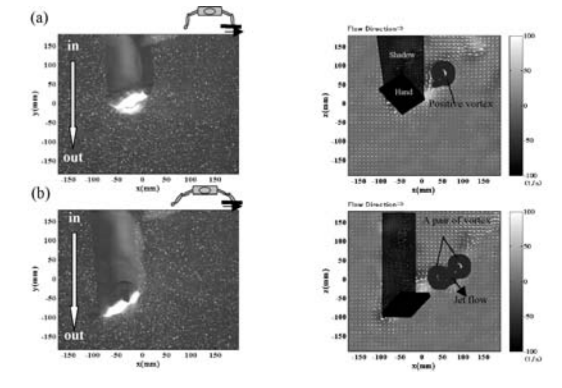

Fig. 3. Velocity vector-vorticity map at the shift phase from in-scull to out-scull. (Image picture: left, velocity vector-vorticity map: right)

Figure 2(a) depicts the middle of the shift phase from out-scull to in-scull. At that time, changing the hand direction formed a negative vortex opposite to the circulation around the hand; the flow of the back of the hand had separated. Subsequently, at the end of the shift phase, a pair of vortices was formed by a positive vortex that formed separate from the back of the hand and a negative vortex that had been formed previously (Fig. 2(b)). Additionally, velocity vectors (jet flow) were confirmed in the direction of the flow between a pair of vortices. Figure 3(a) is the middle of the shift phase from in-scull to out-scull. At this time, the flow had separated from the palm and the back of the hand; a positive vortex was observed to the palm side. Finally, at the end of the shift phase, the flow separated from the hand, and formed a pair of vortices. In addition, the jet flow was observed to the direction of the flow between a pair of vortices (Fig. 3(b)). Moreover, the jet flow to the direction of the flow was confirmed in the flow field other than between a pair of vortices.

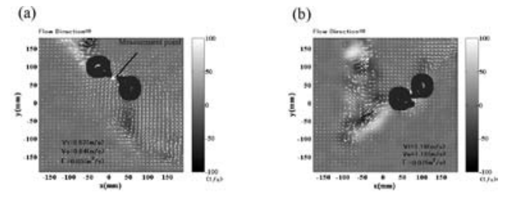

Fig. 4. The circulation value calculated from a pair of vortices formed in shift phase, the theoretical value and the experimental value of the jet flow. (a) Shift phase from out-scull to in-scull, (b) Shift phase from in-scull to out-scull.

The circulation value, the theoretical value and the experimental value of jet flow are shown Fig. 4. The circulation value of the shift phase from out-scull to in-scull was 0.05 m^2/s, the theoretical value was 0.63 m/s, and the experimental value was 0.64 m/s (Fig. 4(a)). In the opposite phase, the circulation value was 0.07 m^2/s, the theoretical value was 1.18 m/s, and the experimental value was 1.16 m/s (Fig. 4(b)).

DISCUSSION

Despite the plethora of opinions about propulsion mechanisms in fluids, those mechanisms have not been clarified. Such is also the case for swimmers' propulsive mechanisms. Positive and negative vortices were formed as characteristics of flow field phenomena of both shift phases in this study. After the change of direction of the hand motion, the vortex of opposite direction to that of circulation was formed around the hand. The flow separated from the hand as the angle of attack increased; then another vortex was formed. Moreover, the velocity vector to the direction of the flow between a pair of vortices was inferred to be a jet flow because the vortex of the reverse rotation is a vortex ring.

Sakakibara et al. (6) measured flow fields around propelling fish in water, thereby confirming the jet flow shown in the present study. Underwater creatures generate jet_flow using a wave motion. The resultant reaction force was inferred to be a propulsive force. A swimmer also uses the jet flow, generated by the sculling motion, as a propulsive force.

In this study, the flow separated from the hand was observed at the shift phase from out-scull to in-scull. This is thought to apply to the phenomenon called "delayed stall". Dickinson (2) reported on this phenomenon by observing the wing strokes of a fruit fly. This phenomenon increases the lift force using a "leading-edge vortex". In short, the flow separated from the hand in the end of the shift phase was the "leading-edge vortex" that caused a "delayed stall". Consequently, the swimmer increased the lift force through the sculling motion: the resultant lift force served as a propulsive force. Skill sug-

5, 10, 15, 20 and 25m of each lap (fig. 1). A manual switch was used to direct the signal from each camera to one recorder, after applying a timestamp, and after superimposing graphical lines representing the distances of 5, 10, 15, and 20m of the pool. Calibration of the lines was done by poolside markers. The video recording timestamp was synchronized with the official (Omega) time system by means of a flashing light at the starting signal visible on the video picture. This setup assures the possibility to analyze a number of parameters during each race for each swimmer. Time was measured when the head of the swimmer passed the 5, 10, 15 or 20 m mark, and time for 3 mid-pool strokes were measured for ach swimmer. In the present study stroke rate (SR), clean swimming velocity (v_{clean}) and stroke length (SL) was calculated. Clean swimming velocity (not affected by starts and turns) was calculated timing the swimmers head using distances 15-20m (lap 1) and 10-20m (lap 2-4) and divided by 5 or 10m respectively. Stroke length was calculated as: SL= $v_{clean} \cdot SR^{-1}$ (1). These methods of race analysis have also been described by Thompson, Haljand and MacLaren (9).

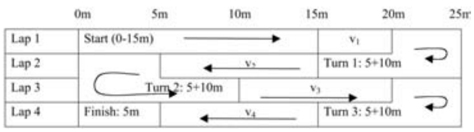

Fig. 1. Distances recorded to analyse temporal aspects of a 100 m race.

Before the study, six main models for SR strategies during a race were constructed, partly using models from (5). The models are displayed in fig. 2. These were model A - increasing SR throughout the race; model B- decreasing SR; model C - no change in SR; model D - a U-pattern, decreasing – then increasing; model E - a inverted U pattern - increasing then decreasing and model F - decreasing, increasing and decreasing. However, within these main characteristics several submodels existed (see fig.2). The frequency of use of these models for NOR and EUR were identified for finalists (rank 4^{th} – 6^{th} and 4^{th} – 8^{th} respectively) and the top 3 performers for all 100m races in all strokes. χ^2 statistics and two way ANOVA was used for comparisons.

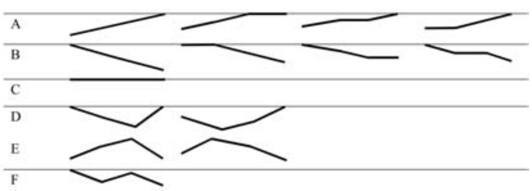

Fig. 2. The different models for stroke rate development in a 100m race. Each main model has several alternatives. Amplitude increase and decrease indicate stroke rate development during a race.

RESULTS

A summary of the results is displayed in table 1, showing which models are preferred for all the finalists and the top 3 performers of EUR and NOR. The most common strategy was model D for the top 3 performers (decreasing, and increasing SR in the end of the race) and model B for the finalists. Using a χ^2 test to check if the frequency distribution of models were significantly different than expected, revealed a significant different distribution ($p<0.001$). Performance, at two levels, championship type, and medalists or finalists, was found to significantly alter the expected frequency distribution of SR models ($p<0.01$). Attempting to explain the results from SR analysis, further analysis of v and SL was performed. The results of a two way ANOVA analysis of the development of v_{clean}, SL and SR from lap 3 to the last lap are shown in table 2. The effect of both performance factors was significant for stroke length differences ($p<0.01$). Furthermore medalists had a significantly lower SR difference compared to finalists ($p<0.05$) and EUR swimmers had additionally significantly higher difference of v_{clean} from lap 3 to lap 4 compared to NOR swimmers ($p<0.001$).

Table 1. Fraction of swimmers using each of the SR models for finalists and medalists, all numbers in %.

	Finalists			Medalists		
Model	EUR	NOR	Total	EUR	NOR	Total
B (\)	35	45	39	25	50	38
C (--)	15	0	10	17	8	13
D (U)	30	45	35	50	42	46
E (∩)	10	0	6	0	0	0
F (\/\)	10	9	10	8	0	4

Table 2: Mean (SD) of the difference in clean swimming velocity (v_{clean}), stroke length (SL) and -rate (SR) from lap 3 to lap 4 for EUR, NOR, medalists and finalists.

	EUR		NOR	
	Finalist (4-8th)	Medalist (1-3rd)	Finalist (4-8th)	Medalist (1-3rd)
$\Delta\ v_{clean\ 3\text{-}4}(m \cdot s^{-1})$	0.05 (0.05)	0.07 (0.04)	0.02 (0.06)	0.02 (0.05)
$\Delta\ SL_{3\text{-}4}(m \cdot cyc^{-1})$	0.05 (0.11)	0.11 (0.04)	0.05 (0.06)	0.05 (0.07)
$\Delta\ SR_{3\text{-}4}(cyc \cdot min^{-1})$	0.26 (2.87)	-0.93 (1.42)	-0.47 (1.37)	-0.68 (1.36)

DISCUSSION

The main results from this study is that the most common SR models for the medalists is model D (increasing SR at the end of the race), and model B for the finalists. The least successful models were model E and F, failing to keep up or decreasing the SR at the end of the race. This may be due to fatigue. By first sight, it seems as the ability to increase the SR at the end of the race is important to achieve a top performance. This is supported by the data in table 2, medalists have a lower difference of SR from lap 3 to lap 4 – this implies that SR is increasing more. Furthermore in a study of 100m races in Atlanta Olympic games it was found that the most common stroke rate model for the top 3 performers corresponds to model D (8 of 12 male medal winners) (5). However, the results from Atlanta were obtained in a 50m pool, which is different than for our data, obtained in a 25m pool. The two studies show that medalists are more likely to use model D, regardless of the pool length.

Additionally results from 159 males and 158 female 200m long course breaststroke races shows that mean SR develops according to our model D (9). Whether the appearance of model D is a chosen strategy or a result of changed technique due to fatigue is unknown in our study and not reported in other studies.

However, looking at SL decrease from lap 3 to lap 4 it is larger for medalists compared to finalists, and for EUR compared to NOR. Additionally medalists had a larger v_{clean} decrease on the last lap compared to finalists. Interpreting these results in the light of the SR development during the race is not straight forward. From studies on SL and SR with stepwise sub maximal testing Keskinen (7) have suggested that above anaerobic threshold, the SL and SR relationship changes in a way towards shorter SL and faster SR. When fatigue occurs, it have also been demonstrated that decrease of v_{clean} might be connected to the inability to increase SR and to a decrease in SL (8,10). More precisely we could possibly attribute the onset of fatigue at the end of the race as an explanation for changes in SR and SL revealed in the present study. This is also supported by the data from Craig et al. (2), who found that the faster swimmers compensated for the deteriorating SL by increasing SR more than did their slower competitors. In the study of Craig et al. (2) SL and velocity was measured as an average over the whole lap (i.e not measuring clean swimming velocity as in our study), and changes in underwater phases after the start and turn may have influenced these results.
Our results show that medalists increase SR more from lap 3 to lap 4 compared to the other finalists. Moreover, the medalists of EUR showed a larger decrease in v_{clean} from lap 3 to lap 4 compared to other finalists. It is thus tempting to conclude that top performers adopt a compensatory strategy of increasing SR at the last lap to avoid further decrease of v_{clean}. A higher v_{clean} on lap 3 for top 3 EUR performers is explaining their larger decrease in velocity from lap 3 to 4 compared to the finalists.
It may be speculated that the athletes which are least fatigued have the energy to increase SR and by this compensate for a decrease in SL and thus win the race. However, a closer analysis of these phenomena seems important, especially to the factors that may explain why medalists are able to increase SR at the end of the race by possible physiological mechanisms.

CONCLUSION
The strategies most often used by the best performers in 100m short course races are decreasing during the first part of the race, and increasing at the end. Moreover, swimmers should not try to increase SR in the end of the race per se, but use it as a compensatory mechanism for a decreasing SL, focusing on the last lap to minimize the decrease of SL.

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THE TEMPORAL DISTRIBUTION OF RACE ELEMENTS IN ELITE SWIMMERS

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The purpose of this study was to examine race element (start, turning and finishing) strategies of elite and national level swimmers in short course 100m races. For 56 finalists at the Norwegian junior national (NOR) and the European Short course championships (EUR) race analysis was performed by videography. Start- (0-15m), turn- (5m in and 10 m out) and finishing time (last 5m) were analyzed for each race, and these times were normalized to the total race time. The results show that EUR swimmers spend less time in starting, turning and finishing together ($p<0.001$), starting ($p<0.05$) and during the first turn ($p<0.02$) compared to NOR swimmers. The top 3 performers of both groups were found to have a stronger finish normalized to their end performance compared to the other finalists.

Key Words: Race analysis, swimming performance, starting, turning, finishing action.

INTRODUCTION
For many years it has been customary to perform race analysis of all finals during major swimming championships. A race analysis usually consists of timing of different parts of the race, like start (0-15m), turns (5+10m or 7.5+7.5m in and out of the turn), and finishing actions (last 5m). Furthermore measurements of stroke parameters like clean swimming velocity, stroke rate and stroke length is measured. Meta studies of race analysis have been published by various groups (e.g. 1-3, 5-8). An analysis of the 1992 Olympic swimming races revealed that starting time, turning times and finishing times were components of successful performances and correlated positively with performance (1). The strategies

of medallists and finalists were compared for the 200m freestyle event at the Sydney 2000 Olympics, and it was found that the velocity of the 2nd 50m and turn time for the 3rd turn were the most important parts of the race (2). In both studies, significant correlations were found between starting and turning parts and end time of the race. Furthermore Thompson, Haljand and MacLaren (8) found that main correlates of end time in breaststroke races was mid-pool (clean) swimming velocity, accompanied by moderate correlations for turning time and start time.

However, these studies have not considered starting, turning and finishing actions normalized for each individual swimmer's end time. By looking at the start, turning and finishing actions normalized, it is possible to determine if individual swimmers may choose different strategies of their temporal distribution of race elements within their end race time. Whether the temporal distribution of the race elements is different for elite performers compared to other competitive swimmers is not well, if ever documented. The purpose of this study was thus to examine the race strategies of elite swimmers compared to national junior level competitive swimmers in terms of their temporal distribution of start, turning and finishing elements within their end race time of 100m races, and in addition to investigate whether medalists have a different distribution of race elements compared to other finalists (rank 4th-8th).

METHODS

Races from the finals at the Norwegian short course junior national championships (NOR, n=24) and from the finals at the European Short course championships (5) (EUR, n=32) were studied. The races were all male 100m events. Mean (±SD) international point scores for the two groups were 626 (±59) and 911 (±31) respectively ($p<0.05$).

For all races, race analysis was performed by videography. Three or four cameras (50 Hz) were mounted perpendicular to the pool, making it possible to record all lanes at positions 0, 5, 10, 15, 20 and 25m of each lap (fig. 1 and fig. 2). A manual switch was used to direct the signal from each camera to one recorder, after applying a timestamp, and after superimposing graphical lines representing the distances of 5, 10, 15, and 20m of the pool. Calibration of the lines was done by poolside markers. This setup assures the possibility to analyze the time when the head of the swimmer passed the 5, 10, 15 or 20 m mark, and from these data the time spent starting - t_{ST} (0-15m), turning t_{TRN} (5m in and 10m out of the turn) and finishing t_F (last 5m of the race) and their corresponding velocities were calculated. The video recording timestamp was synchronized with the official (Omega) time system by means of a flashing light at the starting signal visible on the video picture. These methods of race analysis have also been described by Thompson, Haljand and Lindley (7).

The starting, turning (the sum of 3 turning times) and finishing times were each normalized by dividing by the end race time. Furthermore the normalized sum of times spent for starting, turning and finishing is called non-swimming score, it was calculated according to this equation: $(t_{TRN1} + t_{TRN2} + t_{TRN3} + t_{ST} + t_F) / t_{TOT}$. Thus a high non-swimming score means that more time is spent in these phases of the race, reflecting a worse performance in these phases. To compare two levels of performance (medalists 1st – 3rd place vs finalists 4th – 8th place and EUR vs NOR) a two way ANOVA was applied.

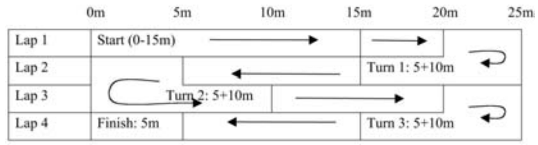

Fig. 1. Distances recorded to analyse temporal aspects of a 100 m race.

Fig. 2. Camera placement at different positions perpendicular to the pool, from the NOR championship.

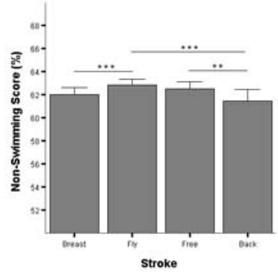

Fig. 3. Mean (error bars are SD) non-swimming score for the 4 strokes.
*** p< 0.01, *** p<0.001.*

RESULTS

A summary of the results is displayed in table 1. All participants in the EUR championship used a significantly lower portion of their end race time to starts, turns and finishes combined (non-swimming score) compared to the Norwegian junior swimmers ($p<0.001$). Furthermore the starting score was found to be lower ($p<0.05$), the first turn score was found to be lower ($p<0.02$) and the difference between turn 3 and turn 1 scores was found to be higher ($p<0.01$) for the EUR races compared to NOR races. The effect of performance level within the two groups of swimmers was found to be significant only for finish score ($p<0.01$), where the medalists were found to have a lower finish score – meaning that they performed a better finish compared to their own race end time. The correlations coefficient between international points score and non-swimming score was $r=-0.47$ ($p<0.01$) for all the races included in the study, however within the groups no significant correlations was found. The differences in non-swimming score between the four strokes are shown in fig. 3.

Table 1. Mean (SD) race analysis scores for medallists and finalists of short course European and Norwegian junior Championships. See text for statistics.

	EUR		NOR	
	Medallist (1-3rd)	Finalist (4-8th)	Medallist (1-3rd)	Finalist (4-8th)
Non-swimming score (%)	61.81 (0.76)	61.89 (0.70)	62.70 (0.73)	62.64 (0.95)
Start Score (%)	12.19 (0.44)	12.27 (0.55)	12.69 (0.69)	12.48 (0.72)
Total Turn Score (%)	44.41 (0.99)	44.31 (1.03)	44.77 (1.13)	44.70 (0.99)
Finish Score (%)	5.21 (0.22)	5.31 (0.21)	5.24 (0.24)	5.46 (0.19)
Diff. Turn 3- Turn 1 (%)	1.05 (0.33)	1.19 (0.38)	0.71 (0.44)	0.98 (0.39)

DISCUSSION

The results of this study show that the better performers (EUR) use a smaller portion of their end race time for turning, starting and finishing actions compared to the juniors (NOR). This implies that the relative importance of these phases is greater for international level swimmers and might be a success criterion. Several studies have previously shown that better performers have faster starts and turns compared to less successful performers (e.g. 8), however this was absolute and not normalized values. We do not know of any other studies that may confirm the normalized results. For the starting score separately and turn 1 score separately, the EUR races showed significantly lower means. This implies that elite international swimmers spend less time starting and during the first turn as a percentage of their end race time. On the other hand the drop in turn time was significantly larger for the elite international swimmers. Relative to their performance it may seem that the international level swimmers have a faster first part of their race. Previous studies have also suggested that both at international and national level, 200m breaststroke races are swam with a positive split – i.e. a faster first part of the race (8).

Looking at the performance groups within the EUR or NOR championships, i.e. whether the medalists have a different distribution of their race elements than the other finalists another aspect is emerging. The effect of within group performance was significant only for the finish action score. It means that medalists, both in EUR and NOR championships have a stronger finish than the rest of the final. This may not come as a surprise, however, it should be added that the strong finish is in relation to each swimmers own end time. Whether this is due to a better physiological capacity to deliver energy at the end of the race, the ability to maintain adequate race-end swimming technique, a better finish stretch technique or better psychological abilities is not known. Very little research of the last part of swimming races is present, and this research area deserves further attention.

Analyzing the four different strokes, backstroke swimmers seem to have the smallest portion of their race time devoted to starts, turn and finishes. Non-swimming score was significantly lower for backstroke compared to freestyle and butterfly, and significantly lower for breaststroke compared to butterfly. These results may describe the characteristics of backstroke and breaststroke races – normalized to end race time, the sum of start- turning- and finishing time are lower for these two strokes.

Several studies have pointed out that the range of strokes from fastest to slowest is front crawl, butterfly, backstroke and breaststroke (e.g. 4). Our race analysis also shows that for freestyle and butterfly the clean swimming velocities are higher than for back and breaststroke. This may alter the optimal temporal distribution of the different race elements. In this regard one may claim that breast and backstroke races rely more on good starts, turns and finishes, than do freestyle and butterfly races. The under water kicking phase of backstroke and butterfly is very similar (however supine vs. prone positions) and with the butterfly being the fastest mid-pool stroke of the two this may explain why butterfly have a higher non-swimming score compared to backstroke.

Further investigation and analyses are required in this topic. Finally it should be kept in mind that the presented results are only valid for males, and that similar analyses should be done for females.

CONCLUSION

International level swimmers have, relative to end race time, better starts, turns and finishes compared to national caliber junior swimmers in 100m races. One factor that distinguishes medalists from finalists is their stronger finish – relative to their performance. Of the different strokes, backstroke is characterized with the least amount of time spent in starting, turning and finishing phases of the race, relative to end time.

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GOALKEEPER'S EGGBEATER KICK IN WATERPOLO: KINEMATICS, DYNAMICS AND MUSCULAR COORDINATION

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By using a Doppler-Ultrasound-Velocimeter System yielding the vertical speed of a goalkeeper's head during different actions in waterpolo the kinetics of the total body could be determined approximately. Synchronous measurements of the electrical activity of Mmi. glutaeus maximus, vastus medialis and adductor longus were taken to study the muscular coordination during the execution of the eggbeater kick. This leg kick could produce climbing heights up to 0,7 m; the vertical speed varying from +/- 0,8 m/s to 2 m/s. The muscle activation pattern showed a clearly defined order of appearance in time, announcing a high potential of muscular fatigue.

Key Words: waterpolo, eggbeater kick, kinetics, electromyography.

INTRODUCTION

Unlike his colleagues of a waterpolo team the goalkeeper has to maintain an upright position the whole time and must be prepared to raise his body very quickly out of the water, reaching out for the ball thrown in the corner of his goal and catching it. The reaction forces necessary to meet these requirements must be generated by the interaction of the goalkeeper's body parts and the surrounding water since no rigid platform exists for a push-off of the body. Not only to avoid sinking down in the water but even more performing ascending movements out of the water the goalkeeper exerts a special leg kicking motion –the eggbeater kick- as well described by Sanders (1) in a very detailed way. The objectives of this study aree to give some examples of kinematics of a goalkeeper's typical movements, estimates of the forces necessary for "jumping out of the water" combined with the presentation of some activation patterns of leg muscles during eggbeater kick.

Physical Background

The balance of vertical forces acting on the CG of a body in the water is determined by weight, hydrostatic lift and reaction forces caused by the body movements: the weight force is expressed by the product of the body's mass and the terrestrial acceleration (g), the hydrostatic lift is given by the weight of the water displaced by the body (as a function of the immersed body volume), and the reaction forces generated by the flow surrounding the body parts in motion, thus generating propulsive or resistive force effects. So, the sum of external and inertial forces can be written as:

$$L_{stat} - W - F_r - M \cdot \frac{dv_{vert}}{dt} = 0 \qquad \text{(Eq. 1)}$$

L_{stat} = hydrostatic lift, W = weight, F_r = reaction force, M = body mass, v_{vert} = vertical speed (the "+" sign denotes upward direction of forces and speed).

A special situation is described by setting $F_r = 0$: In this case, the body moves vertically to a stable static position depending on the force difference $L_{stat} - W$. The ascending movements of the body in the water due to propulsive arm/leg actions are to be characterized not only by an amount of higher forces with growing climbing height but by the fact that a loss of the static lift occurs when the upper part of the body has left the water, demanding a still higher level of propulsive forces.

METHODS

The kinetics of the goalkeeper's movements (the subject: a skilled male test person, mass: 89 kg) was obtained by using a Doppler-Ultrasound-Velocimeter System measuring continuously the speed of vertical ("up and down") movements of the test person's head (see fig.1). From this signal, the time curves of the vertical distance covered by the jumps were obtained by integration whereas a numerical differentiation yielded the acceleration curves representing an approximation for the acceleration of the goalkeeper's centre of gravity.

By multiplying with the body mass estimate values of the vertical forces generated by the eggbeater-kick could be obtained. The leg kicking motion was examined by observation of an underwater video system operating synchronously with the speed measurements. Muscular coordination was registered synchronously also via underwater electromyograms from M. glutaeus maximus, M. vastus medialis and M. adductor longus of the subject's right hand side. These muscles were considered to play an important role in the execution of the eggbeater kick, giving a first insight into the structure of muscular action. The EMG-signals were high-pass filtered (25 Hz) to avoid movement artefacts and, if necessary, had to undergo a 50 Hz notch filtering process for hum suppression.

Figure 1. Measuring procedure using the Doppler-Ultrasound-Velocimeter System.

RESULTS

In this chapter, the results of three different movement types of a goalkeeper are presented: single "jump" out of the water, multiple, successive lifting and sinking movements, and the maintaining of a certain height above water level for some seconds.

The single jump (cf. fig.2) is characterized by a lifting speed maximum of about 1,4 m/s being reached within about 0,5 seconds. A maximal acceleration value of 8,6 m/s^2 appears in a very early phase of the jump, possibly caused by a synchronous activity of Mm. glutaeus maximus and adductor longus, followed by a strong activity of M. vastus medialis, leading to the maximal speed in upward direction. During the whole lifting movement, at positive speed values, an activation of the M. adductor longus is present. Rapid deceleration of the body and sinking of the body are combined and explained by the sudden stop of the activity of M. vastus medialis while the M. glutaeus maximus is active to stop the sinking movement, supported by a strong activation of M. vastus medialis.

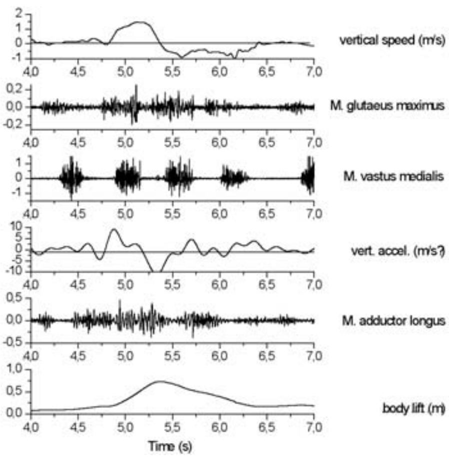

Figure 2. Kinetics and muscular activity in the eggbeater kick: single jump.

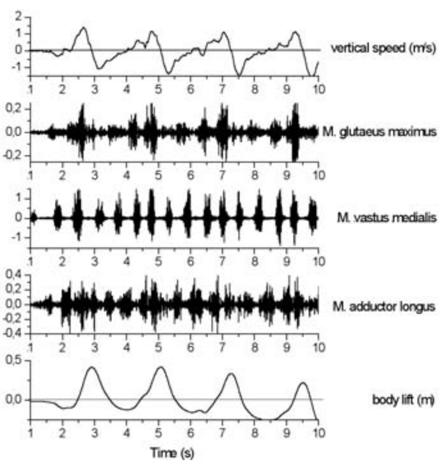

Figure 3. Kinetics and muscular activity in the eggbeater kick: multiple jumps.

In contrast to the single jump pattern, the movement with the generation of quickly repeated lift (see fig.3) leads to a higher frequency of activation of M. vastus medialis working partially alternatively and partially synchronously with M. adductor longus. The activation of the M. glutaeus maximus leads either to an increase of speed directed in an upward direction of the body or to a decrease of sinking speed of the body. It can be seen clearly that a reduction of negative segments of the speed curve means a higher degree of muscular activity in the frequency domain. This effect is intensified for the movement when the goalkeeper is forced to maintain an elevated position in the water for some time (cf. fig.4).

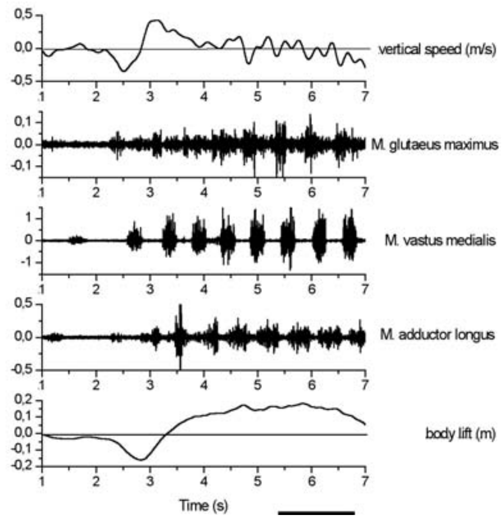

Figure 4. Kinetics and muscular activity in the eggbeater kick: maintaining an elevated position.

This example shows the background of muscular activity necessary to generate a constant propulsive force using the eggbeater kick, i.e. executing oscillatory movements. Of course, the EMG measurements presented here include only a minor part or all muscles of the leg, but it seems to be reasonable to attribute similar activity patterns to the remaining muscles of the lower extremity. Estimates of the vertical reaction forces generated by the eggbeater kick can be derived from *fig.1*: here the maximal acceleration of the total body has the order of magnitude of about 8-9 m/s^2, announcing that a maximal force of up to 700 N must have been generated by the leg kicking movements. With the assumption of lifting 50 % of body mass out of the water for a while a force estimate of 50 % of body weight force is necessary since hydrostatic lift acts only on the immersed part of the body.

CONCLUSION / CONSEQUENCES

Further research of the eggbeater kick can be done by several means: studies using more EMG channels should lead to a deeper insight into muscular coordination of a complex movement. This research can be combined with 3D-analyses yielding the kinetics of the kicking movement (1). Furthermore, the investigation of the relationships between movement parameters and water flow effects due to the generation of propulsive forces could be useful to a better understanding of hydrodynamics of this special kick.

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KINEMATICS AND DYNAMICS OF THE BACKSTROKE START TECHNIQUE

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The investigation is the lack of complex biomechanical analysis of this starting technique based on kinematic, and dynamic data. Nine male backstroke sprinters performed four backstroke starts over a distance of 7.5 m. During the start the over all start time, and split into reaction time, wall time, flight time, and glide time was recorded. Dynamic data were measured as 3-dimensional ground reaction forces. The correlation of the resultant take off force and the final over all start time (7.5 m) turns out to be significant (r=-.83, p<.01; [n=9]). Correlations were found between the times of hands off and take off (r=.71, p<.05; [n=9]) and hands off and hip entry (r=.93, p<.01; [n=9]). The influence of the kinematic and dynamic parameters of the overwater phase (wall and flight activity) of the backstroke start technique is clearly shown by the analysis.

Key Words: backstroke start technique, kinematic, dynamic, reaction force.

INTRODUCTION

The backstroke swim start has been estimated to contribute up to 30% of the total race performance in the 50 m backstroke sprint (3). Despite its importance there is a lack of complex biomechanical analysis of this starting technique based on kinematic, dynamic and electromyographic data (for more information see 4).

METHODS

Nine male backstroke sprinters, all members of the German national team in swimming, performed four backstroke starts over a distance of 7.5 m. The over all start time was recorded by high speed video analysis (125 Hz), and split into reaction time (signal until hands off), wall time (signal until take off), flight time (take off until hip entry), and glide time (hip entry until head passing 7.5 m). The start section of the swimming pool was calibrated and a 2-dimensional video movement analysis was carried out to determine the kinematic parameter of the four starts (see figure 1). Kinematic parameters were calculated by videographic motion analysis (SIMI-Motion, Ger). Dynamic data were measured as 3-dimensional ground reaction forces at a sampling frequency of 1.000 Hz by a mobile water proof force plate (KISTLER, Ger) mounted to the pool wall. All differences in the kinematical and dynamical data between the starts were tested by Pearson correlation test and by paired T-test (SPSS; Version 12.0).

Figure 1. Picture of the backstroke start movement (up) and under water view (down).

RESULTS

In a first step, kinematic parameters of the whole body movement during the different phases of the backstroke start of all nine swimmers were measured. In the elite swimmers the correlation of the resultant take off force and the final over all start time (7.5 m) turns out to be significant (r=-.83, p<.01; [n=9]). Likewise a significant correlation could be found between the take off force and the official start times (head passing 7.5 m) of 8 out of the 9 investigated athletes in the German national championships 2005 (r=-.74; p<.05; [n=8]). Correlations were found between the times of hands off and take off (r=.71, p<.05; [n=9]) and hands off and hip entry (r=.93, p<.01; [n=9]). Other start parameters (wall and flight time, take off velocity and underwater speed) did not show significant correlations with the over all start time at 7.5 m. Table 1 shows the kinematical and dynamical data of the nine athletes during the backstroke start.
Dynamical analysis of the force distribution on the start block (pool wall) leads to a characteristic curve of the individual and time normalized horizontal (F_Z) and resultant (F_R) force that is similar in eight athletes to the backstroke start (fig. 2).

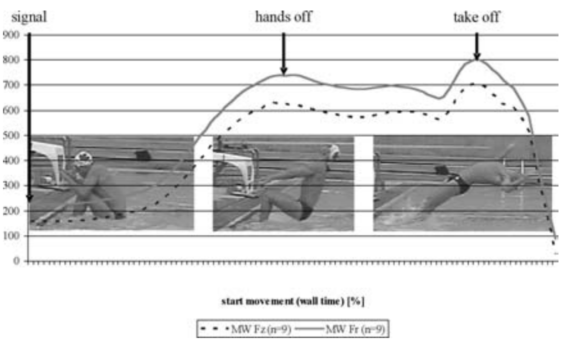

Figure 2. Example of the force reaction of the time normalized force curve of the start movement (n=9).

One athlete shows a different force–time–curve with a higher impulse in the first part and a decreasing second impulse in comparison to take off.

Table 1. Kinematical and dynamical data.

athletes	body weight [kg]	F_{RMax2} [N]	hands off [s]	take off [s]	hip entry [s]	start time 7.5m [s]	$v_{take\ off}$ [$m \cdot s^{-1}$]	best time 50m [s]
T.H.	82.00	1,043.390	0.440	0.772	1.068	3.340	4.72	24.02
R.K.	88.00	1,066.750	0.413	0.747	0.949	3.013	4.18	26.08
T.E.	71.00	742.326	0.482	0.821	1.099	3.688	3.75	26.89
J.G.	70.00	710.362	0.428	0.665	1.027	3.693	2.73	28.40
T.R.	75.00	922.092	0.474	0.770	1.098	3.590	2.95	24.80
R.P.	78.00	1,018.050	0.590	0.874	1.194	3.522	2.74	28.10
H.M.	73.00	1,055.554	0.532	0.760	1.168	2.724	2.92	26.16
M.C.	80.00	983.946	0.453	0.673	1.037	3.233	3.56	25.53
S.D.	90.00	1,243.886	0.491	0.783	1.084	2.767	3.50	25.14
Mean	78.55	976.26	0.478	0.763	1.080	3.285	3.45	26.12
SD	±7.14	±166.12	±0.055	±0.065	±0.074	±0.378	±0.69	±1.47

A higher impulse (F_Z/F_R) in the jump off phase between hands off and take off (**F_Z**: t(8)=-2.448, p<0.05 (*); **F_R**: t(8)=-2.147, p=0.064 (+)) leads to a higher acceleration at the end of the start movement, and a higher velocity (r=0.840, p<0.05 (*), n=6)) in the backstroke start. With these higher take off velocity and take off force (F_R) are associated also faster starting times with the 7.5 m split time (r=-0.825, p<0.01 (**), n=9).

DISCUSSION
This investigation is in extension with the electromyography analysis (4) one of the first complex analyses of the starting technique in the backstroke swimming.
The influence of the kinematic and dynamic parameters of the overwater phase (wall and flight activity) of the backstroke start technique is clearly shown by the analysis. High correlations occure between the absolute (resultant) force at the time of take off from the wall and the over all start time at 7.5 m (3).

CONCLUSION
A higher impulse on the block (pool wall) leads to a higher acceleration and take off velocity (v take off) in the backstroke start. That can be referred to the meaning of a technically good start movement. A high impulse to take off is crucial for fast starting times (head 7.5 m) with the backstroke start and other starting forms (especially track or grab start) (1, 2, 3, 4, 5, 7).

ACKNOWLEDGEMENTS
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FLOW VISUALIZATION OF UNSTEADY FLOW FIELD AROUND A MONOFIN USING PIV

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Swimmers swimming with monofins are much faster than without although the human power is the same. To predict how fast they can swim we have to know the complex flow field which is extremely unsteady. The study of the flow field was executed in a flume using a kind of swim manipulator equipped with a monofin. We set the fin in a flume and drove it by a motor. Flow fields around a monofin in a pitching motion was measured by means of a recently-developed technique called the Particle Image Velocimetry (PIV). Time variations of velocity and vorticity fields were calculated from the image captured by PIV system. Unsteady flow characteristics such as a vortex formation and the movement of vortices were investigated in detail. Information on unsteady flow and vortex motion serves the understanding the mechanism of propulsion in aquatic motion.

Key Words: monofin swimming, vortex-induced propulsion, PIV, unsteady flow.

INTRODUCTION
Swimmers wearing a monofin can swim very fast. The world record of the apnea, which is the one of the categories of fin swimming, is one and half times faster than swimming crawl-stroke using arms and legs. The swimming speed cannot be explained by our knowledge of fluid mechanics using rigid body approach. This is why the much higher speed of dolphins is still a mystery. This mystery is called Gray's paradox and has not been solved yet, entirely. There has not been much work made on monofins except for the direct measurement of propulsive force (1). Research on the flow characteristics still is in need of more attention. The high speed is related to the high momentum generation of water. To know the generation of momentum, the characteristics of unsteady flow field have to be investigated. Vortex formation and movement are known to play an essential role on the generation of propulsive force in the animal locomotion such as insect flight and fish swimming (see, for example, 2).
So far the means to determine the unsteady flow field are very limited, but recently a powerful technique for the measurement of the flow field called the PIV (Particle Image Velocimetry) has been developed. It was found that the method is powerful for analyzing the unsteady flow field around a swimmer (3). This PIV system was adapted to the measurement of the flow field occurred by the pitching motion of a monofin.

METHODS
A monofin model of a half-scale (see Fig.1) was attached to the device that can carry out a pitching motion. The fin was handmade of carbon-fiber sheets by laminating them four times at thickest. The use of the driving device of a fin instead of wearing it on swimmers is better from a practical view of the controllability and reproducibility of the experiment. The device has the ability of varying the pitching angle of the fin between –20 deg and +20 deg whose mean angle is 15 deg upward from horizontal. We used the flume whose test section is 4.6 m in length, 2 m in width, and 1.2 m in depth. Unsteady velocity fields were measured in several horizontal and vertical planes illuminated by the YAG laser of the PIV system. A CCD camera takes the images of tracer particles at two subsequent times. From the distance a particle moved for the time interval, the velocity is determined and vorticity is then calculated. Our PIV system can get 15 planes per second and 100 planes at once.

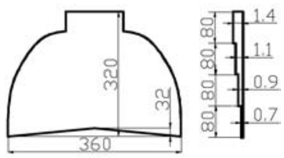


Figure 1. Model fin shape (half-size model).

In Fig.2 it is demonstrated how the effects in the horizontal plane is measured. Similar configuration was used for the measurement in the vertical plane. In this case, a laser sheet was irradiated from the bottom of the flume through the bottom window.

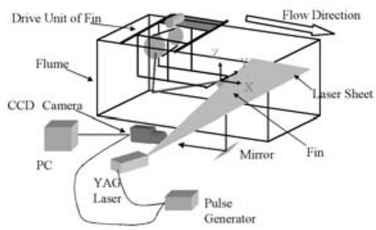


Figure 2. Experimental configuration (horizontal).

RESULTS AND DISCUSSION
Time-sequential variations of the velocity fields were obtained. First we show the unsteady field in the horizontal plane. Figure 3 shows the velocity and vorticity field in upward motion at flume speed u=0.5 m/s. To make the image of vortices more convenient to understand the mean velocity has already been subtracted from the velocity vectors. The gray scale denotes the magnitude of vorticity measured in 1/s. Bright and dark zones correspond to vortex rotating anticlockwise and clockwise, respectively. A black shadow zone extended from the top of the fin to downstream and a white one from the bottom of the fin are clearly discerned. These are the cross-sectional view of longitudinal vortices whose axes are parallel to the flume. The upper longitudinal vortex ends at a vortex rotating anticlockwise existing near (290, -100). The axis of the vortex seems to be vertical to the measuring plane. Similarly, the lower one has a vortex rotating clockwise at the right end the longitudinal vortex.

Next, we consider the flow fields in the vertical plane located at the center of the monofin. Fig. 4 shows the velocity and vorticity fields at three subsequent instants during downward motion of the fin at flume speed u=0.5 m/s. In the figure, the origin of the coordinates is not the same as that in Fig. 3 and the white region is the shadow of the fin where we cannot detect any tracer particles.

Fig. 4(a) shows the instant just after downward motion of the fin started. A thick black line denotes the fin. Near and above the edge of the fin there is a strong vortex rotating anticlockwise. This is separated at the beginning of the downward motion of the fin due to transversal action of the fin. A short time later (Fig. 4(b)), the vortex rolls up and leaves the trailing edge of the fin. The line connecting the trailing edge with the vortex brightens like a white ribbon. This layer means a gap of tangential velocity component above and below the sheet. It is elongated at the next step shown in Fig.4(c).

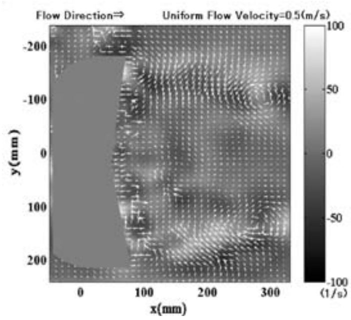
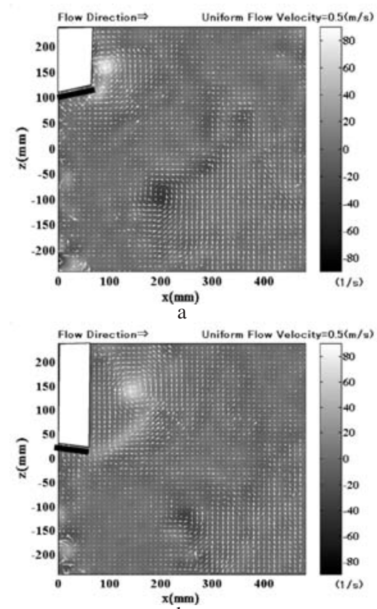
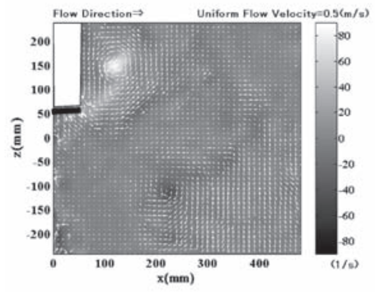


Fig. 3. Velocity and vorticity fields in upward motion of the fin (viewed from below, x-y plane). The mean velocity was subtracted in the velocity vectors.





c

Fig. 4. Sequential variation velocity and vorticity fields in downward motion (viewed from side, x-z plane). The sampling period is 67 ms or 15 Hz. The mean velocity was subtracted in the velocity vectors.

Another distinguished characteristic of the flow field in the wake is the existence of a vortex rotating clockwise (dark shadowed area in the lower part of Fig. 4) whose axis is vertical to the plane. This vortex was released when upward motion of the fin started and carried downstream with the mean flow. A pair of counter-rotating vortices (represented by the white and dark areas in Fig. 4) produces additional flow directed towards the downstream of the flume. The pairs generated continuously construct a vortex street like a Karman vortex street. The vortices induce an additional velocity in the flume direction. From the knowledge on the velocity fields and vortex structure obtained in the vertical and horizontal planes, we can image the three-dimensional vortex structure generated by a monofin. It sees to be similar to the structure appearing in the wake of a still cylinder of finite length (4) except for the direction of rotation.

CONCLUSIONS

By this experimental study the flow field around a fin was visualized and vortices were detected shed from the fin after transversal actions. There are two types of vortices; one is similar to the Karman vortex and the other a pair of counter-rotating longitudinal vortices. The Karman-type vortices change their signs or the orientation of vortex alternatively and produce momentum in the downward direction. Such momentum generation by the vortex shedding is related to the propulsive force. The mechanism of force generation by a fin is therefore very similar to that done by natural lives like birds and fish moving by generating vortices. Studying on a monofin is also an easier and quicker way to clarify the detailed mechanism of generation of propulsive force in comparison with the direct way to animal locomotion.

ACKNOWLEDGEMENTS

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KINEMATICS PARAMETERS OF CRAWL STROKE SPRINTING THROUGH A TRAINING SEASON

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Swimming velocity (SV) is the product of stroke length (SL) by stroke rate (SR). The purpose of this study was to verify training influence on front crawl SR, SL, SV and stroke index (SI) in sprinting trials. Nine competitive swimmers (7 males and 2 females; age = 14.78 ± 1.48 years) participated. The protocol consisted on the evaluation of SR, SL, SV and SI in a 25 m maximal effort test, every ten weeks, before (M1), during (M2), and after (M3) five months of training. Measurements were obtained from manual counting of cycles and time from 10 to 25 m of the trials. Anthropometric data were collected. Intensity and distance during the training season were controlled. Kinematics data showed stability along the training season. There were improvements ($p < 0.05$) on anthropometric data throughout the training season. In this age group, anthropometric characteristics seem to be more important than kinematics adaptations due to training for sprinting.

Key Words: stroke rate, stroke length, swimming velocity, training effects.

INTRODUCTION

Swimming is a modality highly dependent from the athlete's technical level (2). So it's necessary that the coaches and assistants, in competitive swimming, can use easily applicable assessment methods, to verify the training effects above kinematics characteristics related to the specific stroke technique.
Swimming mechanical efficiency evaluation can be made through the kinematics parameters stroke rate (SR), stroke length (SL), swimming velocity (SV) and stroke index (SI) (4,5). It is suggested that swimming performance is the interaction result among physiological systems and biomechanical stroke characteristics (8); this can be understood by increasing propulsive forces and decreasing drag forces. These factors combined lead the swimmer to a better performance: to finish a competitive event in a shorter time (1).
SV can be obtained by the product of SL and SR (4,5) or by the quotient of distance and time (12). In this way, SV is modified by the combinations between SR and SL (7). An optimal relation there should be between the stroke's number and the time to perform them, to get, chronically, increased SV values (2). This adjust is due to the negative relation between SR and SL, when there is an increase in SL, time to perform propulsive phase is either increased, so SR tends to decrease, for the same distance (3,5). SI is the product of SL and SV. Has an incremental behavior due to age, and can be a practical

index for instructors and coaches to assess technique of beginner swimmers (5).
Disposal energy for the swimmer muscle contraction is from, basically, two sources: aerobic and anaerobic, although a small ATP-CP reserve is either utilized (9). To enhance swimming performance, adequate energy supply must be obtained by the training program (10). So kinematics parameters can be altered due to better technique and or better energy supply. The purposes of this study were to verify swimming training, with high percentage of aerobic training, influence on front crawl SR, SL, SV and SI in sprinting trials, among age group swimmers.

METHODS
Nine swimmers (7 males and 2 females; mean age = 14.78 ± 1.48 years) participated in this study. The protocol consisted on the evaluation of SR, SL, SV and SI in a 25 m maximal effort test, every ten weeks, before (M1), during (M2), and after (M3) five months of training. Measurements were obtained from manual counting of cycles and time from 10 to 25 m of the trials. Anthropometric data (height, mass and upper limb span) were measured. Intensity and distance swan during the training season were controlled. Training exercises were classified in technique, aerobic (6), anaerobic (9) and velocity (11). There were four to six training sessions each week. Table 1 shows the absolute and normalized distances (% of all distance swan in the specific period) performed through the 20 weeks training season, in each period (M2 and M3; M1 is related to the pre-season period), for each training exercise.

Table 1. Distance swan (km and %) for training areas in each period of the season.

Training area	M2	M3
Technique, km (%)	23.1 (7.77)	28.7 (9.34)
Aerobic, km (%)	266.9 (89.80)	260.9 (84.97)
Anaerobic, km (%)	2.5 (0.85)	8.4 (2.75)
Velocity, km (%)	4.7 (1.58)	9.0 (2.94)

To verify differences among the variables in each moments to the data were applied ANOVA repeated measures and, when necessary, Bonferroni post-hoc tests. To verify stability, Intra-Class Correlation Coefficients (ICC) were used, adopting a 0.05 significant level. Statistical Package SPSS 12.0 was used.

RESULTS
Mean and standard deviation (s.d.) of anthropometrics and kinematics results for the three evaluation moments are in Table 2.

Table 2. Mean ± s.d. of height, upper limb span, total body mass, SR, SL, SV and SI; M1 = before training season; M2 = during training season; M3 = after training season. Letters indicate significant differences.

Variables	*n*	M1	M2	M3
Height (cm)	9	168.8 ± 0.13 ^{a}	169.3 ± 0.13	170.0 ± 0.12 ^{a}
Upper limb span (cm)	9	172.1 ± 0.13 ^{a,b}	173.3 ± 0.13 ^{a,c}	174.3 ± 0.13 ^{b,c}
Total body mass (Kg)	9	56.2 ± 14.2 ^{a}	57.2 ± 13.3	58.5 ± 13.3 ^{a}
SR (Hz)	9	0.85 ± 0.08	0.91 ± 0.09	0.89 ± 0.08
SL (m)	9	1.79 ± 0.17	1.72 ± 0.18	1.78 ± 0.11
SV ($m \cdot s^{-1}$)	9	1.52 ± 0.135 ^{a,b}	1.57 ± 0.14 ^{a}	1.59 ± 0.15 ^{b}
SI ($m^2 \cdot s^{-1}$)	9	2.73 ± 0.45	2.73 ± 0.46	2.83 ± 0.36

There were improvements ($p < 0.05$) just on anthropometric data hroughout the training season. No differences were found in SR, SL and SI data among the moments. But SV has increased significantly from M1 to M2 and from M1 to M3. Figures 1 and 2 show, respectively, individual SR and SL values' comportment along the training season.

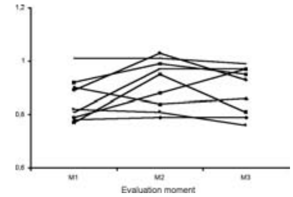

Figure 1. Individual stroke rate values for the three moments.

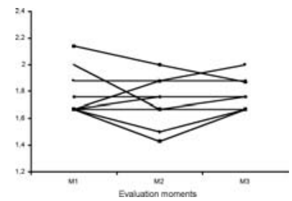

Figure 2. Individual stroke length values for the three moments.

Stroke length and stroke rate showed stability along the training season: SR: (ICC= 0.808; Ic 95%]0.40; 0.953[; $p = 0.002$); SL: (ICC = 0.815; Ic 95%]0.421; 0.955[; $p = 0.002$); Figures 3 and 4 show, respectively, individual SV and SI values' comportment along the training season.

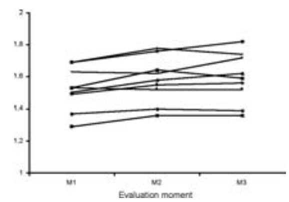

Figure 3. Individual swimming velocity values for the three moments.

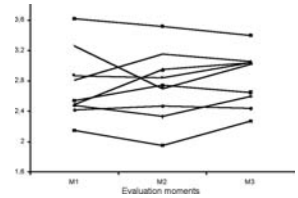

Figure 4. Individual stroke index values for the three moments.

Swimming velocity and stroke index showed stability along the training season: SV: (ICC = 0.977; Ic 95%]0.927; 0.994[; $p < 0.001$); and SI: (0.939; Ic 95%]0.809; 0.989[; $p < 0.001$).

DISCUSSION
Aerobic exercise performed by the swimmers (between 84 and 89%) could be an explanation about the similar values found for the SR, SL and SI during the training season for the 25 m maximal effort. Perhaps, in longer distances, this behavior would be different. High stability values found for the kinematics show that most of the subjects kept in the same track, in response to the applied training.
There are two ways to increase swimming velocity: (a) acutely, when the swimmer normally increases SR and (b) chronically, when, due to training, swimmer increases SL (12). It can be observed, in this study, that verified increases in SV was due to no-significant increases in SR, so, training, per se, was not able to increase SL. When an athlete maintains a high SR to keep high SV, dispends high energy values, which is related to fall in performance (1), when the energetic systems are not prepared to a high intensity work. During training, this could lead to a negative adaptation in the stroke technique, with a poor relation between SR and SL.
Technique exercises, during training, should reach two objectives: (a) to keep the stroke in a better technique level and (b) enhance swimming economy. So, after a training season a reduction in SR values, concomitant to an increase in SL values, is expected (2, 12). It could be verified high stability in all kinematics parameters analyzed. So, the adopted training program just kept the ranking of the swimmers, with just few of changes in the tracks for the variables.

CONCLUSION
In this age group, swimming training, with high percentage of aerobic training, could not increase swimming velocity in front crawl stroke for sprinting trials by increases in stroke length. Stability found for kinematics variables for the subjects indicates that ranking was kept during the training season.

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UNSTEADY FLOW MEASUREMENT OF DOLPHIN KICKING WAKE IN SAGITTAL PLANE USING 2C-PIV

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This study presents a method to visualise and to analyse the wake of a swimmer's dolphin kick in a sagittal plane viewed from the side of a swimming flume using two-component PIV (2C-PIV). One trained male swimmer was instructed to maintain a swimming position with dolphin kicking. Results showed a pair of vortices and jet flow between them. The value of the jet flow velocity showed good agreement with the value of the induced velocity that was predicted by assuming that the pair of vortices represented sections of a vortex ring. It was plausible that the dolphin kicking motion performed in this study generated a propulsive force by generating the vortex ring. The vortex pair confirmed in the present study is likely of a part of this larger structure.

Key Words: PIV, dolphin kick, unsteady flow, vortex ring, jet-propulsion.

INTRODUCTION
In competitive swimming using four modern styles, the dolphin kicking motion, or butterfly kick, is used after the start and turn. The dolphin kicking motion, which resembles the propelling locomotion of the dolphins, produces a high propulsive force by the momentum induced due to the up and down motion of the feet. In addition, the underwater undulation swimming phase after the start and turn presented an advantage of less drag (2). Therefore, effective dolphin kicking is very important to improve swimming performance in competitive swimming (1, 2, 4). Ungerechts et al. (7) emphasises the reverse action of the kick, using a whip-like action as much as possible to propel the swimmer more effectively. Furthermore, Arellano et al. (2) visualised the flow with bubbles in dolphin kicking wake and reported that the efficient undulatory underwater swimmer created a large vortex at the end of the downward kick and a small vortex at the end of the upward kick to obtain a strong propulsive force.
Many studies have been undertaken to estimate the propulsive force of human swimming. Most were estimations of front crawl swimming, which were based on quasi-steady analyses (3). As Ungerechts et al. (8), and Toussaint et al. (6) reported, it was suggested that it was very important to consider the unsteady flow condition to argue propulsion in swimming. Therefore, it seems to be necessary to consider the unsteady flow around a human body in a real swimming situation to reveal the propulsion mechanism. Lately, a new analysis method, particle image velocimetry (PIV), has been established and improved in engineering society. It

allows us to visualise the unsteady flow field instantaneously and to estimate the fluid force. PIV has generally been used to analyse the flow field around an aerofoil in a wind tunnel or that around flying or swimming creatures (5). However, experiments using PIV to analyse the overall human swimming motion are still lacking.
As mentioned above, most past studies that have examined the propulsion mechanism of human swimming have investigated swimmers' hands or arms only, based on quasi-steady analysis. In addition, studies of the propulsion mechanism of kicking motion have used qualitative estimation based on unsteady flow theory, but no quantitative estimations have been reported. The aim of the present study was to visualise qualitatively and to analyse quantitatively the dolphin kicking wake of a swimmer in a sagittal plane viewed from the side using two-component PIV (2C-PIV).

METHODS
The Human Subjects Committee of the University of Tsukuba approved the present experimental design. One trained male swimmer participated in this study and was asked to give informed consent. The experiment was executed in a swimming flume (4.6 x 2.0 x 1.5 m; Igarashi Industrial Inc., Japan). The swimmer was instructed to remain in the same place relative to the oncoming flow with dolphin kicking. Trials were executed with the flume flow speed of 1.0 m/s (five trials). A schematic view of the experimental setup is shown in Fig. 1. Nylon tracer particles (50 μm) were admixed to the flume. A Nd-YAG laser (New Wave Research, Inc., USA) was placed below the flume and illuminated, intermittently and vertically, the flow area in a sagittal plane just behind the swimmer's feet (the wake). From the side window of the flume, 200 time-sequential pictures were captured (15 f/s) using a CCD camera (Kodak Megaplus ES1.0; Kodak Co., USA). The images were stored in a personal computer (Dell Dimension 4200; Dell Computer Corp., USA). The timing of the laser exposure and of the camera shutter were synchronised using a pulse generator (Quantum Composers Inc., USA). A lattice was set at the measurement plane and was filmed in advance to calibrate the image co-ordination system. The particles' displacement (Δx, Δy) was detected using cross-correlation analysis from the sequential two images. Displacement after a short interval Δt (= 1 ms) determined the particle velocity as

$$u = \frac{\Delta x}{\Delta t}, \; v = \frac{\Delta y}{\Delta t},$$

where (u, v) respectively represent the velocity components of x-axis and y-axis. The particle velocity vectors and vorticity (ω) were plotted as a velocity-vorticity map using MATLAB software (MATLAB version 6.5.1, Release 13; The MathWorks, Inc., USA). Vorticity (ω) indicates the magnitude of vortices and direction of rotation (see 5).

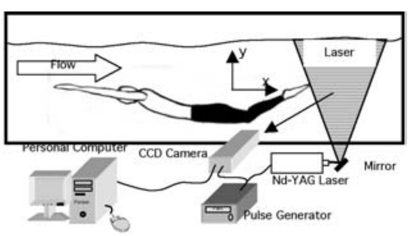

Figure 1. A schematic view of a 2C-PIV setup with the swimming flume viewed from the side window and the coordination system. The flow direction was from left to right. Nd-YAG laser illuminated the wake of a swimmer vertically in a measurement sagittal plane. Timing of the laser exposure and the CCD camera shutter were synchronized by a pulse generator (15 f/s).

RESULTS AND DISCUSSION
The results confirm the existence of a pair of vortices and jet flow in the wake of dolphin kicking motion. Examples of the particle image and velocity-vorticity map of downward dolphin kicking wake are shown respectively in Fig. 2(A) and Fig. 2(B). The left panel (A) shows the toe direction at $t = 0$; the white rectangle frame corresponds to the Fig. 2(B). Figure (B) shows the velocity field 134 ms after downward kicking relative to Fig. 2(A); the curved arrows indicate the direction of the vortices' rotation. The long white arrow in Fig. 2(B) indicates the jet flow. The grey scale is used as an index of magnitude of vortices rotation (ω). The flume-flow direction was from left to right. The mean x-component of velocity has already been subtracted in the velocity vectors plot (B) to clarify the map. Jet flows which are directed to the flume flow direction (positively along the x-axis) are contributing to thrust.

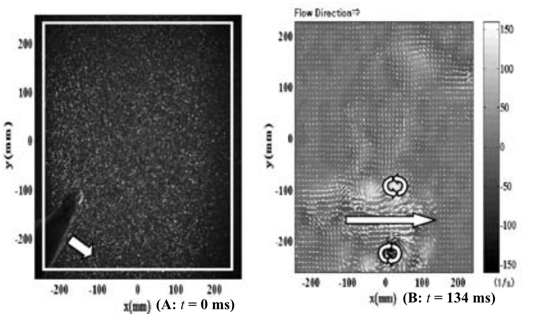

Figure 2. An exemplary image of downward dolphin kicking motion (tiptoe image, A: t = *0) and the velocity-vorticity map (B:* t = *134 ms). The white rectangle in the left panel corresponds to the right panel. The grey scale indicated in the right column denotes the magnitude of vortices.*

Colwin (4) explained butterfly leg (dolphin kick) propulsion by visualising the natural bubble in the wake of the swimmer. He called a mechanism of efficient leg propulsion the fling-ring mechanism. As the feet move downwards forcefully, a bound vortex formed around each foot. These vortices combine to form one large vortex ring that is shed in the vertical plane. Along this concept, we assumed that the vortex pair was the sectional part of a vortex ring; we also compared the value of the jet flow velocity (V_J) to that of the induced velocity of the vortex ring (V_O) when the pair of vortices was observed in the velocity field.
Comparison of the values of jet flow velocity and the induced velocity were confirmed for the pair of vortices in the flow field. The values of jet flow velocity agree well with the values of induced velocity of the vortex ring, as predicted by the assumption that the pair of vortices represents sectional parts of the vortex ring (table 1). It was plausible that the subject in this study generated a vortex ring with the dolphin kicking motion for propulsion in pool swimming or for remaining stationary in the flume swimming.

*Table 1. Examples of the values of jet flow velocity (V***J***) and the induced velocity of the vortex ring (V***0***) when the pair of vortices was confirmed in the velocity field. The distance between the vortices (***D***) is also listed. Not all data are shown.*

Trial No. (Plane No.)	Flume speed (m/s)	***D*** (m)	V_J (m/s)	V_O (m/s)
Trial 2 (25)	1.0	0.12	1.3	1.3
Trial 5 (20)	1.0	0.12	2.0	1.8

After the upward kicking motion, some pairs of small vortices and the jet flow were also confirmed (Fig. 3). However, the appearances of the pairs of vortices and the jet flow directed to the *x*-axis were observed mainly after downward kicking. Most of the jet flow observed after the upward kicking directed slightly upward along the *y*-axis.

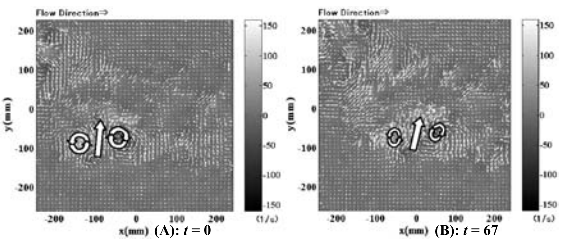

Figure 3. Examples of time sequential velocity fields after the upward dolphin kicking motion in a given moment. The jet flows in between the pairs of vortices directed slightly upward along the y-axis.

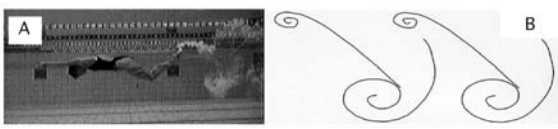

Figure 4. An exemplary image of the vortices generated during underwater undulatory swimming with the injecting bubble visualisation technique (A) and a sketch of the generated vortices of the wake (B) (alteration from Arellano, 1999).

The subject apparently propelled by downward kicking and kept the consequent position by upward kicking.
According to the reports of Arellano (1), the undulatory underwater swimmer generated the large vortex after the downward kick and the small vortex after the upward kick (Fig. 4). However, their visualisation technique and the point of view to the flow fields were completely different from ours. Their method was to see qualitatively the larger flow field and the larger vortex structure behind the dolphin kicking motion. On the other hand, our method is to visualise the instantaneous flow fields and to analyse quantitatively the smaller flow fields. From the difference of the visualisation method between Arellano's and ours, the vortex pair confirmed in the present study might be likely of a part of the larger vortex structure reported by Arellano (1). As mentioned above, our visualisation technique is limited to a smaller flow field. Therefore, further research to clarify the mechanism of efficient dolphin kicking propulsion is necessary.

CONCLUSIONS
We applied the 2C-PIV to the unsteady flow field of the dolphin kicking motion. We can visualise the flow field of the dolphin kicking wake. The subject created the vortex ring for propulsion. Although there might be larger vortex structures in the dolphin kicking wake for propulsion, our measurements were executed only in a sagittal and vertical plane. In addition, our measurements were restricted to two-dimensional flow analysis. Therefore, further research is necessary for understanding the generation mechanisms of propulsive force.

ACKNOWLEDGMENTS
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"SWUM" AND "SWUMSUIT" – A MODELING TECHNIQUE OF A SELF-PROPELLED SWIMMER

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The author proposes a simulation model "SWUM" (SWimming hUman Model) and a simulation software "Swumsuit" (SWimming hUman Model with Synthetic User Interface Tools) as its implementation. This modeling technique is developed to analyze various problems in the mechanics of a self-propelled swimmer. The overview of SWUM and Swumsuit are firstly described. Next, the validity of the model is examined by comparing the simulation results of swimming speed with the actual values for the four strokes. A sufficient agreement between the actual and simulation was obtained, indicating the validity of SWUM.

Key Words: simulation, self-propelled swimmer, modeling, fluid force, free software.

INTRODUCTION

Many studies have been carried out to date with respect to the mechanics of swimming. However, there is no analysis tool which can take into account of all fluid forces unsteadily acting on each part of the swimmer's body and which can analyze mechanics of dynamic swimming motion. Therefore, the objective of this study is to provide a simulation model, which can compute all the fluid force and inertial force acting on all parts of the swimmer's body, and can be an analysis tool used widely by swimming researchers all over the world for various problems of mechanics in swimming.

For this objective, the authors have already developed such a simulation program and proposed its idea as a conceptual simulation model "SWUM" (SWimming hUman Model) (1). In this previous study, it has been clarified that the simulation model has sufficient capability to discuss quantitatively the mechanics of swimming, since the swimming speed of the simulation agrees well with the actual one in a simulation example of standard six beat crawl stroke. The developed simulation program, however, was written in Fortran of thousands lines and there were no interface part. Therefore, as the next step, the interface part of the simulation program was developed and integrated with Fortran main program as a simulation software (2). This software, named "Swumsuit" (SWimming hUman Model with Synthetic Use Interface Tools) is a free software, and available at the web site (3). In this paper, the overview of this modeling technique by the authors is firstly described. Next, the validity of the model is examined by comparing the simulation results of swimming speed with the actual value for the four strokes.

METHODS

Overview of Simulation Model "SWUM"

In SWUM, the relative motion of the swimmer's body is given as joint motions, and the absolute motion for the whole swimmer's body in six degrees-of-freedom is solved, based on the six equations of motion for a rigid body, whose formulation is similar to that in Robotics (1). Figure 1(a) shows the analytical model of a self-propelled swimmer in SWUM. The swimmer's body is modeled as a series of rigid segments. The segments are represented as truncated elliptic cones, whose actual number is 21 in the analysis. The geometry and density of all the body segments are determined based on the actual data. Figure 1(b) shows the example of the modeled body for averaged Japanese 20-29 years old male.

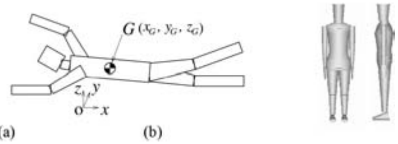

Figure 1. Modeling of a swimmer's body. (a) Analytical model of a self-propelled swimmer. (b) Example of the modeled body for averaged Japanese 20-29 years old male.

As the external force acting on the swimmer's body, unsteady fluid force including the buoyancy and the gravity force are taken into account. The unsteady fluid force is assumed to be obtained from local motion of each body part without solving the flow field. Figure 2(a) shows the schematic figures of the fluid force modeling. The drag force tangential to the longitudinal axis of the cone $\boldsymbol{F_t}$ which basically corresponds to the so-called 'passive drag', the drag force normal to the axis $\boldsymbol{F_n}$ which basically corresponds to the drag and lift force generated by limb motion, and the inertial force due to the 'added mass' effect of the fluid $\boldsymbol{F_a}$ are respectively computed with respect to each thin elliptic plate divided from the truncated elliptic cone. The force $\boldsymbol{F_t}$ and $\boldsymbol{F_n}$ are assumed to be proportional to the local velocity at the thin plate's center in the tangential and normal directions, respectively. The force $\boldsymbol{F_a}$ is assumed to be proportional to the local acceleration in the normal directions. These fluid force components are computed using their coefficients. The authors identified the coefficients by an experiment, in which the relationship between the motion and the fluid force acting on an oscillating artificial limb model in water was measured (1).

For the buoyancy, on the other hand, the side surface of the thin plate is again divided into tiny quadrangles in the circumference direction, as shown in Figure 2(b). The static pressure force $\boldsymbol{F_b}$ is computed for each quadrangle, and its summation becomes the buoyancy acting on the thin plate. Note that the force $\boldsymbol{F_b}$ is only computed for the quadrangles below the water surface, as shown in Figure 2(c).

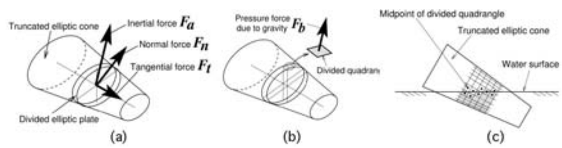

Figure 2. Modeling of fluid force. (a) Fluid force components acting on a thin elliptic plate's center. (b) The static pressure, which is the source of the buoyancy, is computed with respect to the tiny quadrangles. (c) The static pressure acts only on the quadrangles below the water surface.

Summing up all the fluid force components and resultant moment acting on the thin plate with respect to the cone's longitudinal direction, total force acting on each cone is obtained. By summing up again the force acting on all the cones, total force acting on the swimmer's body is obtained. These formulations are solved by time integration using the Runge-Kutta method. As the outputs of the computation, the swimming speed, rolling, pitching and yawing motions, fluid force acting on each part of the body, joint torques and so on are obtained.

Simulation Software "Swumsuit"

The simulation software Swumsuit consists of main program as the analysis engine part and GUI (graphical user interface) part. Figure 3 shows the structure of Swumsuit. The analysis engine part which implements SWUM reads three input files, that is, data files of body geometry, joint motion, and analysis settings. The parameters in these three files can be changed through three GUI editor parts. With respect to the output, a motion data file is produced to display animation of swimming motion. And many other data files are output, such as, swimming speed, time history of absolute position, consumed power, thrust, roll moment, joint torques at all joints, and so on. These data files are displayed by the graph display part.

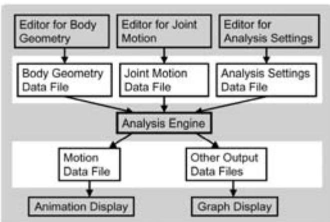

Figure 3. Structure of Swumsuit, which has analysis engine, three editors for input files, animation and graph display parts. Each part has graphical user interface.

RESULTS AND DISCUSSION

Figure 4 shows the screenshots of the Swumsuit. Figure 4(a) is the start window, from which all the function can be invoked. Figure 4(b) is the editing body geometry window. Figure 4(c) is the editing joint motion window, on which the user can edit the joint motion, viewing the graph of the joint angles and the animation of relative motion. Figure 4(d) shows the outputs displayed as graphs and animation. In the animation, the direction and magnitude of the fluid force acting on the each part of the body is displayed by dark (red) sticks as shown in Figure 4(d). The animation can be exported to a MPEG movie file. From movies of model swimming by an athlete swimmer, joint motions for the four strokes, that is, crawl, breast, back, and butterfly strokes, were created. In the simulation, after several cycles of unsteady motion, swimming motions at the 'clean speed' were obtained for all strokes. Figure 5 shows the results. Figure 5(a)~(d) are the screenshots of animation, which are available at the web site (3). Figure 5(e) shows the comparison of normalized stroke length during the steady swimming between simulation and actual value for the four modern strokes. The sufficient agreement between the actual and simulation indicates the validity of SWUM, although the simulation value of the breaststroke is somewhat smaller. The reason of the discrepancy of the breaststroke is thought to be the modeling error of the fluid force during leg kick.

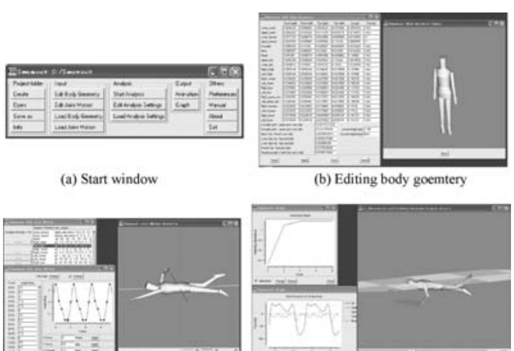

Figure 4. Screenshots of the developed software "Swumsuit".

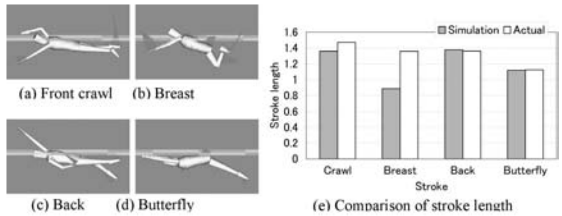

Figure 5. Simulation results of four modern strokes. (a)~(d) animations. (e) Comparison of nondimensional stroke length.

Further detailed investigation for the fluid force acting on the limb will be necessary. Figure 6(a) shows the simulation results of velocity fluctuation of the front crawl during one cycle. Note that the velocity becomes negative value according to the direction of the coordinate. Figure 6(b) is the thrust produced by the left hand. The negative value means positive thrust by definition. It can be seen that the thrust becomes maximal at 8.7s~8.8s, and that its main component is the normal drag. Other full data for the four strokes are available at the website (3). By these output directly outputted by Swumsuit, the phenomenon and mechanics in swimming could be understood.

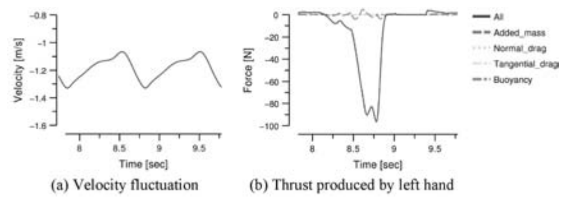

Figure 6. Velocity fluctuation and thrust produced by left hand during one cycle.

CONCLUSION

The author's modeling technique of a self-propelled swimmer, SWUM and Swumsuit, is introduced. This modeling technique can be a powerful analysis tool and can be applied to various fields of training and coaching, for example, understanding the mechanics of swimming, analysis of race and daily training together with a motion capture system, and discover the better swimming form to improve stroking individually.

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PATTERN MATCHING APPLICATION FOR THE SWIMMING STROKE RECOGNITION

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In the field of sports biomechanics, we have been quantifying the similarity between subjects using their kinematics. Many studies applied the normalisation in this procedure. On the other hand, in the field of speech recognition, in order to distinguish a phoneme by different speakers or voices, the dynamic time warping (DTW) method have been applied. In this study, it was quantified the similarity of the swimmers' stroke motion, which depends on their skill level and swimming speed using dynamic time warping.

Key Words: swimming, stroke, dynamic time warping, pattern recognition.

INTRODUCTION

The author has been analysing swimming stroke skill using inertia sensors, such as accelerometer and gyroscope, which were attached on the swimmer's wrist (1, 2). For the improvement of stroke skill in swimming, coaches, swimmers and researchers are eagerly desiring to compare and evaluate different arbitrary strokes. It means that different swimmers' strokes or identical individual swimmer's strokes on different situations. For example, comparing kinematics between top swimmer's and novice's strokes. In case of stroke drill practice, coaches want to know whether or not a swimmer can change his stroke technique as they instructed. However, in order to compare and discriminate two different strokes, durations and kinematics, such as coordinates of stroke paths, velocities and accelerations, depend on subjects and also each lap and each stroke. Granted that it can be obtained three dimensional underwater stroke images, and stroke path can be calculated with orientation of the swimmer's hand, it will be very difficult to determine where is the similar or different phase between their strokes and quantify how much each one differ from the other. In the field of biomechanics, we have been standardizing our single cycle of motion, such as walking, running and swimming, into 100% normalized time duration and then compared each other. But nobody argued the validity of this time normalization. On the other hand, in the field of speech recognition, they have a traditional method, named dynamic time warping (DTW) to recognize different utterances, whose duration vary and depend on the speaker or their voice. In this study, for the purpose of stroke pattern recognition, the author applied DTW using the inertia sensor data which was obtained from the body attached sensor in swimming.

METHODS

Subjects were five well-trained college swimmers. Tri-axial accelerometer and tri-axial gyroscope data logger, Prototype II, was attached on subject's left wrist. Figure 1 shows Prototype II data logger and its local coordinate system for the experiment. Sensor data were recorded at 128Hz sampling rate. In addition to the sensory measurement, three dimensional underwater videography was conducted to acquire swimmer's stroke pattern. All subjects swam 50m trials at slow, middle and fast speeds, in both the crawl stroke and breaststroke. Time series of acceleration and angular velocity in single stroke cycle was extracted from the acquired total data. As for the crawl stroke data, single stroke duration was determined by the impact acceleration at the entry instant. On the other hand, for the breaststroke extraction, the steep transition of the y-axis acceleration at the start of the recovery phase was used. In this study, the author will examine this extracted single stroke time series of both the acceleration and the angular velocity. Dynamic time warping is one of the popular speech recognition algorithm based on the dynamic programming (3, 4). It allows us to recognize utterances by different speakers or different speaking durations. For the stroke pattern recognition, the author applied the classic fixed end point DTW method to examine swimmer's stroke kinematics. In order to measure the distance between two arbitrary time series value, the Manhattan distance function was used.

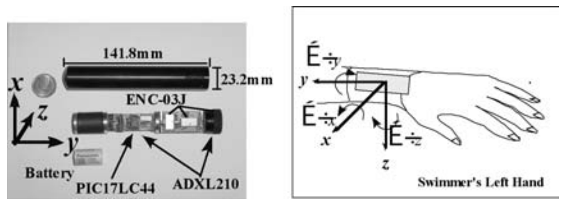

Figure 1. Tri-axial acceleration and tri-axial gyroscope data logger and its local coordinate system on the subject left wrist.

RESULTS AND DISCUSSION

Although, Prototype II data logger was capable to measure six channel data, which corresponding to the tri-axial acceleration and angular velocity of the swimmer's forearm motion, it might be complicated to apply all combined data into DTW algorithm. Thus, the author conducted DTW pattern matching using each selected time series between two different swimming trials. The longitudinal axial acceleration (A_y) and its rotational angular velocity (ω_y), were distinctive of stroke styles (2). Figure 2 shows a result of the pattern matching within subject (sub. B) using y-axial acceleration (A_y) on his different speed crawl stroke trials. The left figure shows two time series of A_y in his middle and fast speed trials, and corresponding value between both time series. The right figure shows the searching path of the DTW process in comparison with both time series.

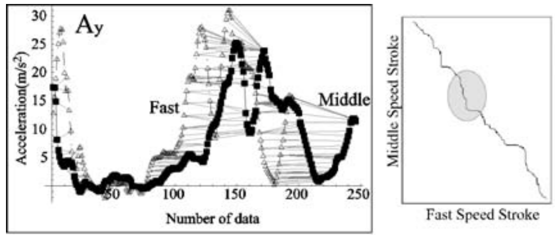

Figure 2. DTW stroke pattern matching within subject using swimmer's wrist y-axis acceleration (sub. B).

Figure 3 also shows a result of comparison using ωy within same subject, sub.B.

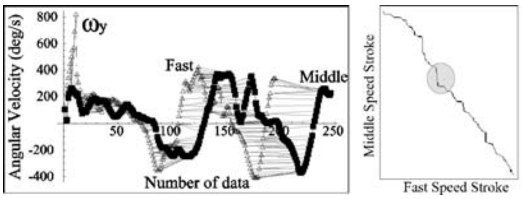

Figure 3. DTW stroke pattern matching within subject using swimmer's wrist y-axis angular velocity (sub. B).

Figure 4 shows a result between subjects by using ω_y. This comparison was examined between sub. B and sub. H on their fast speed crawl stroke trials. For those examples, the cumulative distances between those time series were 261.03 m/s²(fig. 2), 8140.62 deg/s (fig. 3) and 16882.3 deg/s (fig. 4), respectively. When both two time series have same magnitude and differ in only their duration, or differ in their magnitude with same duration, the searching path would be a diagonal line. If a horizontal or vertical line existed in the searching path, there would indicate that there is a different phase between two target time series. Since, the acceleration A_y corresponds to the longitudinal acceleration with the swimmer's forearm, the centrifugal acceleration by his rotational motion around both the shoulder and elbow joint is dominant in this axis (3). It can be seen an almost diagonal line on the result of the stroke pattern matching on A_y in Figure 2, except middle of his stroke. However, there is a vertical and then horizontal line in the middle of his stroke. And also, as for his angular velocity $\omega_{y,}$ which corresponding supination and pronation of the forearm, there is a vertical and horizontal line at the same time. It means that the stroke motion of the swimmer with respect to the y-axis can be quite similar irrespective of the swimming speed, except in the middle phase of stroke. In Figure 4, it can be seen one of the results of pattern matching between subjects. Between sub.B and sub.H, there are several different stroke phases in their y-axial angular velocity, which was equivalent to the forearm supination/pronation motion in their stroke. Thus, we can find out both similar and different stroke phases between two other strokes' inertia data using the dynamic time warping. For example, it becomes possible that we will be able to examine the similarity of the swimmers or whose stroke technique is closest to the swimmer. To be more precise, there is a possibility to distinguish swimmer's attempt to improve his stroke technique in skill training, and predict his fatigue or change of physical condition using sensor data. Since underwater videography is difficult to observe for us, DTW stroke pattern matching on the inertia sensor data will be a strong tool for the stroke monitoring, both in the competitive swimming research and coaching.

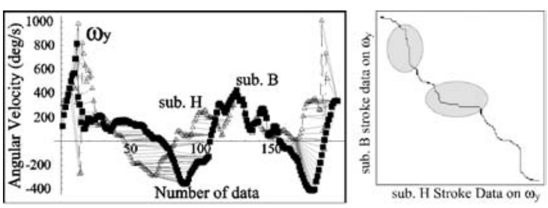

Figure 4. DTW stroke pattern matching between subjects using swimmer's wrist y-axis angular velocity (sub. B and sub.H).

Table 1 shows cumulative distances between subjects stroke comparison using y-axis acceleration, A_y. Because A_y is strongly influenced by the upper arm rotational movement, results tell us that the arm rotational acceleration pattern is similar between sub.A and subH, and also between sub.B and sub.K.

Table 1. Cumulative distances by DTW pattern matching for Ay during the crawl stroke.

	sub. A	sub. B	sub. H	sub. K	sub. T
sub. A					
sub. B	692.6				
sub. H	361.2	506.3			
sub. K	489.4	360.8	500.0		(m/s²)
sub. T	1002.3	1016.7	917.7	818.5	

CONCLUSION

The author propose the dynamic time warping method to the swimming stroke pattern recognition using swimmer's stroke inertia sensor data, such as tri-axial acceleration and angular velocity. Since, the cumulative distance of DTW process is equivalent to the difference between strokes, using DTW method, we can examine between subjects differences or within subject changes of their stroke skill or specified stroke phase.

ACKNOWLEDGEMENTS

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THE INFLUENCE OF REPEATED SPRINTING ON THE KINEMATICS OF BUTTERFLY SWIMMING

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The purpose of this study was to determine the effect of repeated sprint performance and fatigue on the kinematics of butterfly swimming. Six experienced national youth male butterfly swimmers undertook a maximal effort repeated sprint test set, during which swimmers were filmed with two underwater and two above water cameras (oblique plane) at 50Hz. The whole body was digitised during a full stroke cycle for each view, with the three-dimensional coordinates being obtained using a DLT algorithm. The results of this study indicate that as swimming speed decreased (i) stroke rate decreased while

stroke length remained relatively constant, (ii) hand movement patterns remained similar while changes in elbow angle suggested that the effectiveness of joint flexors and extensors may have been reduced, (iii) the Upsweep, Recovery and Catch appear to the critical stroke phases when swimmers become fatigued.

Key Words: repeated sprinting, kinematics, butterfly swimming.

INTRODUCTION

The breakdown of optimal swimming technique has been suggested to be as a result of muscular fatigue during sprint swimming (4), with only a few studies investigating intra-cyclic stroke kinematic variations under exhaustive conditions. Front crawl swimmers spend more time in the propulsive phase of the stroke whilst fatigued (1), displaying a reduced ability to generate propulsive forces due to a decrease in hand velocity (2), an altered hand trajectory (3), and a reduced lever arm length (6). Throughout a 200 metre butterfly swim, decreases in swimming speed have been shown to correlate strongly with changes in three-dimensional hand velocity components (5), specifically during the final phases of the arm stroke. However, front crawl kinematics differ to those of the butterfly stroke and previous research (5) was limited to evaluating swimming speed and hand velocity during a single endurance swim. The purpose of this study was to establish the effect of repeated sprint performance and fatigue on spatial, temporal and kinematic parameters of butterfly swimmers.

METHODS

Six experienced national youth male butterfly swimmers (16.8 ±1.5 years; 1.75 ±0.07 metres, 72.7 ±4.6 kg; 100m P.B. time 58.7 + 2.5) participated in this study.
After a standardised warm-up, each subject performed a maximal effort repeated sprint test: 8 x 50 metres (long-course) at intervals of 1 min 30 sec from a dive start. Time for each repeat was recorded by an experienced timekeeper using a chronograph stopwatch (Model 898). Blood lactate concentrations were measured pre- and post-test from the earlobe using a Lactate Pro™ automated analyser.
On the first and seventh 50 metre repeats, a full stroke cycle was filmed within a previously calibrated volume (5m x 2.25m x 1m; above & underwater) using 36 control points, between 20 to 25 metres. Swimmers were filmed at 50 Hz with two above water (Sony TRV900E DV) and two underwater (M37CHR-IR linked to a Sony GV-D1000E DV recorder) cameras. The four camera views were synchronised using hand entry.
Symmetry between the left and right sides of the body was assumed and accordingly eight body landmarks defined a seven-segment model of the right arm, trunk and right leg. The estimated locations of these landmarks were manually digitised using SiliconCoach Digitiser software for each camera view. The above and underwater image coordinates were then reconstructed to three-dimensional space coordinates using a direct linear transformation algorithm, combined and then smoothed at a cut off frequency of 8Hz using a fourth order Butterworth filter (in MatLab).
The complete motion of the stroke was subdivided into six arm phases: Catch, Outsweep, Downsweep, Insweep, Upsweep, Recovery. The following parameters were used to describe the stroke kinematics: *Stroke length*: distance per stroke cycle; *Stroke rate:* number of stroke cycles per second; *Phase time*: time spent in each stroke phase; *Pull depth*: vertical displacement of the hand from entry to deepest point; *Pull width*: medial displacement of the hand from widest to narrowest point; *Pull length*: horizontal displacement of the hand from most forward to backward point; *Hand velocity*: mean of the finger and wrist velocities relative to the water; *Elbow angle*: angle between the forearm and upper arm viewed in the frontal plane; *Trunk angle*: angle between the trunk and the horizontal viewed in the sagittal plane.
Mean and standard deviations were calculated for all parameters. Significant differences (*p value = 0.05*) between conditions were determined using paired (dependent) *t-tests*.

RESULTS

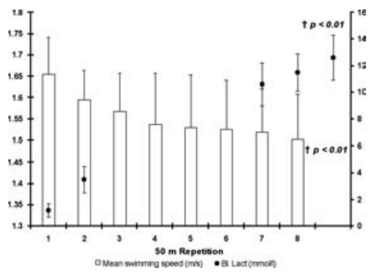

Figure 1. Mean swimming performance decreased by 9 ±5% (p<0.01) over the 8 x 50 metres, mean blood lactate concentration rose to 12.6 ±1.7 mmol.l-1 (p<0.01) post- test.

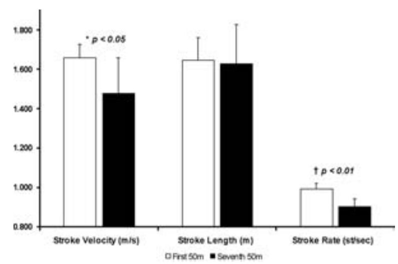

Figure 2. Mean stroke speed decreased by 8 ±6% (p<0.05) between repeats one and seven, with swimmers exhibiting slower stroke rates (p<0.01) but similar stroke lengths.

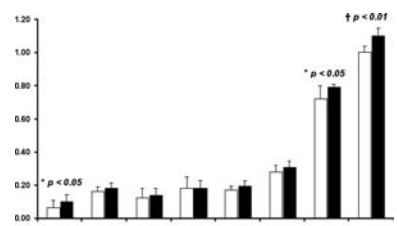

Figure 3. Total stroke time increased by 10 ±6% (p<0.01), as a result of a longer duration in all stroke phases (Recovery and Catch p<0.05).

Table 1. Differences in selected three-dimensional directional components of peak hand velocity ($m \cdot s^{-1}$) during five phases of the stroke.

	Outsweep (lateral $m \cdot s^{-1}$)	Downsweep (downward $m \cdot s^{-1}$)	Insweep (medial $m \cdot s^{-1}$)	(backward $m \cdot s^{-1}$)	Upsweep (lateral $m \cdot s^{-1}$)	(upward $m \cdot s^{-1}$)	Recovery (upward $m \cdot s^{-1}$)
First 50 m (M ± S.D.)	1.87 (± 0.42)	2.40 (± 0.50)	3.09 (± 0.51)	3.12 (± 0.47)	4.05 (± 1.05)	5.13 (± 1.48)	3.44 (± 0.66)
Seventh 50 m (M ± S.D.)	1.55 (± 0.43)	2.37 (± 0.54)	2.75 (± 0.46)	2.74 (± 0.42)	3.11 (± 1.03)	4.26(± 1.08)	3.02 (± 0.86)
P value ($p=0.05$)	0.07	0.84	0.25	0.18	0.09	0.13	0.12

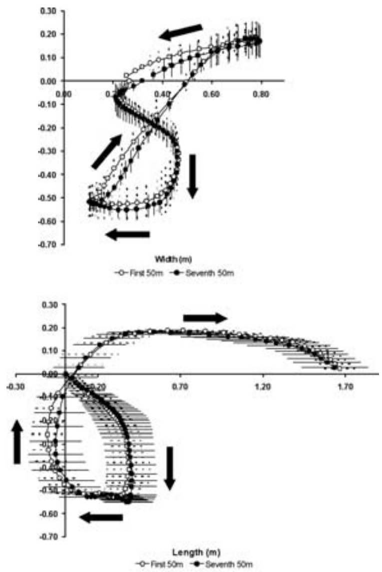

Figure 4a (frontal view) & 4b (sagittal view). Swimmers exhibited slightly deeper (4 ±7%), narrower (7 ±12%) and shorter (3 ±8%) propulsive hand path trajectories.

Table 2. Differences in elbow angle (deg o) during five arm phases of the stroke.

Outsweep	Downsweep (max °)	Insweep (mean °)	Upsweep (min °)	(max °)	Recovery (max °)
First 50 m (M ± S.D.)	163 (± 16)	116 (± 23)	91 (± 18)	134 (± 21)	178 (± 1)
Seventh 50 m (M ± S.D.)	166 (± 9)	113 (± 18)	94 (± 12)	144 (± 14)	175 (± 2)
P value ($p=0.05$)	0.56	0.55	0.70	0.51	0.04

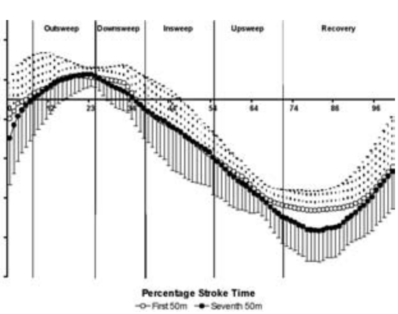

Figure 5: Maximum trunk undulation increased by 13 ±15% during the Recovery phase.

DISCUSSION

Decrease in mean swimming performance and rises in blood lactate concentration (fig. 1) were comparable to previous findings reported in the literature (1, 3), suggesting that swimmers were experiencing muscular fatigue by the seventh 50 metre repeat.

As swimming speed decreased, stroke rate decreased, while stroke length remained relatively constant (fig. 2), contrasting with front crawl swimming, where stroke length rather than stroke rate is influenced by repeated sprinting (1). The reduction in stroke rate was due to swimmers spending more time in all phases of the stroke (fig. 3), in particular the non-propulsive Catch and Recovery phases. This would imply that the decrease in swimming speed may have been influenced by increased duration between the propulsive phases.

Peak hand velocities during all propulsive phases decreased (table 1): Outsweep: lateral by 17 ±18%; Insweep: medial by 11 ±19%; with the greatest changes observed during the Upsweep: backward, upward and lateral by 12 ±17%, 17 ±18% and 23 ±26% respectively. Similar changes have been previously shown during the course of a 200 metre butterfly swim (5), and suggest that the swimmers' ability to generate propulsive forces was compromised, especially during the final propulsive Upsweep phase of the arm stroke.

Swimmers exhibited similar hand movement patterns between the first and seventh repeats (fig. 4 a & b), with 4 ±10% less elbow flexion during the Insweep and 7 ±18% less elbow extension during the Upsweep (table 2). Such changes may indicate that while the hand path trajectory remained relatively consistent, the effectiveness of the elbow flexors and extensors may have been reduced by the seventh 50 metre repeat.

Trunk angle remained relatively unchanged throughout the stroke phases, with the exception of the Recovery phase (fig. 5). This increased vertical inclination would imply that the swimmers were experiencing a greater amount of form drag as a result of reduced streamlining. Such an increase in resistive forces during this stroke phase, following the reduced ability to generative propulsive forces during the preceding phase, would combine to limit the swimmers' forward progression through the water.

No differences in arm and leg phase coordination were observed, and although peak vertical foot velocities during all leg phases decreased, these were not found to be significant.

CONCLUSION

The results of this study indicate that as an effect of repeated sprinting and fatigue: (i) swimming speed and stroke rate decreased while stroke length remained relatively constant; (ii) all stroke phases were longer in duration, in particular the Catch and Recovery; (iii) greatest decreases in hand velocity were observed during the Upsweep; (iv) hand movement patterns remained similar while changes in elbow angle suggested that the effectiveness of joint flexors and extensors may have been reduced; (v) the largest increase in trunk angle occurred during the Recovery.

The Upsweep, Recovery and Catch appear to the critical stroke phases (greatest changes were observed) as swimmers become fatigued. Encouraging swimmers to accelerate the hands outwards during the Upsweep while maintaining a more horizontal trunk and a lower and faster hand recovery, may help to resist changes in stroke mechanics brought about by the onset of fatigue.

ACKNOWLEDGEMENTS
Thanks is expressed to the swimmers of City of Sheffield and Nova Centurion squads for their participation in this study, Matt Pain for his assistance during data collection and British Swimming's Sport Science Research Group for their logistical support.

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INTRA-CYCLIC SPEED FLUCTUATIONS OF UNI-LATERAL ARM AMPUTEE FRONT CRAWL SWIMMERS

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Front crawl swimmers with an arm amputation at elbow level are deprived of an important propelling surface. The purpose of this study was to determine the extent to which uni-lateral arm amputee front crawl swimmers are able to generate swimming speed with their sound and with their affected limbs. Eight trained swimmers (2 male, 6 female) performed front crawl trials (without a leg-kick) at middle distance pace, while attached to a velocity meter (100 Hz). Trials were simultaneously videotaped underwater. Mean intra-cyclic speed fluctuation was 35 ± 5% of the mean swimming speed. Peak swimming speed achieved during the push phase of the sound limb (1.30 ± 0.17 $m.s^{-1}$) was significantly higher than that found during the push phase of the affected limb (1.14 ± 0.11 $m.s^{-1}$). This indicates that the swimmers were able to use their affected limb to increase their swimming speed, but not as effectively as with their sound limb.

Key Words: arm amputees, front crawl, speed fluctuation.

INTRODUCTION
Front crawl is the fastest of the four competitive swimming strokes and the arm action is generally thought to supply more than 85% of the total propulsion (4). Previous studies that have attempted to quantify the propulsive forces generated by the front crawl arm action have assumed that either the hand alone, or the combination of the hand plus forearm, is the major 'propelling surface' responsible for propulsion. No study has considered whether the upper arm segment contributes to propulsion in the front crawl. This is perhaps not surprising given that, whilst the arm is in its propulsive phase, the most proximal end, the shoulder, moves forwards relative to the water and encounters drag forces that resist its forward motion (2).
Competitive swimmers with an amputation at elbow level are clearly at a disadvantage when compared to able-bodied swimmers, as they are deprived of an important propelling surface. Although the majority of these swimmers do perform an arm pull with their affected limb when swimming front crawl, the effectiveness of this pull, compared to that of the sound limb, has not been established.
Although it has been stated (3) that the most efficient type of propulsion is where speed fluctuations are zero, all four competitive strokes are characterised by significant speed fluctuations within each stroke cycle. In able-bodied front crawl swimming, intra-cyclic speed fluctuation may be as much as ± 20% due to the intermittent application of force within a stroke cycle (1). It would seem reasonable to speculate that the intra-cyclic speed fluctuation of uni-lateral arm amputee front crawl swimmers might be even higher than in able-bodied swimmers, due to a reduced force application during the pull of the affected limb. The purpose of this study was to determine the extent to which competitive uni-lateral arm amputee front crawl swimmers are able to generate swimming speed with their sound and with their affected limbs.

METHODS
Participants
Two male and six female, highly trained competitive swimmers (age 17.6 ± 3 years; stature: 1.69 ± 0.09 m; body mass 60.6 ± 13.3 kg) consented to participate in this study. All participants were single arm amputees, at the level of the elbow, and competed in the International Paralympic Committee S9 classification for front crawl. Best 100 m front crawl times ranged from 64.0-65.9 s for the males and from 69.1-99.3 s for the females.

Underwater filming procedure
Participants performed a series of 25 m front crawl trials at their middle distance pace with a small buoy placed between the legs in order to isolate the arm action. To control for the effects of the breathing action on the swimming stroke, participants were requested not to take a breath through a 10 m test section of the pool. Trials were filmed below water from the side view with a digital camcorder (Panasonic NVDS33) sampling at 50 Hz with a shutter speed of 1/250 s. The camcorder was enclosed in a waterproof steel housing that was suspended from a trolley on the pool deck. This set-up enabled the participants to be recorded over the full length of the pool.

Swimming Velocity Meter
The intra-cyclic speed fluctuations of each participant were measured using a custom-built velocity meter, which was secured at the end of the pool. Participants were linked to the velocity meter by a lightweight, inelastic line that attached to a belt around their waists. As the participants swam, the line was pulled from the velocity meter, turning a low inertia wheel

linked to a rotary optical encoder. The encoder produced 500 pulses per revolution and was connected to a frequency-to-voltage converter. The output from the converter was sampled at 100 Hz and then recorded on a laptop PC via a 12-bit A-D converter. To synchronise the output from the velocity meter with the underwater video recordings, a light-emitting diode (LED) was manually triggered in view of the camera during each swimming trial. The trigger simultaneously superimposed a short duration pulse on the velocity meter output.

Data Processing & Analysis

Velocity meter data were smoothed using quintic splines. Three consecutive, non-breathing stroke cycles, for each participant, were then selected for analysis. A stroke cycle was defined from the entry of the hand of the unaffected arm to the next entry of that hand. Digital video footage was transferred to a laptop computer and analysed using SIMI Motion 6.0 software. The time of occurrence of key moments in the stroke cycle (e.g. hand entry) were recorded relative to the time of the LED flash. Thus, it was possible to determine the time of occurrence of these key moments on the velocity meter curves. The gleno-humeral joint centre and the most distal point of the affected limb were digitised (50 Hz) to obtain the angular position of the limb, as a function of time. The angle-time data were smoothed with a 6^{th} order polynomial.

Definition of Variables

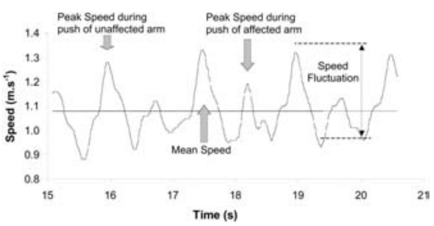

Figure 1. Intra-cyclic speed-time curve for three consecutive stroke cycles of an arm amputee front crawl swimmer.

The following variables were obtained from the velocity meter data or video recordings (mean of three stroke cycles):

— *Mean speed* / m.s^{-1} – mean forward speed of the participant over three stroke cycles.

— *Stroke length* (SL) / m – distance travelled down the pool with one stroke cycle.

— *Stroke rate* (SR) / Hz – number of stroke cycles performed in one second.

— *Peak speed* / m.s^{-1} - maximum forward speed of the participant recorded during the underwater push phase, for the affected and unaffected sides (Figure 1).

— *Speed fluctuation* / % – difference between the maximum and minimum speeds within a stroke cycle, expressed as a percentage of the mean speed (Figure 1).

— *Arm extension velocity* / rad.s^{-1} – mean angular velocity of the upper arm about a horizontal axis through the shoulder, calculated over the middle third of the pull.

Statistical analysis

Between measures analysis of variance tests were conducted to establish the differences between the affected and unaffected limbs with regard to the dependant variables. Pearson's Product correlation tests were used to investigate the strength of relationships between selected variables. The level for statistical significance was set at $p < 0.05$.

RESULTS AND DISCUSSION

The mean speed of the swimming trials was 1.09 ± 0.13 m.s^{-1}. This speed is somewhat lower than that typically reported in studies of trained, able-bodied front crawl swimmers, because the trials were sub-maximal and were performed without a leg kick, in order to isolate the action of the arms. The mean stroke length and stroke rate of the amputees was 1.45 ± 0.13 m and 0.75 ± 0.10 Hz, respectively. This stroke length is substantially lower and the stroke rate higher than those used by trained, able-bodied swimmers at 1.1 m.s^{-1} (1). This difference can primarily be attributed to the physical impairment of the swimmers but may also be linked to the absence of a leg kick and the relatively small stature of the swimmers (1.69 ± 0.09 m).
The mean intra-cyclic speed fluctuation for each swimmer is presented in Figure 2. Swimmer F1 had the greatest speed fluctuation (41%) while swimmer F3 had the least speed fluctuation (30%). On average, the group had a speed fluctuation of 35 ± 5% which is slightly less than the 40% previously reported for trained front crawl swimmers of 'varying skill levels' (1). This result was unexpected, as it was anticipated that the speed fluctuations would be higher in amputee swimmers due to a less consistent application of force through the stroke cycle. Two possible reasons for this finding are: 1) the absence of a leg kick. If the swimmers had been permitted to kick, it is likely that this would have changed the maxima or minima on the speed curve (Figure 1) and, consequently, the speed fluctuation, 2) the timing of the two arm strokes. The amputee swimmers demonstrated a variety of different timings. Some or all of these timings could be more conducive to achieving a consistent application of force, and therefore a low speed fluctuation, than the timing used by able-bodied swimmers. Further work is needed to verify these speculations.

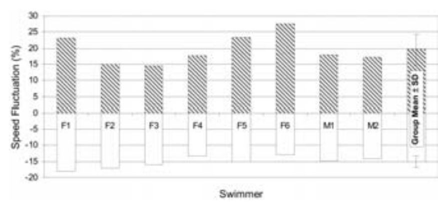

Figure 2. Speed fluctuation, as a percentage of mean swimming speed, for six female (F) and two male (M) arm amputee front crawl swimmers.

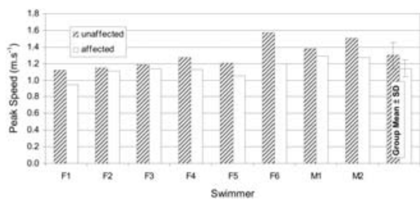

Figure 3. Peak intra-cyclic speed for six female (F) and two male (M) arm amputee front crawl swimmers, during the push phase of the affected and unaffected arms.

The velocity meter curves provide some tentative evidence that the swimmers were able to generate propulsion with their affected limb, as there was a marked increase in intra-cyclic speed during the push phase of this limb. This occurred when the sound arm was either still recovering, entering or in the non-propulsive glide phase. Not surprisingly, the swimmers were more effective at increasing their swimming speed with their sound limb than they were with their affected limb (Figure 3). The peak swimming speed achieved during the push phase of the sound limb (1.30 ± 0.17 $m.s^{-1}$) was significantly higher than it was during the push phase of the affected limb (1.14 ± 0.11 $m.s^{-1}$).
Inter-swimmer correlations revealed a significant relationship (r=0.72, p<0.05) between mean swimming speed and stroke rate. Interestingly, the swimmers who exhibited the highest stroke rates were not necessarily those who pulled their affected limb through the water the quickest, as the correlation between the extension velocity of the affected limb and stroke rate was non-significant (r=-0.36). Extension velocities of the affected limb ranged from 8.8 to 12.9 $rad.s^{-1}$. There was no relationship between the extension velocity and the peak swimming speed that was produced during the push phase of this limb. This indicates that factors other than limb speed, such as the timing and trajectory of the pull, may be more important in determining the effectiveness of the pull.

CONCLUSION
Swimmers with a uni-lateral arm amputation have demonstrated that, in the absence of a forearm and hand, it is possible to use the upper arm to increase swimming speed within the front crawl stroke cycle, but not as effectively as with the complete arm.

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THE EFFECT OF THE BREATHING ACTION ON VELOCITY IN FRONT CRAWL SPRINTING

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Ten competitive, national level adult swimmers (age 25 ± 3 years (mean ± SD) swam three 25m freestyle sprints with different breathing patterns in randomised order to examine how breathing actions influence velocity during a 25m front crawl sprint. Velocity measurements were carried out using a computerized swimming speedometer and data from mid-pool free swimming (10-20m) was extracted. There was no significant difference in mean (±SD) velocity (v) between sprinting with one breath (v=1.74±0.14 m_s^{-1}) compared to no breath (v=1.73±0.14 m_s^{-1}). There was a significant (p<0.05) reduction in velocity when breathing every stroke cycle (v=1.70±0.14 m_s^{-1}), compared to both no breath and one breath trials. Swimmers should breathe as little as possible during 50m freestyle races and breathe no more than every 3rd stroke cycle during a 100m freestyle race.

Key Words: biomechanics, breathing, swimming performance, freestyle, sprint.

INTRODUCTION
To achieve a high swimming velocity, one main goal for swimming technique is to create optimal propulsion and minimal resistance (4). For a front crawl swimmer, minimal resistance winds down to keeping an optimal streamline; the head and body in a straight line and the body as horizontal as possible. Optimal propulsion means keeping effective propulsive forces, high propelling efficiency and high power output throughout the swimming distance. The breathing action in front crawl swimming is in most cases a movement that inflicts the swimmers streamline or propulsion because the head has to move out of normal swimming position to make inspiration of air possible. How long the inspiration lasts will also inflict the swimmers streamline and propulsion (1). Both Cardelli, Lerda & Chollet (1) and Lerda & Cardelli (2) have found in previous studies that there is a connection between how good a swimmer is to coordinate the breathing action in front crawl swimming and their technical level. More expert swimmers tend to use shorter time on the inspiration of air compared to less expert swimmers (1). Furthermore more expert swimmers were found to have an improved ability to coordinate armstrokes and inspiration of air so that body balance and continued propulsion is more efficient also during the breathing action (2). Even so swimmers are often instructed to breathe as little as possible during 50 m sprint swimming, and during a 100 m race swimmers tend to reduce their breathing compared to longer distances.
The purpose of this study was to examine how breathing actions influence velocity during a 25m front crawl sprint by using two different breathing patterns compared to no breathing.

METHODS
Subjects
Ten competitive, Norwegian national level, adult swimmers volunteered to participate in this study (8 males and 2 females, mean±SD; age 25±3 years, personal best 50m freestyle 25.15±1.98 sec, season best 50m freestyle 25.62±2.19 sec). All subjects signed an informed consent after having the protocol explained to them both verbally and in writing.

Test protocol
Before start of the trial the subjects conducted a standardized warm up of about 1500m including four short sprints. The trial consisted of three 25m freestyle sprints with different breathing patterns conducted in a randomised order: a) 25m sprint with no breathing b) 25m with one breath after 15m of swimming c) 25m with one breath every stroke cycle. All breathing was to the subjects' preferred side. Each 25m sprint started every 4 minutes, giving the subjects about 3 min and 45 sec recovery between each sprint. During this recovery they had to swim one 25m to get back to start, the rest of the recovery was passive.

Measurements
Velocity measurements were carried out using a computerized swimming speedometer, connected to the swimmer via a thin non elastic line. The speedometer, attached to the pool side, consisted of the speedometer and a digitizing unit. The speedometer had a reel for the line which was set to give a small, but constant resistance on the line to ensure a trouble free outlet of the line. The line went from the reel via a small wheel to the hip of the swimmer. The small wheel (9 cm inn diameter) was connected to the axis of an incremental encoder (Leine & Linde nr IS630, Strängnes, Sweden) which gave 250 square pulses (0-5V TTL logic) for every rotation of the wheel. The swimmers pulled the line and the incremental encoder produced impulses for every turn of the small wheel. These pulses was digitized in a computer card (DAQ 6024E, National instruments, USA), and the signal was treated with Digital acquisition software LabVIEW 7 Express (National Instruments, USA).
Every impulse from the speedometer gave position data which the program smoothened by a floating mean of 10 measurements. The velocity was then calculated in the program by a mean of two positions. Fig. 1. shows an example of the velocity output vs time. Sampled frequency was 100 Hz. The coefficient of variation for the equipment used was calculated to <2 %.
A camera (Panasonic GS3, Japan) was used to film the swimmers above water while they swam each trial. This film was later used to find out the number of strokes performed in the 10m distance of the one breath trial, and how many breaths the swimmers had on the same distance on the breath every stroke cycle trial.
Data from mid-pool free swimming (10-20m) was extracted and used in all analyses.

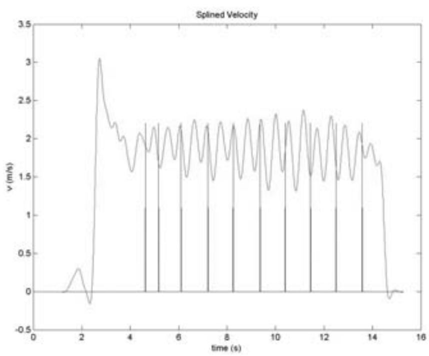

Fig. 1. Example of velocity vs time curve from the speedometer data. Vertical lines represent right arm entry.

Statistics
All data are presented as mean ± standard deviation. A paired t-test was used to determine difference between the trials where $p<0.05$ was considered significant.

RESULTS
There was no significant difference in mean velocity (v) between 10m of mid pool sprinting when the swimmers took one breath compared to no breath. To breathe once every 10 meters equalled about one breath every 3rd stroke cycle for the swimmers in this study. There was a significant ($p<0.05$) reduction in velocity when breathing every stroke cycle, compared to both no breath and one breath trials, see table 1. The swimmers in this study breathed 5-7 times over 10m of mid pool sprinting when breathing every stroke cycle.

Table 1: Mean velocity (±SD) from the three trials.

	No breath	One breath	Breath every stroke cycle
	v_{10-20} ($m \cdot s^{-1}$)	v_{10-20} ($m \cdot s^{-1}$)	v_{10-20} ($m \cdot s^{-1}$)
Mean (±SD)	1.74 (±0.14)	1.73 (±0.14)	1.70 * (±0.14)

** significant different from both no and one breath trials (p<0.05)*

DISCUSSION
The results indicate that swimmers at this performance level may breathe once every 3rd stroke cycle without loosing velocity due to breathing actions in front crawl sprint. If swimmers breathe every stroke cycle they may loose up to about 0.1 sec pr 10m of mid pool swimming.
Unpublished observations of 50m freestyle for males at the Norwegian Long course National championship 2004 showed that all the top 8 swimmers breathed 1, 2 or 3 times with at least 3 stroke cycles in between each breath in the final. Even though there was no significant difference between the one and no breath trial in this study, a difference of only 0.01 $m \cdot s^{-1}$ as found here represents a loss of 0.03 sec over 10 m swimming. Even at this performance level a loss of 0.03 sec because of one extra breath could mean 2nd place instead of 1st place. There were individual differences; the highest difference between no- and one breath trial was 0.04 $m \cdot s^{-1}$ or 0.15 sec. This indicates that all swimmers can gain by learning better breathing technique and breath control, but coaches should know that some individuals have even more to gain.
Furthermore, observations of the 100m freestyle race for both females and males in the same National Championship revealed that 100m freestyle swimmers seemed to vary what breathing pattern they choose, but most common was to breathe every 2nd, 3rd or 4th stroke cycle for the first part of the race, and than increase to every stroke cycle or every 2nd stroke cycle the last part of the race. Only a few swimmers choose to breathe as little as every 3rd or 4th stroke cycle throughout the race, amongst these was the winner of both male and female 100m freestyle. The main reason for swimmers to increase their breathing pattern the last part of a 100m race is caused by an urge to breathe more due to a lower partial CO_2 pressure in the blood caused by the high intensity of the swimming. Peyrebrune et al. (3) found no reduced performance based on physiological markers when swimmers breathed as little as every 4th stroke cycle, during 55 sec of tethered swimming. This indicates that the swimmers can choose to breathe as little as every 3rd to 4th stroke cycle without loss in performance due to either physiological factors or biomechanical factors (breathing action).

CONCLUSION
Coaches should stress breath control both in training and competitions and also teach effective breathing technique to avoid velocity reductions due to breathing actions. In a 50 m freestyle sprint the swimmers should breathe as little as possible, but during 100 m race swimmers must breathe more and can breath as often as every 3rd stroke cycle without to much

loss of velocity compared to breathing more often. To give accurate advice about which breathing patterns to use in 100m races, both individual differences in technique and physiological and metabolic variables must be taken into consideration. A further investigation in this matter seems necessary, combining biomechanical and physiological methods.

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BIOMECHANICAL ANALYSIS OF THE TURN IN FRONT CRAWL SWIMMING

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The main purpose of this study was to investigate the contribution of the dynamic and kinematic variables to the performance in freestyle. The turns of 38 swimmers were analyzing using an underwater force platform and two video cameras that supplied. Angle of knee flexion (AK), maximum normalized force peak (FPn) and contact time (CT) were measured as variables. Through investigation of the contribution of the variables AK, PMn and CT to the variable TT it was possible identify that PMn explains the greatest percentage of variance in turn performance (17,70%). The relation between AK and PMn indicated that larger values of AK (smaller flexions) tend to provide larger values of PMn (r = 0,38). Start from the results analysis, it can be suggested that angles of knee flexion between 110 and 120 degrees tend to provide larger force peaks, smaller contact times and smaller turn times, reaching the best performance of the crawl stroke turn execution.

Key Words: swimming, turn, biomechanics, flip turn, dynamometry, kinemetry.

INTRODUCTION

The final times of swimming tests can be influenced from the turns in up to 20% (6). The process of the biomechanical study of the turns developed by the Research in Aquatic Biomechanics Laboratory of the University of the State of Santa Catarina (UDESC) is described by Roesler (8) and is part of the studies (1), (5) e (7). The present research complements previous studies and researched parameters on improving performance of the turns, investigating the relationships between the variables: Maximum Peak of normalized force (PMn) and Time of Contact (TC) with the performance in the turn in it I swim Crawl (TV), through the time of turn in 15m.

METHODS

38 swimmers, integrant of the team of swimming of the Club “12 de Agosto” of the city of Florianópolis/SC, federated by Aquatic Federacy of Santa Catarina (FASC), participated in the research, chosen intentionally once they have domain over the technique of execution of the flip turn in front crawl swim. They have an average age of 18,2 years, average body mass of 63,8Kg, and average stature of 1,70m.
For the acquisition of the dynamic data, an underwater strain gauge platform (9) with sensitivity of 2N and natural frequency of 60Hz was used. The force plate was associated to a special support to be fixed to the inside of the turning wall of the swimming pool, in the vertical plan, and on the opposite side to the departure blocks, in lane 4. Once the platform cover is 0,2m thick, the black traces in the swimming pool bottom were modified to adapt to the new configuration, respecting the same official distance for the accomplishment of the turns.
For the kinematic data acquisition, a video camera Mini-DV Mega Pixel 3CCD (60Hz) inserted into a water proof box (camera 1), and a VHS camera with acquisition frequency of 60Hz (camera 2) were used. Camera 1 was located inside the swimming pool, allowing a underwater sight from the bottom to the top of the force platform. It was used for the assessment of the angle of knee flexion (AK). To determine the variable AK, a set of anthropometric landmark points were used (great trochanter, lateral epicondilus and lateral maleolus), made with coloured adhesive ribbon for the ulterior recognition in the video analysis. For the assessment of the turning time (TV) in 15m, camera 2 was located outside the water, 17,5m of the departure platforms, allowing a lateral sight of the swimming pool. The measurement of the turning time was initiated at the moment where the image of the swimmer's head reached the mark of 7,5m in direction to the turning wall, and finished when the swimmer's head reached again the mark of 7,5 m, but after the turn.
Data collection of was carried out during a training session. The swimmers warmed-up in accordance with the coach, trying successive impulses with the feet in the platform, in order to adapt themselves to the experimental conditions. Each swimmer started swimming from inside the swimming pool, under the departure blocks, reaching maximum speed at 12m from he starting wall, carrying through the turn and keeping the maximal speed until the 12m. This exercise was repeated 8 times with a resting interval of 12 minutes between each repetition.
The data obtained through the force platform has been separated and filed for swimmer, calibrated and filtered through a Butterworth filter from (30 Hz), and the normalization was conducted dividing the measured force archive by the weight of the swimmers, both carried through in system SAD 32 (10) supplying the PMn, which are the greater value registered of the force and the TC, that is the time during which the swimmer keeps contact with the platform. The swimmers weight was measured directly with a digital scale, Plenna, model MEA-08128 (0,1kg). For the assessment of AK, the images of camera 1 were used, selecting, through the edition images program *Adobe Premiere 6,5*, the picture where the swimmer carries through the maximum knee flexion when touching the force platform. The flexion angle was obtained using the program *Corel Photo-Paint* version 10.

For the statistical treatment it was used multiple linear regression, Pearson´s correlation coefficient for the group, and Spearman for the sub-groups, *One-Way Variance Analysis (ANOVA)* and descriptive statistics with level of significance of 95%. The *Post-Hoc* test of Scheffé was used.

RESULTS AND DISCUSSION
The swimmers carried through a total of 304 turns. However, in some variables, this number is reduced because the turn was considered failed for the attainment of that particular variable. These data are displayed in Table 1.

Table 1. Average, standard deviation and coefficient of variation of the studied variables.

VARIABLES	n	$\overline{X}$	S	CV%
Turn Time – TV: (s)	301	9,06	1,10	12,1
Maximum Peak of normalized force – PMn: (N/N)	293	1,38	0,38	27,5
Angle of Knee Flexion – AJ: (graus)	304	78,34	24,4	31,4
Time of Contact – TC: (s)	291	0,41	0,11	26,8

The smaller value of TV was of 7,08s and the higher was 11,24s, which are in accordance with previous reports (4), the best time of turn in 15m for the tests of 100m and 200m in Freestyle swim, in long course swimming pools (50m), is of 6,86s and 7,54s, respectively. Records of better turning times for short course swimming pools (25m) were not found in literature.
The biggest value of PMn was of 2,78N/N, the smaller value was of 0,61N/N. The biggest value for AK was 161 degrees and the smaller 29 degrees. For the discussion of the data was adopted as higher angles the values equal or above 100 degrees and as lesser angles the values equal or below 99 degrees. The smaller value of TC was of 0,18s and the higher one was of 0,8s.
When investigating the contribution of the PMn variable, TC and AK for the TV, it was observed that the PMn contributed with 17,7% for the turn time, and that the AK contributed with 4,8%. The smaller contribution came from variable TC, with only 1%. Therefore, the PMn variable presents the highest contribution value for the performance of the flip turn in front crawl stroke.
In the correlation between the variables studied, it was observed positive correlation between AK and PMn, indicating that a greater flexion angle of the knee tends to allow higher application of force in the wall during the turn and, consequently, faster turns. These results approach to the theory (12) when saying that the maximum torque of extension is gotten with 110 to 120 degrees of knees flexion. They are also in agreement with Takahashi et al. (11), authors that suggested that angles of knee flexion during the turn must be of about 120 degrees. Nevertheless they are opposing Counsilman (2), that suggests angles of flexion between 50 and 60 degrees.
Between TC and PMn, a negative correlation was observed, indicating that smaller contact times with the wall allow higher peaks for force application. The same negative relationship was obtained between AK and TC, indicating that higher angle of knee flexion seems to be associated to a low contact time.
To better interpret the data, a rank of the turn times was organized in groups: Group A (band of the 7 seconds), Group B (band of the 8 seconds), Group C (band of the 9 seconds) and Group D (band of the 10 seconds or more).
The results gotten with the variance analysis indicated that the groups distinguished significantly between themselves. It was evidenced, also, a reduction of the PMn values as the TV increases, allowing to state that the increase of the applied force is favourable to a reduction of the turn time, improving the performance of the swimmer. This reduction is significant when times of groups A and B are compared. For variable AK the values get smaller when the turn times increase, confirming previous results: greater angles of knee flexion tend to favour higher force peaks and better performance in the turn. This difference was significant only for the groups A and B. For the TC, increased values were noticed with increased turning times, presenting significant differences for groups A and C. Investigating the correlation between the variable in the groups, Group A presented higher correlations between AK and TC ($r = -0,429$, $p = 0,018$) and between AK and PMn ($r = 0,38$, $p = 0,038$), strengthening the results obtained for the variable without the separation in groups for turn times. In Group B, the correlation between AK and TC was $r = -0,297$ ($p = 0,007$), AK and PMn, $r = 0,216$ ($p = 0,049$) and between PMn and TC with $r = -0,406$ ($p = 0,000$). In this group the higher angle of knee flexion tend to be associated to highest peaks of force and smaller contact times, so to better performance in turns. In Group C significant correlations were found for variables AK and PMn ($r = 0,439$, $p = 0,000$), and AK and TC ($r = -0,232$, $p = 0,024$). For Group D, all the correlations had been positive for low times of turn suggesting that these swimmers have an inferior turn technique comparing to the swimmers of the groups of lower times. Although, in Group B it has a correlation between the TC with the other variable (PMn and AK), and the Group A did not have a significant correlation, the general average of the contact time for this group was lesser, thus explaining, in part, the lowest time of these swimmers.

CONCLUSION
It was possible to identify PMn as the variable that mostly contributes to the performance of the turn during front crawl swimming. We can also suggest that flexion angles of the knee between 110 and 120 degrees tend to allow higher peak forces, lower contact times, and lower turning times, providing higher performances during the turning action in front crawl swimming. These results may promote the development of training programs with planning focused in correcting and improving the turning technique.

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BIOMECHANICAL ANALYSIS OF THE UNDERWATER PHASE IN SWIMMING STARTS

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This study analyzed, through kinemetry, the underwater phase of the swimming start. The sample was composed by 4 swimmers of national and state levels. Three VHS video cameras (30Hz) and signal synchronizer equipment were used. Analyzed variables: maximum depth achieved, time, distance and average velocity of the underwater phase and total start time in 15 meters. The maximum depth achieved after the entrance in the water had influenced significantly the underwater phase. The average velocity during this phase seems to be the variable which most affects the total start time in 15 meters. Maximum depth achieved and average velocity are important factors to be observed by athletes and coaches, who should look forward to perform best values of those variables in order to improve the execution of swimming starts.

Key Words: biomechanics, swimming, start, underwater phase.

INTRODUCTION
The swimming start can represent between 0.8% and 26.1% of the overall race time depending on the event distance (1) and, on average, the improvement of the start technique can reduce the event's total time in at least 0,1s (3).
Several studies analyzed the start variables observed during the block and flight phases, previously the water entrance: time (reaction time, impulse time and block time), impulse (vertical, horizontal and resultant), angles (take-off angle and angle of entrance in the water), distance of flight, etc. (3, 4, 5, 6). Despite of analyzing only the block and flight phases, these authors cite the importance of the underwater phase in the swimming start. Even so, studies which do reference to this phase are scarce (1, 6, 7, 8, 9) and show, in the majority of the times, distance and time values observed during the underwater phase. According to Cossor and Mason (1), beyond values of time and distance travelled under the water, the maximum depth achieved after the water entrance is an important factor to be observed, therefore can influence significantly the underwater phase during the swimming start.
The authors of the area recognize the importance and representation of the underwater phase regarding the performance of swimming start. The considerations presented by most of these authors, suggesting the need of analyzing the underwater phase subsequent to the entrance in the water, stimulated the main objective of this study: analyze, through kinemetry, the underwater phase of the swimming start.

METHODS
The sample was composed by 4 swimmers of national and state levels (Florianópolis, SC, Brazil), and chosen deliberately, by being specialists in strokes whose starts are performed from the starting block (freestyle, breaststroke and butterfly). The main characteristics of the subjects were: 20.0 (±3.7) years of age, 74.3 (±7.04) kg of mass, and 182.0 (±0.03) cm of height. For data collection three VHS cameras (30Hz) were used. Two of them were coupled to watertight boxes and were both positioned inside the water, distant 5 meters and 10 meters of the starting wall, enabling the acquisition of the variables: *maximum depth achieved* (maximum depth reached by the swimmer after the water entrance, observed in the moment that the swimmer's head reaches the deepest point under the water surface); *underwater phase distance* (distance from the point of the head entrance in the water to the point of the first arm stroke begins); *underwater phase time* (time elapsed from the moment of the head entrance in the water to the beginning of the first arm stroke); *average velocity of the underwater phase* (average velocity reached by the swimmer since the entrance in the water to the beginning of the first arm stroke). The third camera was positioned outside of the water to provide a lateral view of the swimming pool in order to obtain the variable *total start time in 15 meters* (time elapsed since the start signal to the moment that the swimmer's head reached the mark of 15 meters).
To synchronize the start signal to the kinemetry a starter device was used. This equipment is instrumented to simultaneously produce the starting sound and export a LED signal to the video system, allowing data synchronization.
Data collection was carried out in the swimming pool of the Doze de Agosto Club (Florianópolis, SC, Brazil). Each swimmer performed 6 starts with a 5 minutes rest period. Immediately after the start, the athletes had to perform the Crawl stroke at maximum speed up to opposite wall, totalling up 25 meters. The starting procedures conformed to the swimming rules of an official competition.
The *InterVideo WinProducer 3* software was used to digitize data. According to the analyzed variable one selected the charts originating figures. The image files were exported and analyzed by Microsoft® MsPaint and Corel Photo Paint® 10 softwares.
Data were treated using common descriptive statistics and Pearson's Correlation ($\alpha = 0.05$).

RESULTS AND DISCUSSION

The main results of the study are presented in Table 1.

Table 1. Values of average ($\overline{X}$), standard deviation (s) and relative standard deviation (RSD) of variables maximum depth achieved (DP), underwater phase distance (UPD), underwater phase time (UPT), average velocity of the underwater phase (UPV) and total start time in 15 meters (T15m).

	$\overline{X}$	s	RSD (%)
DP (m)	1,10	0,18	16,98
UPD (m)	5,75	0,87	15,11
UPT (s)	2,18	0,53	24,39
UPV (m/s)	2,70	0,36	13,42
T15m (s)	6,97	0,25	3,65

It can be noticed that the total start time in 15 meters presents the smaller variation (3,65%) when compared to the other variables, indicating that, even performing similar starting times, the swimmers presented heterogeneous values for the variables observed during the underwater phase. It suggests that this phase is intimate connected to the individual characteristics of each subject, like the streamline position and the underwater stroke technique used, being still influenced by several factors and actions that happen since the instant of entrance in the water to the beginning of the first kicking and the first stroke movements.

In order to verify the relationship of the variables observed during the underwater phase with total start time in 15 meters Pearson's correlation was used ($p<0.05$). Table 2 presents the values of "*Pearson's r*" for the correlation between the total start time in 15 meters (T15m) and the variables maximum depth achieved (DP), underwater phase distance (UPD), underwater phase time (UPT) and average velocity of the underwater phase (UPV).

Table 2. Values of "Pearson's r" *for the correlation between T15m and DP, UPD, UPT and UPV.*

CORRELATED VARIABLES	n	r
T15m x DP	24	0,515*
T15m x UPD	24	0,109
T15m x UPT	24	0,376
T15m x UPV	24	- 0,645**

* p<0,05 ** p<0,01

n = number of analyzed starts

It can be observed that the total start time in 15 meters was significantly correlated with the maximum depth achieved (r=0.515) and with the average velocity of the underwater phase (r=-0,645).

The significant coefficient of correlation observed between T15m and DP indicates that higher values of maximum depth correspond to higher values of T15m. Counsilman et al. (2), even without carrying out the correlation between these variables, verified that, on average, the slowest starts were performed when the swimmers presented higher values of depth achieved.

Average velocity of the underwater phase was negatively correlated at a significant level ($p<0.01$) to the total start time in 15 meters, which indicates that higher values of average velocity during the underwater phase correspond to slower starts.

Despite of UPV is a derived variable from UPD and UPT, these did not present significant values for the correlation with T15m (r=0,109 and r=0,376 respectively). This fact suggests that, more important than the distance travelled or the time elapsed under the water, is the great combination between those variables, requiring from the swimmer the ability of minimizing the water resistance and maximizing the propulsion during the underwater phase, performing a longer distance in a shorter time. In order to confirm the importance of the underwater phase to the start performance in 15 meters, Cossor and Mason (1) combined the variables flight distance and flight time; underwater distance and underwater time; and time and distance of the first arm stroke. They verified that the combination of underwater distance and underwater time was the one which more affected the total time in 15m, suggesting that there is a strong relation between the velocity during the underwater phase and the start performance.

Rabalais (4) affirms that one of the factors that affect the underwater phase during the swimming start is the depth reached by the swimmer after the water entrance, which may influence the distance travelled and the time elapsed under the water. In order to confirm the information found in the literature one carried out the correlation between the maximum depth achieved (DP) and the variables underwater phase distance (UPD), underwater phase time (UPT), average velocity of the underwater phase (UPV) and total start time in 15 meters (T15m).

Table 3 presents the values of "Pearson's r" for the correlation between DP and the variables UPD, UPT, UPV and T15m.

Table 3. Values of "Pearson's r" for the correlation Between DP and UPD, UPT, UPV and T15m.

CORRELATED VARIABLES	n	r
DP x UPD	24	0,778**
DP x UPT	24	0,910*
DP x UPV	24	- 0,838**
DP x T15m	24	0,515*

* p<0,05 ** p<0,01

n = number of analyzed starts

Concerning the influence of the DP values in the underwater phase, it was observed a significant correlation between the maximum depth achieved and the variables underwater phase distance, underwater phase time and average velocity of the underwater phase (r=0,778, r=0,910 and r=-0,838 respectively). The correlation coefficients indicate that higher values of DP correspond to higher values of UPD and UPT, at the same time, to smaller values of UPV.

Cossor and Mason (1) suggest that the depth achieved is related to the total time in 15m. One carried out the correlation between DP and T15m and observed a significant coefficient (r=0,515), which indicates that higher values of depth achieved correspond to bigger values of total time in 15m, therefore, slower starts.

CONCLUSION

The characteristics of the underwater phase are inherent to each subject and depend on several factors that happen since the start signal until the beginning of the first stroke movement, requiring from the swimmer the ability of combining actions in order to minimize the resistance forces and maximize the start performance in all of its phases.

The depth achieved after the water entrance and the velocity performed under the water are both important factors to be observed by athletes and coaches, which should look forward to reach best values of those variables in order to improve the execution of swimming starts. It suggests that the swimming start analyses should contemplate, beyond the block and the flight phases, the underwater segment, that is an essential phase to be considered for the determination of performance parameters of the start in swimming.

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RACE PACE CONTROL BY MEANS OF A NEW CHRONOMETER SYSTEM

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This paper describes a new chronometer system that provides feedback in real time and without interfering with the swimmer's execution. The system consists on a leds screen (water resistant) installed on the bottom of the pool, so that swimmers can see it every time they perform a turn. This system can be connected to a PC or PDA, which permits register lap times for further analysis. Feedback provided by the chronometer to control swimming speed was compared with the condition "traditional feedback" provided by the coach and with the condition "no feedback". Results show little dispersion on lap time with this new kind of feedback at aerobic swimming speed. At an anaerobic threshold swimming speed, dispersion was similar between "traditional feedback" and chronometer feedback, and a little more dispersion in "no feedback" condition.

Key Words: chronometer system, race pace control, feedback, biomechanics.

INTRODUCTION

Compared with other terrestrial sports, coach-swimmer communication during training is a very difficult task. However, numerous studies indicate the importance to provide real time feedback for technique improvement (1). The lack of feedback can harm the swimmer learning. In this direction, in the past few years there has been an increasing interest in systems that permit guide swimmers speed and/or systems which permit coach-swimmer communication.

Most of these systems are based on some kind of optical devices that guide the swimmer along the swimming pool (2). These are useful systems, but they only guide swimmers speed with no other kind of feedback. Other systems allow effective coach-swimmer communication using a snorkel with FM and a transmitter base station (3), but the system interferes with swimmer execution.

The aim of the present communications is double: first, to present a new chronometer system that provide real time feedback without interfering with swimmer's execution and, second, to evaluate three different ways to provide feedback to swimmers in order to control swimming speed (and, in a future second phase of the project, "key words" from the coach to provide feedback concerning technical aspects).

METHODS

Six male (age = 16´48 ± 1´10; height = 1´756 ± 0´084 m; mass = 71´29 ± 3´51 kg) well-trained swimmers of national level volunteered for the study. All subjects provided written consent before participating in the study.

1) The chronometer system

We have developed a chronometer system, called SwimTimer (figure 1), based on a leds screen (figure 2) installed on the bottom of the pool, so that swimmers can see it every time they perform a turn. The leds screen receives information from a contact platform placed on the wall of the swimming pool, so that, when swimmers contact it, the chronometer switches on. Lap, total time and lap number can be seen by swimmers and registered by a PC or PDA (figure 3). The system allows to control six swimmers (same order) on the same line. We are working, too, in the possibility that coach could write a little text (key words) to provide technical feedback to swimmers.

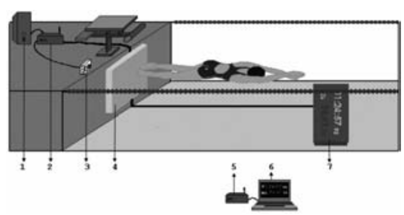

Figure 1. Chronometer system Scheme: 1) battery, 2) and 5) telemetric system, 3) start-stop control, 4) contact platform, 6) PC or PDA, 7) leds screen and subaquatic box.

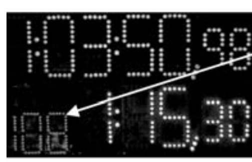

Figure 2: Leds screen putted on the bottom of the pool on the top [green] total time, rigth bottom [red] lap time and left bottom [green] number of laps.

Figure 3. Software on a PC.

2) Feedback tests
Each swimmer swam 200 m under three feedback conditions (independent variable): (1) without feedback, (2) with chronometer system and (3) traditional (coach) feedback. These three conditions were evaluated under two different speeds: aerobic speed and anaerobic threshold speed. These swim speeds were individualy determined by the coach. Lap time for every 50 m was recorded.
Statgraphics v.4.0 was used to perform a descriptive analysis and an ANOVA for repeated measures, for factor "kind of feedback" with the levels above indicated. The level of significance was set at p < 0´05. This analysis was performed for both swim speeds.

RESULTS
Table 1 shows the results for the dispersion (variance and range) descriptive statistics for the aerobic speed condition. As it can see, at the aerobic speed there are less dispersion on lap times with feedback provided by the chronometer system, while dispersion with traditional feedback and without feedback are more or less the same.

Table 1. Dispersion data for lap times at the aerobic speed condition.

Aerobic swim speed	Without feedback	Traditional feedback	Chronometer system
Variance	2´3382 s	2´1154 s	0´9756 s
Range	4´92 s	5´0 s	3´23 s

At the anaerobic threshold speed, dispersion data on lap times were very similar between feedback provided by chronometer system and by coach, while condition without feedback presented a little more dispersion.

Table 2. Dispersion data for lap times at the anaerobic threshold speed condition.

Anaerobic threshold swim speed	Without feedback	Traditional feedback	Chronometer system
Variance	1´7554 s	1´1433 s	1´1317 s
Range	4´76 s	3´86 s	3´28 s

ANOVA analysis show no significant difference among mean values (p > 0´05 for both speed conditions), as it can see in figures 4 and 5.

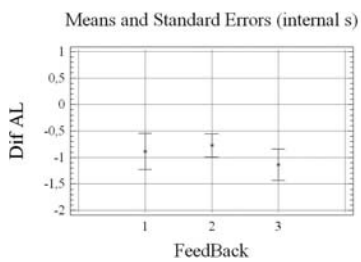

Figure 4. ANOVA do not show differences in mean values for the aerobic swim speed. 1 = without feedback, 2 = chronometer feedback, 3 = traditional (coach) feedback.

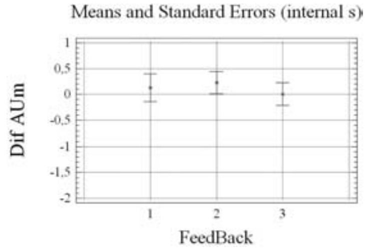

Figure 5. ANOVA do not show differences in mean values for the anaerobic threshold swim speed. 1 = without feedback, 2 = chronometer feedback, 3 = traditional (coach) feedback.

DISCUSSION
Results show little dispersion on lap time with this new kind of feedback at aerobic swim speed. At an anaerobic threshold swim speed, dispersion was similar between "traditional feedback" and chronometer feedback, and a little more dispersion in "no feedback" condition. The reasons why these differences on results between aerobic and anaerobic threshold speeds are not clear, so that, more studies with a greater sample are necessary. However, results show similar data dispersion in aerobic and anaerobic speeds when using the new system which indicates its validity and interest.

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THE INFLUENCE OF TUCK INDEX, DEPTH OF FOOT-PLANT, AND WALL CONTACT TIME ON THE VELOCITY OF PUSH-OFF IN THE FREESTYLE FLIP TURN

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Effective turns play a critical role in the outcome of swimming competition. The purpose of the study was to investigate the effect of three variables on the velocity of the push-off during the freestyle flip turn. The variables are: (a) the distance of the hips from the wall at foot contact (Tuck Index); (b) the depth of the foot plant on the wall during push-off; and (c) wall-contact time (WCT). Twenty three collegiate swimmers participated in the study. Following underwater video-taping, 2D analyses in the saggital plane were made using Motion Analysis software. Statistical analysis of the data found a significant, negative correlation between push-off velocity and Tuck Index. No significant correlations existed between push-off velocity and foot-plant or between "active" WCT and push-off velocities.

Key Words: freestyle flip-turn, push-off velocity, 2D analysis.

INTRODUCTION
Effective turns play a critical role in the outcome of swimming competition. In short-course events, turns comprise up to one-third of the total race time (7, 15, 16). While mid-pool swimming velocity is the primary determinant of race performance at the elite level (11) it does not necessarily indicate a similar proficiency in turning technique (12). In the 2000 Olympic Games in Sydney, Australia, the performances of finalists and semi-finalists in the 200 meter events were studied for the start phase, swimming velocity, stroke frequency, stroke lengths, and turns. One of the study's conclusions was that the velocity of the final turn was a differentiating factor between medalists and non-medalists (5). Consequently, at elite competitive levels, although mid-pool swimming velocity is the primary determinant of race performance, the turns have the potential to determine a winner among swimmers with the same mid-pool swimming velocities.
Kinematic examination of swimming turns have included such parameters as the velocity of the swimmer when approaching the wall; the orientation of body during wall contact; time spent on the wall; orientation of the body during push-off; timing of the initiation of the kick and arm stroke; and the total time taken to complete the turn (1-3, 9, 10, 15, 17). How about "The push-off phase of the turn can be broken down into several components for analysis. These components include Tuck Index, Foot Plant Position, and Wall Contact Time (WCT).
Tuck Index measures how close a swimmer's hips are to the wall at the start of push-off, relative to leg length (1, 2). It is defined as the distance of the greater trochanter of the femur from the wall at foot contact, divided by the actual trochanteric height. A higher number indicates straighter legs at wall contact. Previous analyses of freestyle and backstroke turns have indicated that higher tuck indices (straighter legs at wall contact) are correlated with faster turns (1, 2). One study found that peak forces were generated when the knee was flexed at 120 degrees (14). However, it is clear that a turn performed with the legs in an excessively straight position at wall contact (very high Tuck Index) would not allow the leg muscles the opportunity to generate optimal muscular force (8, 13).
A second component of the push-off phase is the depth of foot plant below the surface of the water. No research published to date has examined the effect of the foot plant position on the ensuing push-off. The foot plant position has the potential to alter the trajectory of the body at push-off. Positioning the feet too high on the wall may result in a push-off with a deep trajectory. In contrast, positioning the feet too far below the surface may result in the swimmer surfacing too quickly.
Total wall contact time (WCT) is the third component of the push-off phase and may be divided into two segments, a "preparatory" segment and an "active" segment. The "preparatory" segment occurs prior to forward motion, beginning when feet make contact with the wall, and ending at the moment before the hips make their first forward displacement. The "active" segment of WCT begins at the first forward displacement of the hips and ends when the feet leave the wall. In freestyle and backstroke turns it has been reported that shorter overall WCT resulted in faster turns, higher peak forces, and faster peak velocities upon push-off (1, 2, 4). However, in examining the two segments of WTC, a longer "active" segment of WCT is reported to be associated with faster velocities upon push-off. One study examining "active phase" of the push-off of elite swimmers reported values ranging from 33% - 94% of the total WCT (9). Consequently, exploring the ideal percentage of total WCT spent in the "active" phase of pushing off may help optimize turning technique.
The purpose of this study was to examine the effect of three variables on the velocity of the push-off during the freestyle flip-turn. These variables are: (a) the distance from the wall a swimmer's hips should be at foot contact (Tuck Index); (b) the depth of the foot plant on the wall during push-off; and (c) the wall-contact time.

METHODS
Twelve male and eleven female members of a United States University -Division I swimming team participated in the study. Subject ages ranged from 19 to 25 years. Each subject was required to perform a series of trials, each trial consisting of a 50-yard freestyle swim over a 25 yard (22.5 m) course which included one turn. Subjects were instructed to perform the flip turn at race pace, swimming at maximum speed for 5 meters before and after the turn. Each turn was videotaped from underwater using a single digital camera. The camera was placed at a depth of half a meter below the surface, and located 2 meters from the end of the pool and 7 meters laterally to the turning surface. A four-point calibration rod was used as a scaling factor for the kinematic analysis. Two-dimensional analyses of saggittal planar movements were conducted using motion analysis software (Vicon/Peak, Denver, Colorado).
The dependent variable selected was the push-off velocity, the average velocity taken to cover the first 60 centimeters upon leaving the wall, as measured by displacement of the hips. Independent variables selected for analysis included tuck index, foot plant index and %WCT Active. Tuck index is defined as the distance of the greater trochanter of the femur from the wall at foot contact, divided by the actual trochanteric height (measured from the ground to the greater trochanter). Foot-plant index is the distance from the ankle to the surface of the water, divided by trochanteric height. %WCT Active is the percentage of the total wall contact time spent actively pushing off the wall. A Pearson correlation matrix was established to investigate the strength of the bivariate association between each independent variable (tuck index, foot-plant index and %WCT Active) and the dependent variable (push-off velocity). Simultaneous regression analysis was conducted using the push-off velocity as a dependent variable to determine the overall predictive characteristics of the variables.

RESULTS AND DISCUSSION
Push-off velocity
The mean push-off velocity for all turns analyzed, males and females combined, was 2.47 ± .40 ms^{-1}, with a minimum value of 1.3 ms^{-1} and the maximum value of 3.29 ms^{-1}. The mean push-off velocity for males in the present study was 2.69 ±.34 ms^{-1}. As a means of comparison, the mean push-off velocities of 30 experienced male swimmers with a mean age of 19.8, were reported as 2.75 ±.25 ms^{-1} (9). Another study which measured push-off velocity on trained young swimmers aged 10 to 14 years old reported average values of 1.14 ms^{-1} (6).

Tuck Index
Tuck Index can be used to indicate how close a swimmer is to the wall after the foot plant. A higher Tuck Index indicates straighter legs. In the present study, the mean Tuck Index of all turns was 0.57 ± 0.14, indicating that the hips were at a

distance from the wall that was approximately 57% of the trochanteric height. Tuck Index was the only significant predictor of push-off velocity in the present study. Tuck Index was negatively correlated with push-off velocity, indicating that the more tucked position (lower Tuck Index) predicted higher push-off velocity. This result appears to contrast with previous studies, which indicated that a higher Tuck Index results in a faster turn (1, 2, 4). However, these studies calculated round-trip time by measuring the time taken to travel in and out of the turn from a prescribed distance from the wall, either 2.5 or 5 meters. In these cases, the time for the round trip can be shorter because the center of mass of the measured body segment is further from the wall upon foot contact. It is important to note that both methods of evaluating flip-turn performance have their weaknesses. When using round-trip time, it is not possible to discern the actual velocity of the push-off. When using push-off velocity, the overall time it takes to perform the turn is not taken into account. As a result, the optimal Tuck Index value of 0.46 is specifically for optimizing push-off velocity, and may not result in an optimal round-trip time. While no research to date has explored the curvilinear relationship between Tuck Index and push-off velocity, the relationship is a logical one. Performing a flip-turn with the hips either extremely close to the wall, or in an excessively straight position, would not allow the leg muscles the opportunity to generate optimal muscular force. This concept was illustrated in a study that examined optimal take-off range in vertical jumping by requiring track athletes to perform squat jumps and countermovement jumps using a force platform (8). Squat jumps performed with legs close to full extension produced approximately 25% less vertical ground reaction force than those with the more optimal starting position. While these numbers do not take into account possible variations in leg length, they provide general support for the concept that the relationship between Tuck Index and push-off velocity may be a curvilinear one. It should be noted, however, that trained swimmers perform their flip-turns with very little countermovement, so it may be more appropriate to examine squat jump rather than countermovement jumps when making comparisons between jumping and flip-turns.

Foot-plant index

Foot plant index was developed as a way to measure the distance of the feet from the surface of the water while taking into account the length of the swimmer's leg. A higher number for foot plant index indicates a deeper foot plant. The mean foot plant index in the present study was 0.45 ± 0.10, indicating that the mean foot plant was approximately 45% of the swimmers' leg length below the water. No other research has been conducted to date examining the depth of foot plant and possible implications for flip-turn performance. Thirty-three of the 109 turns in the present study resulted in glides that were performed above the 0.40 meter depth. While no significant relationship was found between foot plant index and push-off velocity, further examination of the present data could examine the link between foot plant index and push-off depth.

Wall Contact Time

The mean WCT of turns rated "normal" was 0.28 seconds. This value was the lowest when compared to other studies which reported times ranging from 0.29 to 0.32 seconds in experienced adult swimmers who have been studied (9, 10). The mean percentage of the wall contact spent in the "active" push-off phase was 74.3%. The minimum percentage was 35%, and the maximum was 95%. One previous study found that the active push-off segment of elite swimmers ranged from 33% to 94% of the total WCT, with a mean of 67.5% ± 15.2% (9). The positive correlation in that study indicated that longer active segments resulted in faster final push-off velocities. However, in the present study, no significant relationship was found between % WCT active and push-off velocity.

CONCLUSIONS

The following conclusions may be of practical value for the coach:

— Since the values of the push-off velocities in this study reasonably matched with other studies of elite swimmers, ie. those competing at the national and international levels, we can deduce that once a certain level of performance is achieved, swimmers tend to drive off the wall at a fairly predictable velocity. The fact that younger swimmers tested show velocities that are almost half that of the elite groups, implies a on-going need to address this aspect of the turns.

— When examining how close the wall should be approached, as measured by the Tuck Index, the study found that, up to a point, the closer the hips are to the wall at foot-plant, which imply a higher degree of knee flexion, the higher the velocities of push-off. Therefore, it is better to be closer than further from the wall when starting the push-off.

— The depth of the foot-plant for elite swimmers performing the freestyle flip turn appears consistent. However, the range of values that are seen with less experienced swimmers, clearly affecting the trajectory of the body, is a strong reminder of the need to refine turning skills.

— Although this study did not find a clear association between how long the feet should remain on the wall once the knees start to extend, ie. the "active phase of wall contact time", it may be counterproductive to shorten this period of the turn. Consequently, it is better for the swimmer to maintain a firm footing on the wall during the push-off rather that attempting to "bounce" the feet off the wall during the turn.

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INFLUENCE OF TIMING DELAY ON MONOFIN INTRACYCLE SWIMMING VELOCITY

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The aim of the study was to analyze the temporal delay of the body segments and monofin movements while generating propulsion. Swimmers were filmed under water while covering 50m distance without breathing. Input data as time series of kinematics parameters of the points marked on the swimmers bodies and on the monofin were recorded on the basis of randomly filmed single cycles for each swimmer. The data showed inversely proportional relationship between the sum of vertical velocities of the reference points (ΣVVER) and the horizontal velocity of the swimmers' center of mass, indicating the significance of the ΣVVER in generating propulsion. Our study further indicated that the analysis of temporal delays of the time structure in the body segments and monofin tailored for swimmers according to the leg movements and equipment used will allow elimination of the hip and the lower thigh mistakes.

Key Words: monofin, kinematics, technique quality, dynamic statistics.

INTRODUCTION
The mechanics of propulsion classifies monofin swimming as analogous to tuna fish swimming (1). This type of locomotion consists in generating propulsion mainly by caudal fin with the use of unstationary flow (6). The propulsion effect is determined by the shape and trajectory of the fin action, which is the consequence of its shape and flexibility, as well as the leg movements. These factors are described by dynamic and kinematic parameters (1, 2, 3, 4). As it is known, due to the non-parallel water flow along the surface of the monofin, difference in pressure is generated due to the differences in speed of flow caused by the change in angular parameters (angle of attack and angular velocity) of these surfaces' movements. Angular parameters, through their relations with lift (and indirectly with drag), are correlated with the resulting force propelling the swimmer (3). The shape and trajectory of movement also affect the value of additional components of the propulsion force resulting from the vortex around the fin's surface (6) and from the use of additional mass of water a swimmer uses to push oneself in direction opposite to swimming (1). These components are present as the momentum generated by the segments of the biomechanical chain (in a certain time sequence, during the swimming cycle) In this context, the quality of swimming technique may be defined by maximizing of the momentum transferred in water or their most effective transfer through consecutive legs and fin segments. In all cases there is a rule of balance of momentum, which in the aspect of constant speed in the swimming cycle, is the basis for developing criteria for the quality of technique. High stability of the swimming speed is represented by the parameters' features determining it (2). Therefore, delay of these parameters with respect to swimming velocity is also the measure of the monofin swimming technique, which can be quantified with the use of dynamic statistics tools (cross correlation and retardation). This study aims at analyzing the retardation of the body segments and monofin movements while generating propulsion to resolve the problem of efficiency and effectiveness of fin swimming. Such analysis is possible because the legs and monofin movements occur in one dimension. This describes explicitly the transfer of momentum mechanism during undulatory movements. Moreover, a fin surface, due to its size, is treated as the main source of propulsion.

METHODS
16 men – participants in Monofin Swimming World Championships - were filmed under water while covering 50 m distance without breathing. A digital camcorder was placed in the middle of the pool. The equipment parameters, filming procedure and computer movement analysis (SIMI) were compliant with the ISO 9002 standards. Input data as time series of kinematics parameters of the points marked on the swimmers bodies and on the monofin were recorded on the basis of randomly filmed single cycles for each swimmer (frequency - 50 Hz) (fig. 1). Reference points were the following: middle finger, wrist, elbow, shoulder, hip, knee, ankle, as well as tail, middle and edge of the fin. Each of the parameters was recorded during the test, after which the average was calculated. On the basis of the analyses of the sums of vertical velocities of the reference points reduction of data was carried out, which limited the calculation to the analysis of legs and fin movements. The basis for this was the classification of the monofin swimmer's movements to the category of tuna movements, (1) (Highest fluctuation in the vertical velocity referred to the legs and fin movements respectively, and the vertical actions of the upper body were insignificant). Preliminary analysis showed also (fig. 2) inversely proportional relationship between the sum of vertical velocities of the reference points (ΣVVER) and the horizontal velocity of the swimmers' center of mass

(VHOR). This shows the significance of the (ΣVVER) in generating propulsion. The role of it is due to the correlation: the lower the ΣVVER fluctuation, the higher the VHOR stability. The speed stability in the cycle is the effect of the balance between the momentums generated as a result of the monofin propulsion movements (2). It seems logical then that the temporal delays in the momentum transfers in the swimmers leg – monofin chain water will have an adverse effect on the swimmer's speed. Therefore, the main part of analysis was based on the calculation of the cross correlation coefficient and retardation with the average function of recorded parameters (movements in leg joints and in reference points in tail (T), in the middle (M) and on the edge (E) of the monofin) with respect to VHOR (Fig. 2). On the basis of CC ≥ 0,7 values, 16 parameters were assigned, which were assumed to be significant for the swimming speed. These parameters are the following: trajectories - vertical of the hip movement (HIP), knee (KNEE), ankle (ANKLE) and the fin's tail (TAIL); angles of knee flexion (H-K-Aα), in the monofin's tail against foot and the middle of the fin (front part (A-T-Mα)), in the fin's tail against foot and edge (entire surface (A-T-Eα); angular velocities of flexion in hip joints (S-H-Kω) and ankle joints (K-A-Tω) as well as the entire fin's surface against foot (A-T-Eω); angles of attack (against tail) of the front part of the fin (T-M-Hα), and its end part (M-E-Hα), as well as the entire fin's surface (T-E-Hα); angular velocities of attack (against tail) of the fin's front part (T-M-Hω), its end part (M-E-Hω) and its surface (T-E-Hω). The results were empirically verified based on the analysis of directly input data (Fig. 1, 2).

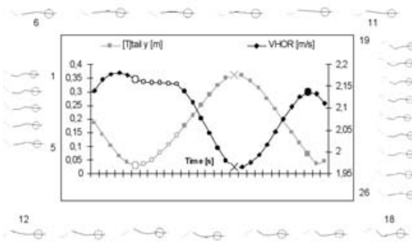

Fig.1. Description of average breakdown of monofin's tail (T) trajectory against horizontal velocity of the center of mass (VHOR), illustrating the way in which a movement cycle is differentiated from the total cycle and consecutive legs and monofin sequences.(● – start of cycle; ❍ – most stable part of cycle (seq.6-11); ✖ – time of movement shift monofin's tail up to down, ■ - end of cycle).

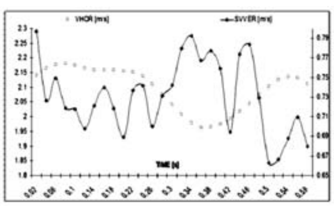

Fig. 2. Correlation between the sum of vertical velocities on points on the swimmers body and monofin (ΣVVER) against horizontal velocity of the center of mass (VHOR).

RESULTS

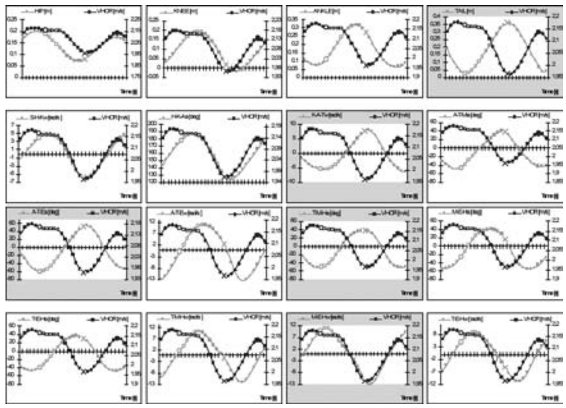

Fig. 3. Graphs illustrate average breakdown of the parameters in the biomechanical chain leg-monofin against horizontal swimming speed. Function graphs with '0' retardation - marked grey.

DISCUSSION

The parameters of legs and monofin movements correspond to the parameters, which had been specified on the basis of the neural network development (4). We have identified parameters describing angles of attack and angular velocities of legs and monofin parts. In this way, we have developed the basis for validation of the diagnostic value of the method based on statistics tools.

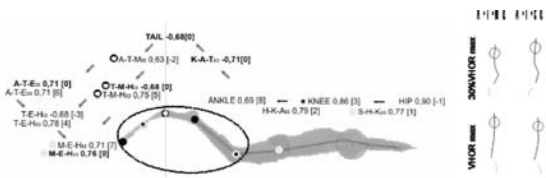

Fig.4. Interpretation of balanced and stable mechanism of momentum transfer based on the correlation between parameters of legs and monofin movements against tail as the transfer point (marked with similar points). Segments marked in the ellipse and sequences A-T-Mα and A-T-Mα are analogous to "tuna like" propulsion mechanism (1).

The analysis of the cycle's parts where horizontal velocity is most stable shows many regularities (Fig. 2, 4). The analysis of trajectory HIP against VHOR shows how the hip movement contributes to maintaining constant intra-cycle velocity. Slightly higher speed of HIP in relation to VHOR (R=-0,02s) is caused by an early start of the hip downward movement. S-H-Kω has a strict correlation with VHOR, (R=0.02s). Intervention in the structure of hip movement (assuming the rigidity of the corpus) suggests the extension of time in which the speed of lowering hips is highest. In the case of the trajectory KNEE and A-K-Tα (R= 0.06s and 0.04s) it is feasible to maintain constant VHOR thanks to an earlier commencement of the knee upward movement and their earlier extension. ANKLE trajectory with respect to VHOR shows retardation (0.16s) which is suggested by the earlier ankle upward action and its limited scope of movement. Time structure of K-A-Tω precedes VHOR changes and causes the fall of the retardation to zero. Limiting the angular velocity of hip and feet upward movement contributes to maintaining constant, high swimming velocity. High correlation and the lack of temporal delay between VHOR and TAIL, as well as A-T-Eα trajectory suggests the limitation in feet and fin upward movement which sag at an angle showing parallel distribution of its segments. Similarly, increase in A-T-Eω contributes to maintaining constant VHOR. In the context of the retardation (0.12s), limiting VHOR decrease means flexing the tail while aiming at maximizing the speed. In the case of A-T-Mα stability, VHOR is helped by the positioning of feet and the front part of the fin in one line. Slight overtaking of VHOR by the action of the tail flexion (-0.04s) is due to the latter's early flexion. High correlation and the lack of retardation was recorded between VHOR and T-M-Hα. Maintaining constant velocity in the cycle is helped by lifting the front part of the fin to the position parallel to the swimming direction. In the case of T-E-Hα, slight overtaking of VHOR by the attack angle of the whole surface (-0,06s) suggests a longer period of its edge downward movement. M-E-Hα in relation to VHOR (0.14s) suggests that the constant swimming velocity is secured by quick start of the further part of the fin's movement which leads to its positioning parallel to the swimming direction first and next quick positioning of its end part so as the angle of attack is as high as possible (M-E-Hω). Relationships between VHOR and T-M-Hω, and T-E-Hω are similar. In both cases the retardation in angular velocities changes (0.1s and 0.08s) leads to the situation where the maximum angular velocity falls on the last part of the stable VHOR cycle.

From the description and fig. 3, 4 one may conclude that the monofin's tail, as the point of transfer of the momentum generated by legs on its surface, is the key element in the action of the biomechanical chain analyzed. The monofin's tail divides it into two parts: one – controlled by the swimmer- chain of leg segments and a chain composed of monofin components, which depends on the legs structure and the fin's characteristics. In this context the interpretation of the stable, balanced transfer of forces mechanism in the whole cycle is based on the correlation dependencies between legs and monofin movement parameters which shows high cross correlation and zero or minimum retardation (fig.4.). Knee movements determine the trajectory of the monofin's middle part. The lower the amplitude and the longer the time of the knee movement, the bigger the amplitude of the monofin's middle part. This correlation applies to the phase of the legs upward movement, where the slowing down of the movements in direction of the swimming is justified from the hydrodynamics point of view. Angular velocity of the flexion in the hip determines the parameters of the monofin's rear part's angle of attack. Longer time of maintaining maximum (S-H-Kω) with extended knee joints results in faster positioning of the monofin's end part at the maximum angle of attack in the described position (M-E-Hω). Earlier flexion of the monofin's rear part results in its positioning along the swimming direction (M-E-Hα). It may be assumed that the correlations shown support the transfer of the momentum occurring between the leg and the fin. More so as the influence of the angles of attack on swimming velocity has been documented, with particular attention to the role of the monofin's rear part positioning in relation to the direction of flow (3, 4). The angle of flexion of the fin's tail determines the angles of attack of the monofin's front part and its whole surface. Positioning of legs and the monofin's front part in one line, (A-T-Mα) in a cycle contributes to the shift of its front part to the position parallel to the swimming direction (T-M-Hα) and extending in time the movement of its edges (T-E Hα). This correlation refers to the transfer of momentum in the structure of leg flexion and the sag of the monofin's parts. That is because the shift in the mutual positioning of the fin segments with the adequate breakdown of velocities of flow leads to a vortex which, at a stable vortex circulation, generates additional propulsion (6) in the form of added mass of water pushed backward (1). Speaking more broadly, the structure of the further segments of legs affects the movement of the monofin's further elements. In the same manner, front elements of the leg chain affect the monofin's front segments. The lower the retardation (more stability) of the angular velocity around the furthermost point of legs (HIP), the smaller the retardation of the angular velocities of attack with respect to the fin parts which are furthest from the tail (M-E-Hω and T-E-Hω) According to this method, based on the balance of momentum generated by both parts of the chain, one may interpret the mechanism of the legs and fin movement. Such evidence results from analogy between analyzed monofin and legs movement and the structure of the fish movements (1, 5). The angles of the tail flexion, together with the angles of attack, illustrate the features of the material the monofin is built from. The lower the A-T-Mα angle, the smaller the monofin's tail and front part flexion (harder tail). The lower the A-T-Eα angle, the bigger the fin's tail and middle flexion (softer fin). The shape and the hardness suggest that in the monofin's structure there are premises to maintaining the balance of momentum transferred in water, and vice versa, in both phases of the propulsion. This is supported by the analysis of angles of attack, which (with the exception of T-E-Hα are characterized by R=0 in relation to VHOR may signify that the source of errors which disturb the balance of momentum should be looked for in the fin upward phase time structure. This is supported by delays in the angular velocities of attack (with the exception of T-E-Hω) in relation to VHOR. Additionally, the monofin's upbeat phase is accompanied by delays M-EHORα and T-E-HORα in relation to VHOR, which may be interpreted that more rigid fin would eliminate time shift. The balance of momentum generated by legs is more difficult due to the different nature of the upbeat as compared to downbeat. What seems to be the most important is that due to the hip downward and the thigh upward movement in the limbs chain degrees of freedom are created (which do not occur in the downbeat), which changes the breakdown of momentum in both phases. Adverse balance of momentum in the upbeat is due to the shortening of the arm of the force generated by the movable segments. Additionally, increase in the number of degrees of freedom does not positively affect the stability of the system, which transmits momentum-propelling (2, 4). Thigh downward action is justified from the propulsion generation perspective, as it is performed against the swimming direction. However, the upward action is not justified, which generates additional resistance. The consequence of the movements along the swimming direction applies most of all to improper shape and its trajectory and, as a consequence, to avoiding the water resistance (3, 4). The loss of propulsion results from the lack of the sources that could generate such propulsion (direction and components of the propulsion force – lift and drag) (3, 5), which is the prerequisite for the generation of the vortex circulation which propels the swimmer (6) and the direction in which the added mass of water is pushed (1). It may be assumed that upbeat (in limited scope) is necessary to prepare the push with the thighs in the downbeat. However, a purposeful thigh movement seems to be pointless.

CONCLUSION
Analyses of temporal delays of the body segments and monofin movements tailored for swimmers according to the leg movements and also equipment used will allow elimination (or limiting) of the hip downward movement to the torso level. In effect, it will be possible to search for the optimum scope of the thigh upward movement. Insufficient swimmer's force potential to properly carry out leg movements constitutes the basis for interference in the monofin's properties to use it in the tail's downward movement. One should be focused on optimization of the monofin's hardness in points responsible for its shape and trajectory in conditions of water resistance. This means that optimization should ensure best hydrodynamic conditions (angles of attack and momentum balance).

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INTRACYCLIC VELOCITY SIGNAL AS A TOOL TO EVALUATE PROPULSIVE PHASE DURATION

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This paper examines how intracyclic velocity signals may be helpful in determining propulsive phase duration in front crawl swimming, serving, thus, as a basis for Index of Coordination (IdC) calculation. Nine swimmers performed two experimental tasks: (i) swimming with one arm at maximal speed and (ii) swimming at eight individual swim paces. Video analysis was mixed with the intracyclic velocity signal. The duration of the propulsive phase was then determined visually and using the inversion of acceleration as determined from the velocity signal. The results indicated a gap between the beginning and end of the propulsive phase as determined visually and the same propulsive phase measured from the velocity signal. Thus, the visual method gave lower IdC values. However, the adoption of one or the other method has no significant impact on the assessment of the magnitude of coordination change within swim paces. It was concluded that IdC could be calculated with or without the help of the intracyclic velocity signal.

Key words: front crawl, swimming, biomechanic, coordination, methodology.

INTRODUCTION
Chollet et al. (1) proposed a methodology to investigate changes in coordination with pace in freestyle swimming. This concept, called the Index of Coordination (IdC), is based on the determination of five key-points that delimit four stroke phases. However, these key-points are determined visually, which could introduce bias. The use of direct kinematic measurement might thus be an alternative in determining the propulsive phase duration. Indeed, in breaststroke, Seifert et al. (2) proposed the use of the intracyclic velocity signal to determine the beginning of the propulsive phase. In this case, the swimming phase was considered propulsive when the acceleration signal became positive. In front crawl, the methodology of Chollet et al. (1) assumes that arm propulsion continues up to the hand's exit from the water. However, experimental data from Schleihauf (4) showed that propulsive forces are not applied until the end of the underwater phase, and that an additional non-propulsive phase named "exit" occurs. It thus seems that the methodology of Chollet et al. (1) may overestimate the duration of the propulsive phases, although the impact of this potential methodological bias has not yet been investigated. Once again, data from intracyclic speed variations may provide a useful tool for increasing the precision of visually determined values. Indeed, when the application of propulsive force stops, the swimmer faces resistances that imply speed reduction, or negative acceleration. The aim of this study was thus to determine how data from intracyclic velocity might help in determining the duration of the propulsive phases. We then sought to quantify any differences in IdC values obtained by the two methods, i.e., one with, and one without the intracyclic velocity signal.
The tested hypotheses were:
— the propulsive phases determined by the method of Chollet et al. (1) and the phases of positive and negative acceleration do not correspond;
— the gap between the beginning of the pull (method: Chollet et al., 1) and the beginning of the positive acceleration is due to a persistent higher intensity of active drag;
— The gap between the hand's exit from the water and the end of the acceleration phase does not depend on swim speed.

METHODS
Nine swimmers of national and international levels (7 men, 2 women; 20.3±2.1 years) performed two experimental tasks. Firstly, they swam 25 m at maximal speed with only one arm. Secondly, they performed eight swim trials over 25 m at the speeds corresponding to those adopted for different competi-

tive distances. We thus differentiated between swimming speed (in $m.s^{-1}$) and swim pace, which corresponded to the mean speed adopted for specific race distances (from 3000-m to maximal speed on 25 m).

Arm stroke phases
The arm stroke was divided into four distinct phases, similar to those presented in the front crawl study of Chollet et al. (1): *entry and catch* of the hand in the water (entry of the hand into the water and the beginning of its backward movement), *pull phase* (time between the beginning of the backward movement of the hand and its entry into the plane vertical to the shoulder), *push phase* (time between the positioning of the hand below the shoulder to its exit from the water), and *recovery phase* (time between the exit of the hand from the water and its following entry into the water).
The duration of each phase was measured for each stroke with a precision of 0.02 s and was expressed as a percentage of the duration of a complete arm stroke. The IdC was calculated as the mean time gap between the end of the push phase for one arm and the beginning of the pull phase for the other arm, and expressed as a percentage of total swim stroke duration.

Video-velocity system
Video analysis was synchronized with a swim speedometer (Fahnemann 12 045, Bockenem, Germany). The swimmers wore waist belts connected to an unstretchable cable driving an electromagnetic angular velocity tachometer in order to analyze the evolution of intracyclic velocity variations, at a sampling rate set at 100 Hz. The resistance applied to the swimmers' forward displacement was 10N. The lateral view of the video and the video timer were associated with the instantaneous velocity curve read on the computer. For each subject, three to four complete strokes were filmed and analyzed. The time between the measured positive and negative acceleration of the hip was quantified with the swim speedometer (fig. 1) and compared with the duration of the propulsive phase obtained with the visual method. Then, the gap between the beginning of the pull phase and the beginning of positive acceleration, as well as between the hand's exit and the beginning of negative acceleration, was quantified. Three swimming cycles were analyzed per trial.

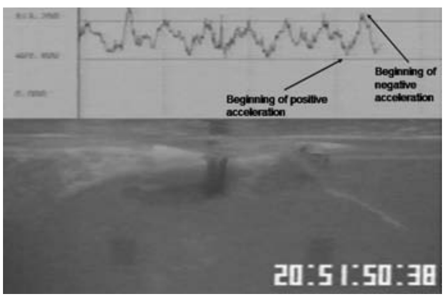

Figure 1. Moment of the change in acceleration with intracyclic velocity signal.

Statistical analysis
For all variables, a normal distribution (Ryan Joiner test) and the homogeneity of variance (Bartlett test) were verified and allowed parametric statistics (Minitab 14, Minitab Inc., 2003). Two-way ANOVAs (pace, 8 levels; random factor: subject, 9 levels) were used to determine the pace effect on swimming speed, IdC, and the temporal gaps between visual and intracyclic velocity determination of propulsive phase. Then, the mean values of IdC obtained on the basis of three methods [(i) speedometer: intracyclic velocity signal only, (ii) Chollet: visual determination only, and (iii) visual-speedometer: beginning of pull determined visually and end pull phase with beginning of negative acceleration] were compared with one-way ANOVAs. Last, one-way ANOVAs compared the standard deviations of IdC obtained with the three methods. For all tests, the level of significance was set at $P < 0.05$.

RESULTS
Table 1 shows the gap between the beginning of the pull phase determined visually and the beginning of the positive acceleration with a speedometer in the one-arm swimming condition.

Table 1. Temporal gap in the propulsive phase as determined visually and with the acceleration signal.

Gap between beginning of pull and re-acceleration (%)	Gap between beginning of deceleration and hand exit (%)
11.7 ± 6.6	11.2 ± 8.7

Table 2 presents the coordination parameters with swim pace, and the gaps regarding the beginning and end of propulsive phases using the method of Chollet et al. (2000) and the method based on intracyclic speed determination.

Table 2. Changes in speed, IdC and gaps regarding the beginning and end of the propulsive phase determined visually vs. speedometer, with swim pace.

Swin paces	spedd (m.s-1)	IdC (%)	Gap between pull beginning acceleration (%)	Gap between deceleration beginning--hand exit (%)
25	1.72±0.11	-2.8±4.1	16.4	5
50	1.69±0.11	-3.2±4.3	16.3	5
100	1.6±0.16	-7.3±6.8	14	7.5
200	1.56±0.16	-8.2±6.9	10.2	6.1
400	1.56±0.09	-8±4.5	8.6	6.1
800	1.46±0.12	-10.9±5.3	7.5	6.6
1500	1.43±0.12	-11.5±5.9	5.5	7.6
3000	1.35±0.11	-11.8±6.3	7.2	6.2
	*	*	*	*NS*

**: significant difference with p<0.05 NS: no significant difference*

Table 3 shows the mean values of IdC from the eight swim paces calculated on the basis of three different methods.

Table 3. Mean IdC values calculated on the basis of three methods.

Name of the method	Video (Chollet)	Visual+ speedometer	Speedometer
IdC (%)	-9.5±5.9	-15.2±6.7	-21.5±5.3
Difference	a, b	b, c	a, c

a: significant difference with visual+speedo method; b: significant difference with speedometer method; c: significant difference with chollet method p<0.05

The standard deviations of IdC with swim pace (SD IdC) are listed in table 4. This compares the SD IdC of the three methods of calculating IdC.

Table 4. Comparison of standard deviations of IdC calculated with three methods.

Methods	SD IdC
Chollet	4,1±1,6
Visual-speedometer	5,3±1,7
Speedometer	4,2±1,6
	NS

NS: non significant difference

DISCUSSION

In the first part of the experiment, the swimmers were asked to swim with only one arm, thus with only one source of propulsion. The results showed a temporal gap between the beginning of the pull phase (visual determination) and the beginning of the positive acceleration measured with the swim speedometer, as well as between the hand's exit from the water and the beginning of deceleration. In the latter case, the gap can be easily explained by the end of the hand's application of propulsive force, in accordance with the experimental data from Schleihauf (4). Our data indicate that the method of Chollet et al. (1) may overestimate propulsive phase duration, once it assumes that propulsion ends at the hand's exit from the water.

Two hypotheses can explain the gap between the beginning of the pull phase determined visually and the re-acceleration signal:
— either the catch phase duration is visually underestimated
— or the propulsive force generated during the catch phase is of lower intensity than the drag force that the swimmer suffers during the same phase.

In this last case, the beginning of the pull phase might have corresponded to the beginning of propulsive force application, even though its magnitude was not high enough to create positive acceleration.

To determine which of these hypotheses was correct, we tested whether the temporal gaps in visual vs. speedometer propulsive phase determination changed with swimming speed. Eight swim paces were performed by the swimmers, according to the methodology proposed by Chollet et al. (1). The changes in IdC across these swim paces was in accordance with previous studies (1, 3). Moreover, our results indicated that the gap between the beginning of the pull phase (determined with the method of Chollet et al., 1) and the positive acceleration increased significantly with swimming speed. It thus seems that the swimmers drag, once it grows with swimming velocity, required the propulsive forces to be high enough to produce positive acceleration.

The same methods were applied to quantify the gap between the hand's exit and the beginning of negative acceleration. Table 2 shows that this gap did not significantly change with swim pace, having, thus limited methodological impact.

We also evaluated the impact of adopting different methods to calculate IdC. Table 3 shows the results of a comparison of the method of Chollet et al. (1), the method using only the intracyclic velocity signal, and an intermediate method that used visual determination of the pull beginning and the speedometer signal to assess the end of the propulsion. The results showed that the method had a significant effect on the IdC value. The more intracyclic velocity data were used, the lower the IdC was. In agreement to our hypothesis, the methodology from Chollet et al. (1) seems to overestimate the IdC by 5.7 to 12%. In this case, the superposition model proposed by Chollet et al. (1) may be questioned. However, the analysis of the standard deviations of IdC for the different swim paces indicated that the magnitude of the measured adaptations did not statistically differ between the three methods. In this case, it seems that these three methods of determining IdC can be used to estimate the magnitude of a swimmer's adaptation to changes in swim pace.

CONCLUSION

The combination of visual determination for the beginning of the pull phase and intracyclic speed signals for the end of the push phase appears to offer an interesting opportunity to better assess propulsive phase duration, thus resulting in a more precise value of IdC.

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THE BREASTSTROKE START IN EXPERT SWIMMERS: A KINEMATICAL AND COORDINATIVE STUDY

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This study used a video camera to compare the kinematics and coordination of the grab start in one international and eight national breaststroke swimmers at the 100-m pace. The kinematical analysis assessed the durations of leave block, flight, entry and glide, pull-out phases, and the swim up to 15 m. The coordination analysis assessed the time spent with the arm close to the thigh after a complete arm pull-push and the time gap between the end of the arm recovery and the beginning of the leg propulsion. The international swimmer had a shorter 15-m start time than the national swimmers, which was explained by a shorter swim phase, more time in the underwater phase and more time with the arm close to the thigh after the pull-push of the arms. The whole population showed a superposition of two contradictory phases: leg propulsion began whereas the arms were not extended forward because their recovery was not finished.

Key Words: motor control, biomechanics, swimming starts.

INTRODUCTION

Recent studies have quantified the start time in relation to the actual swim and turning times, during competition, to assess their relative contribution to overall race performance (1, 3). The 15-m start times have been found to range from 0.8% to 26.1% of the overall race time, depending on the event (3). Most of the kinematical analyses of the start phases have focused on the reaction time on the starting blocks, and the flight and entry phases, comparing the grab with the track start (6). Although differences were noted in start techniques, Sanders and Byatt-Smith (5) emphasised that, in all cases great consideration should be accorded to the underwater phase. Indeed, Arellano et al. (1) showed that 95% of the variance in start times was explained by the glide. Cossor and Mason (3) noted a negative correlation (r=-0.734) between the underwater velocity and the 15-m start time in the 100-m breaststroke, which suggested that great velocity during the underwater phase of the start is critical to achieving high swim velocity. Although the FINA rules require that the swimmer's head break the surface of the water before the 15-m mark for the front crawl, backstroke and butterfly, the only constraint to the breaststroke is that the head must break the surface before the hands turn inward at the widest part of the second stroke. Unlike the actual swim, during which the hands cannot be brought back beyond the hip line, the FINA rules allow a complete arm and leg stroke with a push of the arms back to the thighs during the first stroke after the start and each turn. Therefore, the arm to leg coordination of the underwater start phase is different from that of the swim segment because it includes: (1) a more propulsive phase of the arms (push from the shoulder to the thigh) and (2) some glide time within the complete stroke of the arms and legs. Several recent studies have emphasised the need for high arm to leg coordination in breaststroke to minimise the propulsive discontinuities, either by reducing the glide time, or by overlapping two contradictory phases (i.e. the propulsion of one pair of motor limbs during the underwater recovery of the other pair of motor limbs) (2,4). Similarly, during the underwater phase of the breaststroke start, the arm to leg coordination is an important variable that coaches and swimmers should not neglect. The aim of this study was to analyse the kinematics and coordination of a start in breaststroke, comparing eight national swimmers with the bronze medallist of the Athens 2004 Olympic Games in the 100-m breaststroke. We hypothesised a longer underwater phase in the Olympic swimmer due to a better start technique, notably higher arm to leg coordination.

METHODS

Eight national swimmers (age: 21.3±1.7 years, mass: 75.7±2.8 kg, height: 185.3±2.9 cm, 100-m time: 66.9±1.7 s) were compared with the bronze medallist of the Athens 2004 Olympic Games (age: 21, mass: 85 kg, height: 193 cm, 100-m time: 60.01 s) during a simulation of the 100-m breaststroke event over 25 m and after a grab start. Two aerial lateral cameras (50Hz) placed at the 5-m and 15-m marks and a trolley on which an aerial lateral video camera was superposed to an underwater lateral video camera (50Hz) were video timed, synchronised and genlocked. The kinematical analysis included five phases: (1) the leave block phase, (2) the flight phase, (3) the entry and glide phase, (4) the pull-out phase (the sum of the entry and glide phase, and the pull-out phase was termed the underwater phase), and (5) the swim phase until the head reached the 15-m mark. The arm to leg coordination of the start was assessed at two key points of the pull-out phase: (1) the time gap between the arm's arrival to the thigh after the complete arm pull-push and the beginning of the arm recovery, and (2) the time gap between the end of the arm recovery and the beginning of the leg propulsion. The duration of each time gap was measured for each stroke with a precision of 0.02 s by three operators who analysed the key points of arm and leg phases using a blind technique. The absolute duration of each phase was expressed in seconds, while the relative duration was expressed in percentage of the 15-m start time. Kinematical and coordinative parameters between the international swimmer with the eight national swimmers were compared by *t*-test to the norm (the international swimmer) at $p<0.05$.

RESULTS

The international swimmer had a faster 15-m start time than the national swimmers, due to the shorter durations of the swim phase, the greater durations in the underwater phase (notably, the higher durations of glide and pull-out phases) and the greater time durations spent with the arms close to the thighs after the pull-push of the arms (Tables 1 and 2).

Table 1. Kinematical differences between international and national male swimmers.

Skill level	Leave block	Flight	Glide	Pull-out	Underwater	Swim	15-m start time
	(s)	(s)	(s)	(s)	(s)	(s)	(s)
International	0.74	0.35	2.16	2.78	4.94	1.43	7.46
National	0.75 ±0.07	0.36 ±0.07	1.55 ±0.37 *	2.63 ±0.43	4.18 ±0.57 *	3.12 ±0.77 *	8.41 ±0.52 *
	(%)	(%)	(%)	(%)	(%)	(%)	(%)
International	9.9	4.7	28.9	37.3	66.2	19.2	100
National	8.9 ±1.1	4.3 ±0.9	18.4 ±4.4 *	31.4 ±5.6	49.9 ±7.3 *	36.9 ±7.7 *	100 100

Table 2. Coordination differences between international and national male swimmers.
**: significant difference between the international swimmers at p<0.05; absolute values are in seconds (s) and relative values are in percentage of the 15-m start time (%).*

Skill level	Arms to things	Arm recovery / Leg propulsion
	(s)	(s)
International	1.08	-0.14
National	0.39±0.19 *	-0.13±0.05
	(%)	(%)
International	14.5	-1.9
National	4.6±2.1 *	-1.5±0.6

DISCUSSION

In agreement with the proportions observed by Cossor and Mason (3), the relative duration of the underwater phase of the start represented most of the international swimmer's 15-m start time, and was related to the greater relative durations of the glide and the pull-out phases. This swimmer also spent more time in the glide with the arms close to the thighs after the pull-push phase of the arms. According to Sanders and Byatt-Smith (5), these results indicate the capacity of elite swimmers to maximise propulsion and minimise drag, notably by adopting a streamlined position during the glide phase, and by monitoring the glide times. Indeed, in breaststroke, the swimmer must distribute the glide time from the entry to the beginning of the arm pull, and from the end of the arm push to the beginning of the arm recovery. In other words, the swimmer must decide when to start the arm pull and how much time should be spent in the glide with the arms close to the thighs. Normally, the glide ends and swimming begins when the mean swimming velocity has been reached. Therefore, Sanders and Byatt-Smith (5) has advised focusing on the underwater part of the start in front crawl, particularly to determine the appropriate moment to initiate the kick in turns and starts. Kicking too late leads to a loss in velocity and kicking too early wastes energy and increases drag. By digitizing the joints of the body, Sanders and Byatt-Smith (2001) proposed a method to calculate the velocity of the centre of mass, which indicates when the instantaneous velocity of the swimmer attains the mean swimming velocity, and thus when swimming should begin. This feedback can be quickly provided to the swimmer by calculating the velocity of a marker fixed, for example, on the hip (5). Based on the hip instantaneous velocity in the 100-m breaststroke of the bronze medallist of the Athens 2004 Olympic Games, Figure 1 shows the key start events for each arm and leg and the velocity differences in relation to the mean velocity (1.52 $m.s^{-1}$). The relatively long time that the Olympic swimmer spent with the arms close to the thighs may not be as effective as previously suggested because, when the video was synchronised to the speedometer (Fahnemann 12 045, Bockenem, Germany, see 2, 4), this swimmer seemed to have waited too long before beginning the arm recovery. Figure 1 show a velocity difference in comparison with the mean velocity, which decreased from -3.9% when the arms were close to the thighs to -21.7% when the arms began their recovery. The combination of too much time spent with the arms to the thighs and the high drag due to arm and leg underwater recoveries led to a velocity decrease of -93.4% as regards the mean velocity when the legs initiated their propulsion.

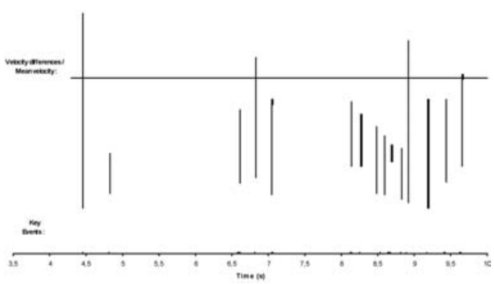

Figure 1. Velocity differences in relation to the mean velocity for the key start events of each arm and leg.

Thus, it appears to be very important to adopt a streamlined position when leg propulsion begins. However, our results showed that both the Olympic and the national swimmers had negative superposition coordination because they overlapped two contradictory phases: the end of arm recovery and the beginning of leg propulsion. Although this coordination mode can be effective in sprint events to help some elite swimmers to maintain high mean velocity (2), it was detrimental to performance in non-expert swimmers (4). Figure 1 confirmed the ineffectiveness of this arm to leg coordination for the start, because it increased a drag that was already high from the underwater recovery of arms and legs. Indeed, the velocity differences decreased from -93.4% to 100% as regards the mean velocity due to a late recovery and the extension of arms. The fact that swimmers can bring their hands back beyond the hip to the thigh during the underwater phase may explain a lack in their habit, which should be corrected to enable effective arm to leg coordination.

CONCLUSION

One of the practical applications of these findings has been the recommendation to monitor the durations of the start phases, particularly the underwater phase, especially for the Montreal 2005 World Championship, for which the FINA rules allowed a single downward dolphin kick followed by a breaststroke kick while the swimmer was wholly submerged. Thus, the glide times (1) before the downward dolphin, (2) between this leg propulsion and the beginning of the arm pull, and (3) with the arms close to the thighs, should be monitored so that too long or too short glide times in relation to the mean swim velocity can be corrected. Similarly, the arm to leg coordination during the first stroke should be monitored so that contradictory superposition that increases drag can be replaced by a more effective coordination mode.

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COMPARISON OF SUBJECTIVE AND OBJECTIVE METHODS OF DETERMINATION OF STROKE PHASES TO ANALYSE ARM COORDINATION IN FRONT-CRAWL

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The aim of this study is to evaluate the reliability of the subjective method of determination of the arm stroke phases in front crawl 1) by studying the influence of the expertise level of the operator, and 2) by comparing the phases results determined subjectively by an operator with data obtained from a digitizing process. These two methods were used to calculate an index of coordination (IdC) based on phases durations. The IdC values assessed by the novice operators were higher than those of the expert operators, due to a higher of the pull phase and to a smaller catch phase. Smaller standard deviations of IdC were observed for experts compared to novices indicating a greater reproducibility in the phases determination. No significant differences of stroke phases and IdC were observed between the results obtained from the expert operators and the digitising process.

Key Words: motor control, phases, kinematic, subjective method.

INTRODUCTION

The decomposition of the front crawl arm stroke was largely studied and determined arm phases (1, 2, 3, 4, 5, 6). Based on 3D hand kinematic analysis, the handsweeps (entry, downsweep, insweep, outsweep, upsweep) were determined by seven characteristic points of the fingertip trajectory: entry into water, maximal forward coordinate, maximal backward coordinate and exit from the water on x-antero-posterior axis, maximal outward coordinate, maximal inward coordinate on y-transversal axis, maximal depth on z-vertical axis (2, 3, 6). The arm stroke phases have also been determined from trunk-arm angles with five phases (4, 5): catch phase was from hand entry until a arm-trunk angle of 45° , pull phase occurred from 45 to 90°, push phase occurred from 90 to 135°, upsweep was from 135° to the hand exit, and the aerial recovery. Based on this last method, Chollet, Chalies and Chatard (1) proposed to decomposed a complete arm stroke in four phases (entry and catch, pull, push, recovery), which were subjectively defined in the sagittal plane from hand positions appreciated by an operator. Then, inter-arm coordination in front crawl was most of time quantified by an index of coordination (IdC), based on the time lag between the end of the push phase of the first arm and the beginning of the pull phase of the second arm (1). This subjective method is related to the expertise of the operator to recognize the key points of the stroke. This study evaluated the reliability of the subjective method 1) by studying the influence of the expertise level of the operator on the phases determination, and 2) by comparing the phases results determined subjectively by an operator with data obtained from a digitizing process.

METHODS

Comparison between expert and novice operator using subjective method

Two elite swimmers simulated two freestyle race paces (the 1500-m and the 50-m) on 25-m and were filmed by two synchronised frontal and sagittal underwater video cameras (50Hz). Six expert operators who have more than 30 hours of experience and nine pair of novice operators (i.e. eighteen operators) subjectively video-determined the hand positions of the arm stroke for three strokes of the central portion of swims. According to Chollet, Chalies and Chatard (1), the hand positions enabled to define four arm phases: 1) Entry and catch of the hand in the water: this phase corresponded to the time between the hand entry into the water and the beginning of its backward movement. 2) Pull: this phase corresponded to the time separating the beginning of the hand's backward movement and its position in a vertical plane of the shoulder and constituted the first part of propulsion. 3) Push: this phase corresponded to the time from the hand in the vertical plane of the shoulder to the hand exit of the water i.e. the second part of propulsion. 4) Recovery: this phase corresponded to hand exit to the following hand entry. The duration of the propulsive phase was the sum of the pull and push phases, and the duration of the non-propulsive phase is the sum of the entry and recovery phases. The index of coordination (IdC) is defined as the time gap between the beginning of propulsion of the first right arm stroke and the end of propulsion of the first left arm stroke, and between the beginning of propulsion of the second left arm stroke and the end of propulsion of the first right arm stroke (1). For each trial, the average IdC was calculated on three complete strokes and expressed as a percentage of the mean duration of the stroke. When a lag time occurred between the propulsive phases of the two arms, the coordination was called "catch-up" (IdC < 0). When the propulsive phase of one arm started when the other arm ended its propulsive phase, the coordination was called "opposition" (IdC = 0). When the propulsive phases of the two arms overlapped, the coordination was called "superposition" (IdC > 0).

Two sample *t*-tests were used to compare expert to novice operator phases for each swimmer and each race pace. The difference of variance between the two skill levels groups of operators for each trial was determined from *F*-tests the level of significance was set at 0.05.

Comparison between subjective and objective method

Nine elite swimmers (mean weight: 79±6.5 kg, mean height: 187±0.7 cm, mean age: 22.5±2.3 years, mean time on 100-m front crawl: 50.63±2.12 s) swam a 50-m at their maximal velocity. They were filmed by two synchronised frontal and sagittal underwater video cameras (25Hz). The subjective analysis of the hand positions was conducted as previously described, but only on one stroke and by one expert operator. For the objective method, the hand was digitised frame by frame for one arm stroke, using Schleihauf's software (Kinematic Analysis, 2004). The coordinates corresponding to the hand positions (hand entry, maximal forward coordinate of the hand, hand in the vertical plane of the shoulder, hand exit) were extracted from the smoothed 3D hand trajectory. One-way ANOVA compared the phases and the IdC obtained from the expert operator and the digitising process (P<0.05).

RESULTS

The IdC values assessed by the novice operators were higher than those of the expert operators, due to a higher pull phase duration and to a smaller catch phase duration (table 1). Smaller standard deviations of IdC were observed for expert operators compared to novice operators (table 1).

Table 1. Mean and variance differences between expert and novice operator subjective analyses.

	Expert operators				Novice operators			
	Swimmer 1		Swimmer 2		Swimmer 1		Swimmer 2	
	1500-m	50-m	1500-m	50-m	1500-m	50-m	1500-m	50-m
IdC (%)	-13±3	-3.1±2.6	-9.7±3	-9.6±3.3	-1.2±6.1 a b	4.3±3.3 a	- 2±5 a b	0.4±4.6 a b
Entry (%)	32.8±3	29.5±3.8	34.9±3.6	32.8±3.2	26.3±5.7 a b	20.3±3.6 a	25.6±5.6 a b	22.9±4.6 a
Pull (%)	15.8±2.8	22±4.2	19.6±8	17.7±3.2	28.5±6.9 a b	31.3±6.1 a	27.4±4.2 a b	28.7±6.9 a b
Push (%)	21.5±1	23.2±1.4	18.6±8.2	20.4±1.3	21±6.3 b	24.5±5.1 b	19.8±5.1 b	21.8±6 b
Recovery (%)	24±1.1	25.4±1.5	26.9±2.7	29.1±1.2	24.2±2.1 b	23.9±5 b	27.2±3.3 b	26.7±4.7 b
Propulsion (%)	37.3±3.1	45.2±4.3	38.2±3.3	38±3.7	49.5±6.7 a b	55.8±5 a	47.2±6 a b	50.5±5.7 a b

*a: significant difference of mean with expert operators (*t*-test at P<0.05); b: significant difference of variance with the group of expert operators (F-test at P<0.05).*

No significant differences of stroke phases and of IdC were observed between the results obtained from the expert operators and the digitising process (Table 2).

Table 2. Differences between subjective and objective methods.

	IdC (%)	Entry (%)	Pull (%)	Push (%)	Recovery (%)	Propulsion (%)
Objective method	-0.2±4	23.8±3.4	27.6±3.8	23.5±2.3	25.1±2.5	51.1±3.6
Subjective method	-0.6±3.8	26.2±3.4	27±4.4	23.1±2.1	23.7±3.5	50.1±3.9

DISCUSSION

The higher pull phase duration and the large standard deviations of IdC for the novice operators could be related to their confusion to determine the beginning of this phase, because for them, the phase started when the hand went downward instead of downward and backward. After discussion with the two groups of operators, the novice operators said that they focused on the maximal forward extension of the arm before going downward rather than focusing on the maximal forward coordinate of the hand before going downward and backward. Therefore, the higher pull phase duration corresponded to an overestimation of this phase that also lead to overestimate the propulsive phases and hence the IdC. These results showed the non-reliability of the subjective method for operators without experience and underlined the necessary training process to use this method. Conversely, the reliability of the visual determination of the hand positions from the expert appeared to be sufficient to evaluate the stroke phases in regard to the similar results obtained from the digitising process. Consequently, the phases determination did not automatically required the digitising method and thus allowed to minimise the time process.

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ASSISTED VELOCITY SWIMMING TRAINING IN TWO AND SIX BEATS AGE GROUP FRONT CRAWL SWIMMERS

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The aim of this study was to verify the effects of an assisted velocity training (AVT) on stroke rate (SR) and time to perform 25 m in front crawl stroke with 2 and 6 beats kicks in age group front crawl swimmers. Ten swimmers (13 to 15 years old) allocated in group 2 beats (TB; n = 5) and group 6 beats (SB; n = 5) performed, before and after 6 weeks of training, a 25 m maximal effort in front crawl. First 5 stroke cycles, after 10 m, were recorded manually, to obtain SR and time to perform the 25 m. AVT was applied twice a week. It consisted of 8 trials of 20 m (1 min rest). A 7 m length and 203 mm thickness rubber band was fixed to the pool edge and to a belt around the swimmer's waist. Subjects were towed by the coach into the 20 m to perform back in high assisted velocity. Results showed increased values just on SR for TB after the AVT. This increase in SR values has not affected the time to perform the 25 m.

Key Words: assisted swimming, stroke rate, stroke length.

INTRODUCTION

Swimming performance is closely related to the stroke kinematic parameters (4). Swimming velocity (SV) is the product of stroke length (SL) and stroke rate (SR) (6). In front crawl stroke, swimmers adopt determined number of kick beats for each stroke cycle. Two beats for each stroke cycle is a characteristic of long distance swimmers as six beats for each stroke cycle is a characteristic of short distance swimmers, and economy is a main factor for this stroke characteristic (1). Two beats swimmers usually show more difficulties to increase their swimming velocities. Under such situation, assisted velocity training could help them to increase SR, and, consequently, SV. Assisted velocity training (AVT) is a method commonly used by coaches and swimmers to increase SV, by increasing SR without decreasing SL (5). In this training method, swimmer performs the stroke towed to a rubber band, which increases his velocity. It is recognized that assisted swimming, as resisted swimming, can alter stroke's characteristics (2). So, the aim of this study was to verify and to compare the effects of an AVT program on SR and time to perform 25 m in front crawl stroke in two and six beats age group front crawl swimmers. The hypothesis formulated in this study was that AVT effects would be more present in swimmers who perform front crawl stroke with two beats, than in swimmers who perform with six beats.

METHODS

Ten age group swimmers (four female and six male; age = 13.9 ± 0.8 years old; height = 1.66 ± 0.8 m, body mass = 52.7 ± 7.4 kg; upper limb span = 1.70 ± 5.4 m), allocated in group two beats (TB; n = 5) and group six beats (SB; n = 5), participated in this study. Front crawl kick characteristics were defined by the coach. All swimmers have been participating in competitive official events for, at least, three years. Subjects performed a 25 m maximal effort in front crawl stroke before and after a six weeks training program, each time after a 1000 m swimming warm up. First five stroke cycles, after 10 m, to obtain SR, and time to perform the 25 m, were recorded with a manual chronometer. Performance (T25) was considered the time to perform the 25 m front crawl in maximal effort.
AVT program was applied twice a week (six weeks) and consisted of eight trials of 20 m (1 min rest interval). It was used a 7 m length and 203 mm thickness rubber band fixed by its extremities to the swimming pool edge and to a belt around the swimmer's waist. Subjects were towed by the coach and

assistants until they reached the mark of 20 m and then swam back in maximal velocity assisted by the rubber band. Statistical analyses were made assuming a 0.05 significant level: Wilcoxon and Mann-Whitney Tests. Statistical Package SPSS 12.0 was used.

RESULTS

Mean and standard deviations (s.d.) of SR results for both groups, before and after AVT program, are summarized in Figure 1.

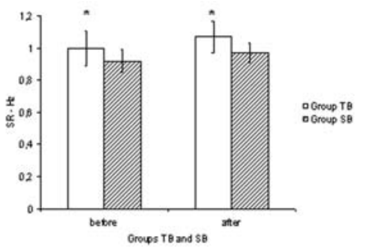

*Figure 1. Mean ± sd of stroke rate (SR - Hz) for both groups (TB – two beats; SB – six beats), before and after assisted velocity training; * indicates difference between groups for* $p < 0.05$*; n = 5 each group.*

For TB group mean SR values were 1.00 ± 0.11 Hz and 1.07 ± 0.10 Hz, respectively before and after AVT. For SB group mean SR values were 0.92 ± 0.07 Hz and 0.97 ± 0.06 Hz, respectively before and after AVT. The only difference found in SR was for TB group, when compared before and after AVT. No differences were found when compared the groups. Figure 2 summarizes mean T25 results for both groups, before and after AVT program.

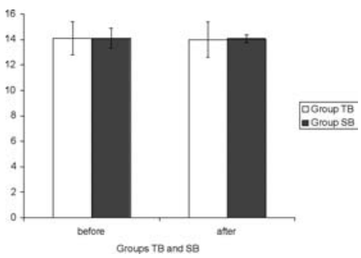

Figure 2. Mean ± sd of time to perform 25 m (s) for both groups(TB – two beats; SB – six beats), before and after assisted velocity training; n = 5 each group.

For TB group mean T25 values were 14.1 ± 1.3 s and 14.0 ± 1.0 s, respectively before and after AVT. For SB group mean T5 values were 14.1 ± 0.8 s and 14.07 ± 0.6 s, respectively before and after AVT. No differences were found in T25 when compared the values for groups or moments.

DISCUSSION

This study was planned to verify if effects of an assisted velocity training program, in swimming, would be different among swimmers who perform front crawl stroke with two and six beats kick. Both groups started and finished this study with similar SR and T25, but TB group has increased its SR values during a 25 m maximal effort. But this increased SR was not sufficient to increase performance in 25 m, which has not change after the six weeks program. Since swimming velocity is the product of stroke rate and stroke length, it is supposed that stroke length has decreased concomitantly to the increase in stroke rate in this group.

When compared to free swimming, assisted swimming has shown some distinct biomechanics aspects (6): during assisted swimming, SR and SL tend to be higher, while maximal hand depth is lower (6). It seems that there is transference of higher SR values to the free swimming after an AVT program, but it does not happen with the SL. In this study, even with higher SR values after AVT, TB group has not reached a better performance in a 25 m maximal effort. It could be explained, perhaps, by a less deep position of the hand, as a negative adaptation of the technique by the AVT. So, when swimmers are not able to position the hand in adequate depth, possibly they decrease their ascencional lift, one of the propulsion sources in swimming (1). This could, substantially, decrease stroke length (4).

The formulated hypothesis for this study has been partially confirmed: AVT program effects were more presented in swimmers which perform front crawl stroke with two beats kick. This effect was just in stroke rate and could not increase swimming velocity. Maybe a longer training program, with a special attention to stroke length, would be more effective.

CONCLUSION

An assisted velocity training program, during six weeks, for age groups swimmers, increased stroke rate in swimmers who performed front crawl stroke with a two beat kick. But performance, in 25 m maximal effort, was not increased. This training method can be detrimental to technique.

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THE IMPACT OF VELOCITY ON PULL AND RECOVERY TIMES AND AVERAGE PULL FORCE IN FREESTYLE SWIMMING

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Twelve non competitive swimmers participated in this study. The purpose of the study was to evaluate the impact of two different velocities on arm pull and recovery times, as well as to evaluate the average force applied. Force sensors, were positioned between the swimmers' fingers and were connected through cables to a computer. Participants swam two 25-meter length trials, a slow swim trial (SS) and a fast swim trial (FS), with a rest of 2 minutes in between swims. As velocity increased, stoke rate increased, stroke length decreased, and reductions in swimming (20%), arm pull (15.4 %) and arm recovery (45.7%) times (seconds) were recorded. A significant increase (62.3%) in average pull force (N) was recorded in the fast swim trial. As far as arm contribution to swimming speed is concerned it appears that pull and recovery times as well as forces exerted by the arms directly affect velocity.

Key Words: swimming, freestyle, pull/recovery times, pulling force.

INTRODUCTION

To date, the time space variables of armstroke in freestyle that have been extensively studied as determinants of speed, are stroke rate and stroke length. Relatively little attention has been drawn on the impact of pull and recovery times and forces exerted by the hands underwater on performance. In limited studies arm recovery times have been reported, with data demonstrating that the non-propulsive phase seems to be a key factor for better performance (6, 7). Stroke rate and stroke length are very often the only variables mentioned in connection to speed when other arm variables may contribute equally or even greater on speed and acceleration. The relationship of stroke length to stroke rate has not provided definite guidelines since it greatly depends on the distance and the intensity of the effort swam and creates certain difficulties for training applications. Researchers suggest that an optimum combination, without however reaching maximum or minimum values, of both stroke rate and stroke length would appear to produce the fastest swims (2, 5). It also appears that the longer the distance, the lower the velocity the longer the length of the pull and the lower the stroke rate (3). The impact of other arm pull characteristics such as speed of pull and/or recovery on speed, as well as forces exerted during fast and slow swim trials have drawn little attention perhaps due to the difficulty of data collection. However, due to the advancement of aquatic equipment coaches, trainers and investigators nowadays can obtain information for their swimmers that in the past could have only been performed in well equipped laboratories. It is necessary to focus on parameters that affect performance, such as the ones in our study in order to provide coaches with measurable indices that can help them evaluate swimmers' progress.
The purpose of this study was to investigate the contribution of pull and recovery times and average force on swimming velocity.

METHODS

Table 1: Anthropometric characteristics of swimmers (mean ± SD).

	Male (N=3)	Female (N=9)
Age (years)	21.66±0.57	21.77±0.58
Height (cm)	186.00±1.41	170.33±5.29
Body mass (kg)	83.66±2.49	62.55±5.71
BMI (Kg.m^{-2})	24.17±0.87	21.60±2.07

Twelve, non-competitive swimmers participated in this study. Subjects' characteristics are presented in Table 1. All subjects were University students and trained 4 times per week in a scheduled swimming course and swam an average of 2850±245 meters per session. Arm pull characteristics and forces were measured by a hydrodynamic measuring device incorporated in a portable laptop (Aquanex by swimming technology research, Inc., Florida, Tallahassee, USA).
Prior to entering the water, cables with RSU Type A sensors (Aquanex, Florida, Tallahassee, USA) were secured with elastic bands from the back of the swimmers' waist to their fingers and were connected to an interface and a laptop computer (Picture 1). The force sensors were placed between the swimmer's third and fourth finger from the back of the hand on both hands. The cables were secured with a strap worn around the wrist and the upper arm and also looped under a belt that was worn around their waist. The cables led from the swimmer's waist to the side of the pool, to the interface, perpendicular to the direction of the swim to keep the cables free of the kicking action. The laptop was powered by a battery in order to eliminate any risks of electrical shock or injury to the participants. The swimmers entered the water without a dive and performed two consecutive 25 meter trials with a 2 minute rest in between the trials at two different velocities. The slow swim was relaxed and easy (warm-up pace) (SS) and the fast swim (FS) was at their fastest perceived velocity.

Figure 1. Preparation of the swimmer by securing force sensors prior to water entry.

RESULTS

The increase in velocity of the fast trial produced the expected results in certain variables. As a result of increasing velocity, swimming times decreased (20%), stoke rate (strokes per second) increased and stroke length(yards per stroke) decreased as expected (table 2).

Table 2. Stroke rate, stroke lenght and stroke count at two velocities.

VARIABLE	SLOW SWIM	FAST SWIM	P
Swimming Velocity yds /sec	0.48±0.05	0.60±0.07	P<0.0001
Stroke Rate (strokes/sec)	1.04±0.09	1.48±0.12	P<0.0001
Stroke Length (yds/stroke)	0.47±0.05	0.40±0.04	P<0.05
Stroke Count (strokes)	20.54±3.12	23.61±3.12	P<0.05

The average pull time and the recovery times of the FS were shorter than the SS (table 3). However, the decrease in pull time of the FS was of a magnitude of 15.4% when compared to the SS while the decrease of the recovery time interestingly was of a magnitude of 45.7% when compared to the SS freestyle. The average force (N), and the swimming velocity (yds/sec) were greater in the FS. Also a significant increase (62.3%) in average pull force (Newton) was recorded in the fast swim trial (Table 3).

Table 3. Arm Pull and Recovery times and Average force at two speeds.

VARIABLE	SLOW SWIM	FAST SWIM	P
Trial Time (sec)	21.10±2.50	16.90±2.20	P<0.0005
Average Pull Time (sec)	0.91±0.17	0.77±0.12	P<0.05
Free Recovery Time (sec)	1.03±0.28	0.56±0.12	P<0.0001
Average Pull Force (N)	18.05±8.10	28.96±13.30	p<0.01

DISCUSSION

Great emphasis has been placed on the effects of stroke rate and stroke length on velocity and generally stroke rate increases while stroke length decreases with increasing velocity (1). However, no attention has been drawn to the contribution of speed of pulling and recovery on velocity. The important finding of this study was that in the freestyle swim, the increment of speed of the recovery phase was much greater (45.7%) than the increment of speed of the pulling phase (15.4%) during the fast swim in freestyle. It appears as was also evidenced in other studies focusing on breastroke, that the non-propulsive phase is a key factor for better performance (2). Takagi et al, have suggested that swimmers must avoid rapid deceleration during the non-propulsive phase by adopting a low resistance posture and stroking technique (7). Boons et al also have also noticed a limited deceleration during the first arm recovery phase of the undulating breastroke style as opposed to the flat style, perhaps basically due to reduced drag which in turn affects velocity. (6) There aren't any other studies reporting the effect of speed of arm recovery, i.e. the non-propulsive phase, in relation to other determinant of speed in freestyle. Speed is a result of the product of applied power in relation to time according to Newton's Law of acceleration, thus even if the relationship of stroke length to stroke rate indirectly reflects changes in velocity, the power applied under water may be a major determinant of speed and its fluctuations attained by swimmers (4). In this study speed was affected by the, increase in stroke rate which was accompanied by a decrease in stroke length. This was in agreement to the existing literature one of the determinants of the increase of velocity (3). However, the great increase in power evidenced during the pulling phase cannot be regarded secondary but of equal or even greater importance to its effect on speed. The average increase of power during the pulling phase was accompanied by a decrease in the average pull time during the 25 meters of fast crawl swimming. Thus, on the basis of our results a faster, shorter and more powerful pulling phase with a considerably even faster arm recovery time appear to be the major determinants of the increase in velocity. The impact of stroke rate to stroke length upon velocity needs to be reevaluated taking into consideration changes in the average force of pulling and the time(sec) of pulling and recovery of each armstroke. As it appears from the data the increase in swimming velocity in freestyle may be generated by a greater pulling force and an acceleration in the arm recovery time (table 3). Further studies need to elucidate whether the increase of stroke rate and the decrease in stroke length, are primary or secondary to force changes and fluctuations in arm pull and recovery times.

CONCLUSION

Since speed and high level performance are considered the goals of most swimmers training at a higher level, it is also very important for the coach and the swimmer to realize the determinants of performance. A great performance is equally affected by physiological and medical parameters as well as technical and biomechanical ones. Very often, after swimmers appear to have mastered an efficient stroke, coaches do not systematically re-evaluate the efficiency of their stroke but focus mainly on physiological adaptations. However, fatigue is multidimensional and can be manifested in the face of either poor training practices or poor technique and failure of the coach to realize the swimmer's weaknesses. The emergence of advanced technical tools, however, could offer the coach and the athlete greater insight on stroking and kicking assessment and evaluation. Also, underwater video analysis depicting the various pull phases parallel to the measurement of force and stroke characteristics could provide ample information for the study of efficient performance (fig. 2). Propulsion can be greatly affected by the way forces are exerted under and over the water by both the upper and lower limbs and further research is necessary to establish measurable guidelines for every stroke. This study, was an attempt to use easily accessible and applicable to the coach and swimmer devices and study the pulling determinants of speed in freestyle. Further research, will combine the impact of leg action to overall speed as well as the measurement of overall efficiency of swim through respiratory gas analysis in relation to arm force and stoke characteristics. Also the determinants of speed for every stroke (i.e. butterfly, backstroke, breastroke, and freestyle) as far as forces exerted and stroke characteristics need to be separately evaluated.

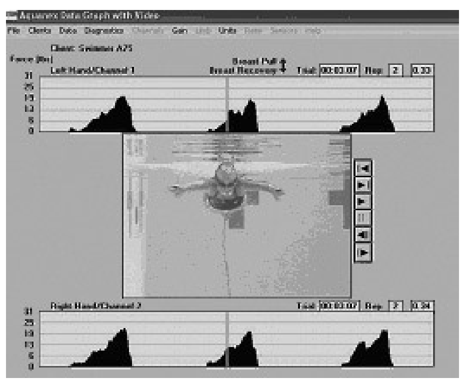

Figure 2. Sample data of force curves in combination to video stroke analysis.

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THROWING WITH DIFFERENT KINETIC CHAINS

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Overarm throw is determined by a so called proximal-to-distal principle (9). Our concept of studying kinetic chain was to gradually add the active muscles in the throwing kinetic chain, and measure the throwing velocity. Doing so, the contribution of the newly added muscles to the final velocity of the ball can be estimated. As kinetic chain was prolonged from P1 to P3 position, the throwing velocities increased with both normal and heavy ball. However, in water throw (P4) normal ball velocity was additionally increased while in heavy ball decreased, very likely due to insufficient leg/pelvis stabilization in water during heavy ball throw. On individual basis, players playing in different positions (driver, center-forward, goalkeeper) had different velocity increase due to changed kinetic chain.

Keywords: overarm throw, water polo, kinetic chain, throwing velocity.

INTRODUCTION
Ability of throwing a ball with high velocity is an important factor of performance for water polo players. An individual's maximal throwing velocity depends on optimal throwing mechanics and body segments characteristics. Overarm throw is determined by a so called proximal-to-distal principle (9). This principle has been observed in various sport throwing movements – baseball pitch, handball, javelin throw, tennis serve and water polo throw. Proximal-to-distal principle describes progressive contribution of the body segments to the momentum of the throwing object, beginning from the base of support and progressing through to the hand/ball. Because of the constant mass of the ball or other throwing objects, the change in momentum corresponds to the change in throwing velocity. Using computer simulation (1) it has been reported that there is an optimal delay between the activation of the more proximal muscle corresponding to the more distal one. If the delay is shorter than optimal, the throw is completed sooner, and less time is available for contraction of the proximal muscle which then does less work. If the delay is longer than optimal, less time is available for the contraction of the distal muscle, which, therefore, does less work (2).
Beside proper muscle activation, other factors can influence throwing velocity. Elastic energy stored by muscles contracting eccentrically, and myotatic reflex, also contributes to powerful concentric contraction, therefore generating higher acceleration (stretch-shortening cycle). Skilled throwers are able to move the arm through greater range of movement, and into more extreme positions, compared to less skilled throwers (8), which results in applying force, and accelerating the ball, over a higher distance, and enhancing greater ball velocities.
Until now, proximal-to-distal principle has been mostly studied using kinematical analyses and electromyography. Our concept of studying kinetic chain was to gradually add the active muscles in the throwing kinetic chain, and measure the throwing velocity. Doing so, the contribution of the new added muscles to the final velocity of the ball can be estimated.

METHODS
Seven Slovenian national team water polo players (26,9 ± 5,1 years, 192,1 ± 5,5 cm, 97,6 ± 6,7kg), all skilled throwers, participated in the study. After explained the nature and the purpose of the study, they all signed a written form of consent.
Subjects were asked to throw the ball with dominant arm with maximum velocity three times in four different body positions: (ascertains were irrelevant?)
P1: subject seat on a chair, so that the trunk (chest) was fixed on the back of a chair. This position allowed the subject to throw the ball only with the arm;
P2: subject seat on a chair, so that pelvis was fixed on a chair. This position allowed the subject to rotate the upper trunk while throwing the ball;
P3: subject stand with the opposite leg stepped forward. This position allowed the subject to fix legs at the base of support (floor) and rotate the pelvis while throwing the ball;
P4: subject threw the ball from the basic floating water polo position in the water.
Throws were executed with two balls of different weight – normal (N) water polo ball (0.43 kg) and 3 kg medicine (H) ball. The ball was thrown in the direction of a 5 m distant radar (Speed Check Personal Sport Radar, Tribar Industries, Quebec, Canada), which measured the velocity of the ball. Radar was positioned behind the net of a water polo goal, which protected it from the impact. The radar was positioned in front of subject's right shoulder, approximately at the height of the release of a ball, to enable its most direct (optimal) path to the radar. The throws were executed without faints, like penalty throws in water polo. The highest velocity of three throws was used for further analysis. Basic descriptive statistics and ANOVA were conducted.

RESULTS AND DISSCUSION
Average values of ball velocities, and comparison between normal and heavy ball velocities are presented in Figure 1. In all positions throwing velocities with normal ball were greater than with heavy ball. The highest average normal ball velocities were detected in a P4N position, 77.3±4.3 km/h (21.47 m/s). The velocities in a P3N positions were slightly lower (but not statistically significant). The highest velocity measured was 84 km/h (23.3 m/s) in a P4N position, which corresponded to other references where values from 15 – 20.2 m/s (3, 4, 5) and maximum 25.8 m/s (10) were reported. The highest velocity of a heavy ball was measured in a standing P3H position – 40.0 ± 3.3 km/h. On the contrary to normal ball throws, the heavy ball velocities measured in a P4H position were significantly lower than in a P3H.

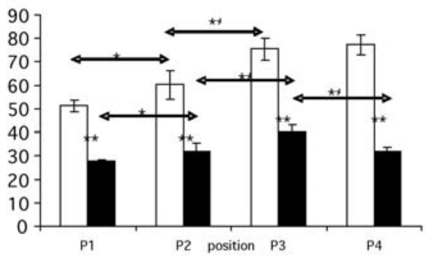

*Figure 1. Comparison between normal (white) and heavy (dark) average ball velocities. *p<0.05, **p<0.01.*

Increasable throwing velocity from P1 to P3 supports proximal-to-distal principle in throwing both balls. More muscles are activated in throwing kinetic chain, more energy is transferred from joint to joint and higher final velocity of the ball is achieved. There are no statistically significant differences between P3N and P4N. Because subjects were not familiar with any throwing positions except P4N (in the water), the lack of experience/training on the obtained velocities in P1, P2 and P3 positions can be rejected. Expressing the ball velocities as percentage of a P3 (P3 position was 100 %), throwing the ball with arm only (P1) resulted in a 68% and 70% of the referent maximum velocity of the ball, for normal and for the 3 kg ball, respectively (fig. 2). By activating the trunk muscles (P2), the average ball velocity increase was 11 % (P2N) and 9 % (P2H), respectively. In standing position (P3N and P3H) the velocity was further increased by 20 %.

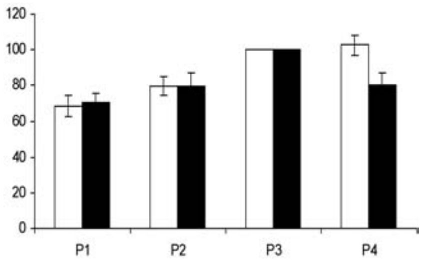

Figure 2. Comparison between normal (white) and heavy (dark) average ball velocities, expressed as percentage of a P3.

However, in water throw (P4) normal ball velocity was additionally increased for 3%, on average (no statistical significance), while heavy ball throwing velocity decreased significantly for 20%. Very likely, this happened due to insufficient leg/pelvis stabilization in water during heavy ball throw, where greater forces are produced. While throwing normal ball, players were capable of fixing the pelvis and therefore the normal function of upper trunk and arm were enabled. Theoretically, increased pelvis and upper torso velocities would allow more momentum to be transferred from the trunk to the throwing arm, and ultimately to the ball, leading to the increased throwing velocities (6, 7). Using legs properly in the water, players enable stable position similar to the base of support on dry land. This stabilization seemed to fail when throwing heavy ball. The highest correlation between P2H and P4H (r = 0.92) showed on smaller pelvis/leg action involvement in heavy ball water throws. This data underlines the importance of proper leg work when throwing in the water.
The N/H throw velocity relationship [(v_{norm}/v_{heavy})*100] did not change in first three positions and therefore showed no dependence on the length of the kinetic chain (fig. 3). Every position actually represents different throwing technique, because new (more) muscles were added to the kinetic chain. This showed that throwing technique might be independent on the ball weight when throws were performed on dry land. However, this might not be true for throws in the water.

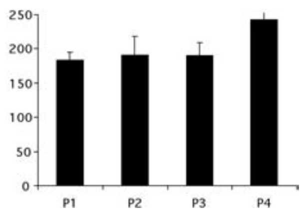

Figure 3. Velocity coefficient between normal and heavy ball.

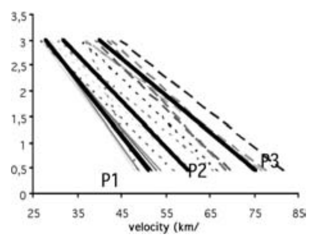

Figure 4. Force-velocity relationship for each subject. Bold lines represent mean relationship for each position.

Connecting the velocities of H and N ball, we can present the force-velocity relationship. Steeper line is assumed to be more on the left side of the force-velocity curve representing greater relative load. Since in every position stronger muscles were added, the same balls became relatively lighter. We believe that non-systematic differences were due to individual characteristics and specific adaptation, which was a consequence of long term specific training. Figures 5 in 6 show ball velocities increase for all subjects for N and H ball respectively. Subjects are arranged on the basis of the maximal P3N throw. Similar patterns (except subject C) of ball velocity increase from P1-P3 can be observed for both normal and heavy ball. The player who threw the ball with the highest velocity was able to increase ball velocities from P1 to P4 most proportionately with both the normal and heavy balls. On an individual basis, it could also be observed that players playing in different positions (driver, center-forward, goalkeeper) had different velocity increases profiles due to changed kinetic chain. With longer kinetic chain, center-forward and goalkeeper were not able to perform throws with such velocities as players playing in field position. This could be explained with conditional and technical specificities of goal-keepers and center-forwards. Goalkeepers normally do not perform throwing with maximal velocities (shots), and center-forwards perform throws from positions near the goal using, most of the time, rather different techniques than overarm throw.

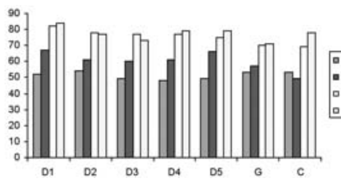

Figure 5. Normal ball velocities for all subjects. D1..D5-drivers, G-goalkeeper, C-center-forward.

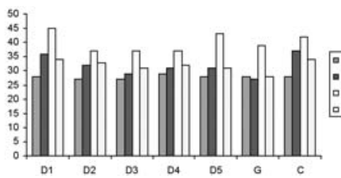

Figure 6. Heavy ball velocities for all subjects. D1..D5-drivers, G-goalkeeper, C-center-forward.

CONCLUSIONS

It is concluded that method of adding muscles to the active throwing kinetic chain provide important information for water polo players in order to characterize their throwing performance.

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ESTIMATION OF THRUSTS GENERATED BY EACH BODY PART DURING UNDERWATER DOLPHIN KICK USING "SWUM"

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It is important to understand the dynamics of the entire human body during swimming, but measurement of the fluid force of a self-propelled human body is extremely difficult. A simulative model of human swimming "SWUM" (SWimming hUman Model) incorporates dynamics of the entire human body. This study is intended to use the simulation model to calculate the thrust generated by each body part during underwater dolphin kick. First, an outline is described for the simulation model. Second, the methods of measuring input data for the simulation model are described. Third, methods to recreate dynamics on the simulation are described. Consequently, the dynamics of the underwater dolphin kick were recreated through the simulation. Results showed that the feet mainly generate thrust during the underwater dolphin kick. Furthermore, both increased thrust and drag are important for faster swimming because greater thrust generates greater drag.

Key Words: Fluid dynamics, dolphin kick, simulation model, thrust.

INTRODUCTION

It is important to understand the dynamics of the entire human body during swimming for proper evaluation of swimming motion because swimming motion is a movement of the entire body in water. Nevertheless, a quantitative method of unsteady fluid forces affecting each body part during swimming has not been established yet because humans change their posture during propulsion through the water. For that reason, a simulation model of human swimming, SWimming hUman Model (SWUM), was developed to incorporate the dynamics of the entire human body during swimming (1). This study calculates the thrust generated by each body part during swimming using the simulation model. In this study, the underwater dolphin kick was taken as an object of this study because swimming motion is symmetric and simple.

METHODS

Outline of SWUM

In SWUM, the entire body is represented as a series of elliptic cylinders whose radius can vary along the axial direction. Three unsteady fluid forces (added mass, F_a; resistive force for normal direction, F_n; resistive force for tangential direction, F_t), buoyancy and gravity all act on the elliptic cylinders. They are computed from the shapes and densities of the elliptic cylinders and the joint motions as relative body motions for one cycle. These computed forces provide six degree-of-freedom absolute motion of the entire body as one rigid body from equations of motion for the human body. The simulation yields the swimming velocity and angular motions of roll, pitch, yaw, etc.

Input data

The input data for the simulation are the shapes and the densities of the elliptical cylinders and joint motions as relative body motion for one cycle. This study measured these input data in one well-trained male swimmer (Masters world-record holder). The human body was represented as 21 elliptical cylinders. Lengths of the major and minor axes and the height of each elliptic cylinder were measured in the subject's body shape. The weight of each elliptic cylinder was computed using a mass ratio (2) and the subject's body weight. Then the density of each elliptic cylinder was computed from the weight and the volume of each elliptic cylinder.
Joint motions as relative body motions for one cycle were measured in an underwater dolphin kick with two different velocities (slow and fast), as determined by the subject's intention. Swimming motions were recorded on video recorders (WV-PR9; Sony Corp.) at each trial using two synchronised cameras (TK-C1381; Victor Inc.) that had been positioned to take underwater images. Co-ordinates on the right side of the body were calculated using three-dimensional DLT method. The co-ordinates on the left side of the body were computed from right-side data, assuming that underwater dolphin kick motion was symmetric. Only joint motions of the sagittal plane were incorporated into the simulation in this experiment because the underwater dolphin kick motion mainly comprised the rotation in the sagittal plane.

Identification of fluid coefficients

To recreate the dynamics of the underwater dolphin kick motion on the simulation, three fluid coefficients, used to calculate the three unsteady fluid forces (F_a, F_n, F_t), were identified as slow and the fast trials. The combination of the three fluid coefficients was determined to fill differences in the swimming velocity changes for one cycle between simulated values using measured input and measured values by motion analyses. After identification of the fluid coefficients, the fluid forces acting on the human body were simulated. The thrust generated by each body part was analysed.

RESULTS

Figure 1 shows the subject's body represented by 21 elliptic cylinders applied the measured subject' body shapes. Figure 2 shows stick pictures of underwater dolphin kick motions analyzed from motion analyses and animations of the elliptic cylinders applied those motions and the subject's body shapes. By adapting the measured input data to the 21 elliptic cylinders, the subject's body geometry and the underwater dolphin kick motions were recreated in the simulation.
At both slow and the fast trials, the simulated velocity changes for one cycle almost corresponded to the measured ones (Fig. 3). The swimming velocity increased at the extension phase of the knee joints and decreased at the preparation phase of the next downward kick motion at both trials. As Fig. 4 shows, the thrust generated by the entire body nearly corresponded to the value generated by the lower limbs. During the slow trial, the thrust generated by the lower limbs was generated almost entirely by the feet. Moreover, the trunk with the head, also contributed to the thrust. Along with slow trials, the thrust generated by the entire body closely corresponded to the value generated by the lower limbs, and the thrust generated by the lower limbs was almost entirely generated by the feet during the fast trial (Fig. 5). However, the trunk with the head did not contribute to the thrust. During both trials, the thrust reached a maximum value at the extension phase of the knee joints. The maximum thrust of the fast trial (665 N) was almost twice that of the value of the slow trial (371 N). The minimum thrust of the fast trial (-247 N) was smaller than the value of the slow trial (-163 N). This results shows the maximum drag of the fast trial was greater than the value of the slow trial because negative thrust means drag.

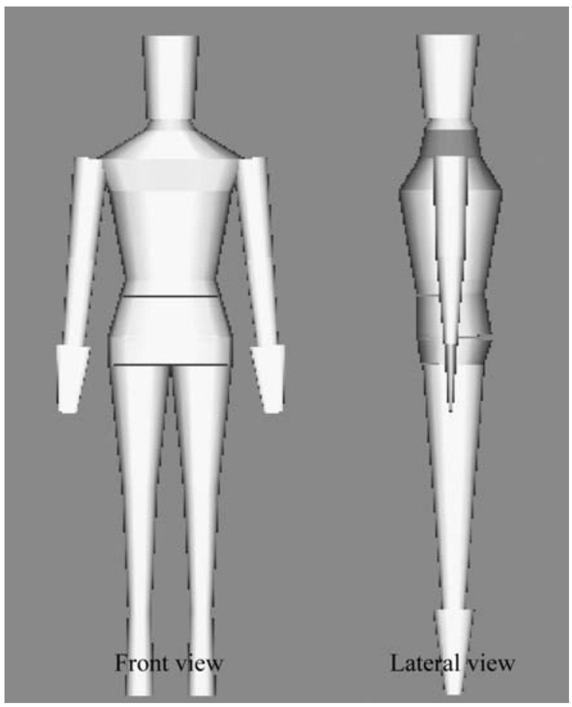

Fig. 1. Subject's body represented by 21 elliptic cylinders. The entire body is divided as follows: head, neck, shoulder, upper breast, lower breast, upper waist, lower waist, upper hip, lower hip, right upper arm, left upper arm, right forearm, left forearm, right hand, left hand, right thigh, left thigh, right shank, left shank, right foot, and left foot.

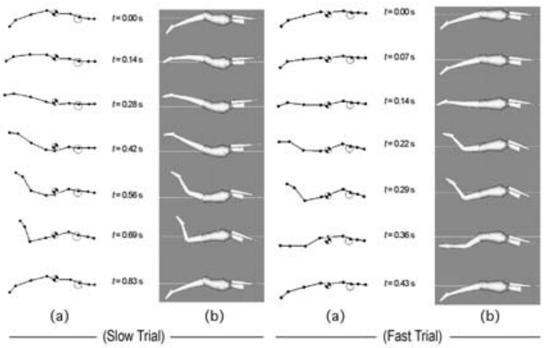

Fig. 2. Stick figures (a) of underwater dolphin kick motions (slow and fast trials) drawn from motion analyses and animations (b) of elliptic cylinders that applied those motions. The required time of the underwater dolphin kick motion for one cycle is 0.83 s during the slow trial and 0.43 s during the fast trial.

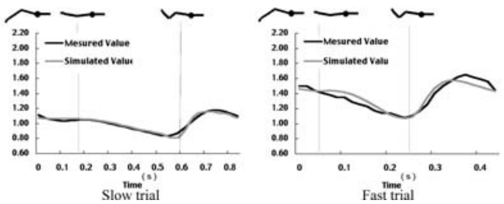

Fig. 3. Velocity changes for one cycle (slow and fast trials). During the slow trial, the mean measured swimming velocity was 1.01 m/s; the mean swimming velocity simulated using the identified coefficients was 1.02 m/s. During the fast trial, the mean measured swimming velocity was 1.36 m/s; the mean swimming velocity simulated using the identified coefficients was 1.37 m/s. The stick figures above the graphs show the phase of the underwater dolphin kick motion.

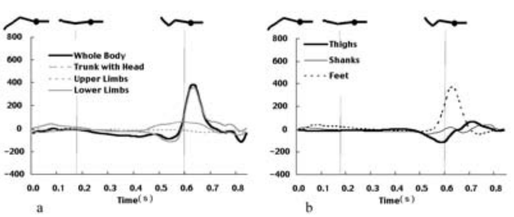

Fig. 4. Contribution of each body part to thrust for one cycle during the slow trial. The left graph (a) shows the respective contributions of the entire body, the trunk with the head, the upper limbs, and the lower limbs to the thrust. The right graph (b) shows the respective contributions of the thighs, the shanks and feet to the thrust.

DISCUSSION AND CONCLUSIONS

The subject's body geometry and the underwater dolphin kick motions were recreated through the simulation by adapting the measured input data to the 21 elliptic cylinders. The simulated velocity changes for one cycle almost corresponded to the measured one at both slow and the fast trials. Results showed that the dynamics of the underwater dolphin kick were recreated on the simulation through identification of the fluid coefficients. That simulation verified that feet mainly generated the thrust of the underwater dolphin kick. In addition, by increasing the swimming velocity, both the maximum thrust and drag were increased. As expected, both increased thrust and drag were important to swim faster because generating greater thrust was attended by generating greater drag.

Further research should examine how joint torque is generated and how it contributes to thrust during the underwater dolphin kick. Moreover, analytical methods that can determine the best dolphin kick motion suitable for each swimmer's figure can be established using this simulation model. Results can be used to instruct swimmers and their coaches, facilitating faster swimming.

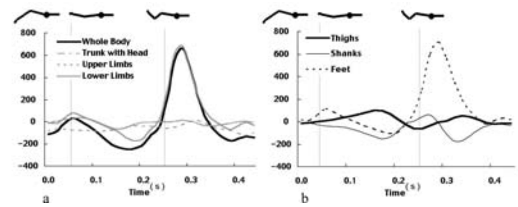

Fig. 5. Contribution of each body part to thrust for one cycle during the fast trial. The left graph (a) shows the respective contributions of the entire body, the trunk with the head, the upper limbs, and the lower limbs to the thrust. The right graph (b) shows the respective contributions of the thighs, shanks and feet to the thrust.

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WHAT ARE THE DIFFERENCES BETWEEN GRAB AND TRACK START?

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This study was intended to explain the difference in kinematic characteristics between a grab start and a track start in competitive swimming. The starting movement was modeled using a pendulum model. The take-off velocity (V_t) was resolved to a rotational component (Vr_t) and an extensional component (Ve_t). The Vr_t of the track start was higher than that of the grab start, although Ve_t of the grab start was higher than that of the track start. A swimmer with a track start would be able to generate the high Vr_t through the large moment of vertical force acting on the rear foot about the center of gravity. In contrast, swimmers using the grab start would be able to generate high Ve_t because the foot placement is in the same position on the front edge of the starting block. The take-off velocity of the grab start is higher than that of track start because of the great contribution of Ve_t to take-off

velocity. In addition, the rotational displacement of the track start around the front edge of the starting block was small. Therefore, the track-start block time was shorter than that using the grab start.

Key Words: swimming start, grab start, track start, pendulum model.

INTRODUCTION
The grab start and track start are major starting techniques of competitive swimming. Numerous studies have compared both starts (1, 2, 4, 5, 6). Differences in their kinematic characteristics are that the take-off velocity of the grab start was faster than that of the track start, whereas the block time of the track start was shorter than that of the grab start (3-5). Most studies have concluded that no difference exists between these starts in terms of the start performance time (1, 2, 5, 6).
The number of swimmers using the track start has increased recently. It is important for swimmers to know the kinematic characteristics of both starts to allow rational selection of either the grab start or track start. Nevertheless, the differences in kinematic characteristics between both starts have not been explained adequately.
The apparent difference between both starts is the placement of feet on the starting block at the set position. With the track start, the swimmer's foot placement is open and back and front; one foot is on the edge of starting block and the other foot is behind its foot. With the grab start, both feet are in a similar position on the front edge of the starting block. Such feet placements are inferred to be attributable to the respective kinematic characteristics of both starts. This study is intended to explain the differences between both starts according to foot placement on the starting block.

METHODS
In the experiments of this study, 12 elite college competitive swimmers (age=20.4 ± 1.0 yrs, height=178.4 ± 5.7 cm, weight=70.2 ± 6.5 kg) participated. They were separated into two groups according to their type of starting technique (grab: $n = 6$ or track: $n = 6$). After a warming-up period, each subject performed a maximal effort trial of each starting technique. Starting movements of subjects were recorded from a sagittal view using a high-speed camera at 125 fps. Video images were taken, and then stored in a personal computer. Kinematic variables were calculated using 2D-DLT method with motion analysis software (Frame Dias 2 version 3; DKH, Japan).

Modeling

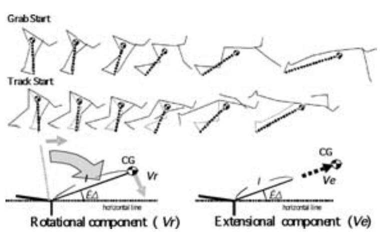

Figure 1. The pendulum model diagram. The starting movement was modeled as a movement including the rotation of segment l around the front edge of the starting block (rotational component: Vr*) and expansion-contraction of segment l (extensional component:* Ve*). The body angle (θ) represents the angle between the segment l and horizontal line.*

In this study, starting movements were modeled using a pendulum model. In this model, swimmers were depicted by segment *l*, which is the center of gravity (CG) connected with the front edge of starting block. The starting movement comprised rotational movement around the front edge of the starting block, and expansion-contraction of segment *l*. Figure 1 shows a diagram of this model. The velocity vector of CG was resolved to the rotational component (*Vr*) and the extensional component (*Ve*).

Definitions of kinematic variables
The block time was measured from the starting signal until take-off, which was defined as the time of swimmer's foot leaving the starting block. The body angle (θ) was defined as the angle between segment *l* and the horizontal line. The respective body angles at the set position and take-off were θ_s and θ_t. The take-off velocity (V_t) was the magnitude of resultant velocity vector of CG (V) at take-off. The rotational component (*Vr*) and the extensional component (*Ve*) were calculated from the following equations (i). In addition, *Vr* and *Ve* at the take-off were expressed respectively as Vr_t and Ve_t.

$$Vr = -l\theta$$

$$Ve = l \qquad \text{(Eq. i)}$$

The take-off angle (Φ) was defined as the angle between the take-off velocity vector and the horizontal line. The flight distance was the horizontal distance from the wall on the water surface to the entry point of CG.

Data smoothing and statistical analysis
Coordinate data were smoothed using a second-order Butterworth digital filter; with cutoff frequencies determined for each subject based on the horizontal velocity of CG after take-off until water entry became constant (6–8 Hz). Statistical analyses of the grab and track starts were performed using a non-paired *t*-test ($P<0.05$ was inferred as significant).

RESULTS
Mean values and standard deviations of each kinematic variable are shown in Table 1. Block time was significantly shorter for the track start. No significant difference existed between the groups in take-off velocity (V_t) ($P=0.11$). Vr_t was significantly faster in the track start and Ve_t was significantly faster in the grab start. θ_t was significantly larger in the track start. Figure 2 showed changes of the mean velocity of CG (*V*), *Vr* and *Ve* until the take-off in grab and track start. The x-axis is the normalized time to assume the mean block time of the grab start as 100%. Regarding the patterns of velocity change until take-off, after increment of *Vr*, *Ve* increased.

Table 1 Comparisons of kinematic variables between grab and track start.

		Grab start (n=6)		Track start (n=6)		
		Mean	±SD	Mean	±SD	
Block time	sec	0.78	0.03	0.71	0.05	*
V_t (Take-off velocity)	m/s	4.38	0.13	4.26	0.11	
Vr_t (Rotational component at the take-off)	m/s	1.99	0.11	2.56	0.05	**
Ve_t (Extensional component at the take-off)	m/s	3.91	0.12	3.42	0.12	**
Flight distance	m	3.25	0.20	3.15	0.10	
θ (Take-off angle)	deg	-1.6	4.1	-3.4	1.6	
θ (Body angle at the set position)	deg	95.1	2.5	99.0	5.6	
θ (Body angle at the take-off)	deg	24.7	3.7	33.4	1.4	**

*: Significant difference between grab start and track start. ($P<0.05$)
**: Significant difference between grab start and track start. ($P<0.01$)

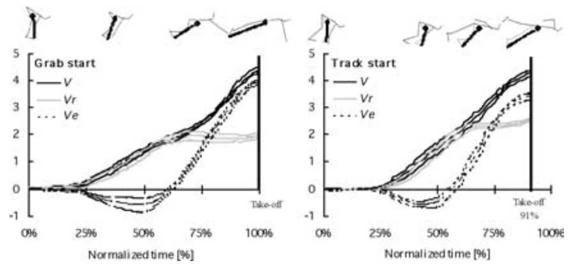

Figure 2. Changes of velocity of CG (V), Vr and Ve for the grab (left) and track start (right). Each velocity was plotted as a mean (thick) ± SD (thin). The normalized time was the percentage, assuming the block time of the grab start was 100%. The mean block time of the track start corresponded to 91% of the normalized time of the grab start.

DISCUSSION

Using the pendulum model, the swim-starts can be explained as a movement composed of rotation (*Vr*) and expansion-contraction (*Ve*) of the segment *l*. Rotation of segment *l* was caused by the moment of forces that the body received from the starting block (fig. 3). When the body angle (θ) was less than 90 degrees, vertical forces would generate the moment about the center of gravity, which tends to sink the head, whereas horizontal forces would generate the moment that tends to elevate the head.

Results of this study show that the track start was superior to the grab start in Vr_t (grab: 1.99 ± 0.11 m/s, track: 2.56 ± 0.05 m/s). It was therefore deduced that the moment in the track start was larger than that of the grab start. The apparent difference between both starts was the foot placement on the starting block. In the track start, swimmers generate greater moment of vertical force acting on the rear foot ($Fy_{rear\text{-}foot}$) because the moment arm of $Fy_{rear\text{-}foot}$ about the center of gravity is greater (fig. 4b). In contrast, it would be difficult to generate a moment of vertical forces acting on the feet (Fy_{feet}) in a grab start because of the shorter moment arm of Fy_{feet} about the center of gravity (fig. 4a).

In relation to Ve_t, the grab start was superior to the track start in Ve_t (grab: 3.91 ± 0.12 m/s, track: 3.42 ± 0.12 m/s). The expansion-contraction of segment *l* depends on pushing off the starting block using the legs. It would be difficult for the track start to push off the starting block strongly using the lower limbs in comparison to the grab start because of the foot placement. The rear foot in the track start was not on the front edge of the starting block, so the horizontal force acting on the rear foot depends almost entirely on the frictional force to the surface of the starting block. Consequently, the track start was inferior to the grab start in Ve_t. Ultimately, the take-off velocity of the grab start was higher than that of the track start because Ve_t contributed a greater deal to take-off velocity. Although there was no significant difference between both starts in take-off velocity, this suggestion would be supported by literatures reporting on take-off velocity of both starts (3, 5).

The block time would be associated with the body angle at take-off (θ_t), which indicates the angular displacement of θ until take-off. As a result, the θ_t of the track start was larger than that of the grab start, but no significant difference existed between both starts in the body angle at the set position (θ_s).

This lack of difference indicated that the angular displacement of θ from the set position to take-off was smaller than that of the track start. Therefore, a shorter block time of the track start resulted from the small angular displacement of θ and the higher *Vr*. In the pendulum model, θ_t, Vr_t and Ve_t were factors to determine the take-off angle (Φ). This relationship is expressed by following formula (ii).

$$\Phi = \theta_t - \arctan\left(\frac{Vr_t}{Ve_t}\right) \quad \text{(Eq. ii)}$$

The arctangent of track start was larger than that of the grab start because of the higher Vr_t and the lower Ve_t. Therefore, the θ_t of the track start was larger than that of the grab start. Even if a swimmer using a track start would take off at the same take-off angle (Φ) as that of the grab start, the angular displacement of θ until take-off would become small (fig. 5). Consequently, the block time of the track start might be shorter than that of the grab start.

The difference between the techniques is attributable to foot placement, especially the rear foot on the starting block. The rear foot in the track start was inferred to contribute to generation of high *Vr* and lower angular displacement of θ than that of the grab start.

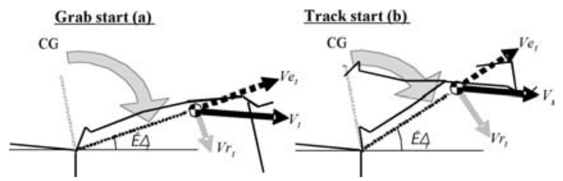

Fig. 5 Stick-pictures of grab (a) and track start (b) at the take-off. The body angle at the take-off (θt) in track start was large because of a great contribution of the rotational component (Vrt) to the take-off .velocity (Vt), if the take-off angle were equivalent.

CONCLUSION

In the track start, the great contribution of rotational component (*Vr*) by the rear foot leads to a lesser angular displacement of the body angle (θ) until take-off, thereby shortening the block time of the track start. In the grab start, the great contribution to the extensional component from pushing off of both legs engenders the high take-off velocity. It might be necessary in future studies to analyze the starting movement using kinetic data, and to verify the implications of this study.

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INTRACYCLE SPEED AND COORDINATION VS FATIGUE IN SWIMMING

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Intracycle speed variations have been widely studied. However, few studies have focused on the fatigue effect on such intracycle speed in freestylers. The aim of this study was to analyse such effects. Hence, a synchronized speedmeter connected with a video camera was used and 17 swimmers were recorded with and without fatigue conditions. A complete cycle, four phases average speed and arms coordination were analysed in both conditions. There is a correlation of the average speed with phases 1 and 3 speed in both genders with and without fatigue. Also phase 2 speed in male and phase 4 in female swimmers are related to the average speed with fatigue. Coordination is related to the phase 4 in female swimmers with fatigue. Summarizing, the whole analysis of the partial speed and the coordination index gives us relevant information about intracycle kinematic responses of freestyle swimmers.

Key Words: intracycle speed, fatigue, coordination index and freestyle.

INTRODUCTION
The analyses of the speed variations carried out within a swim cycle provides information about the way in which the different phases of the cycle contribute to the swimmer's movement (2). The unequal application of the propulsion forces and the resistance forces to the advance is the cause of the changes of acceleration and, as a consequence, of the fluctuation of the speed during a complete swim cycle (4). Interaction between both generates fluctuations of the intracycle speed (5). A coordination index is used to evaluate freestyle coordination. This index is focused on the position of the upper limbs (3). For the study of the intracycle speed, 4 phases can be established in freestyle swimmers (6). Before and after appearing the muscular fatigue to a maximum intensity, the average speed of the complete cycle diminishes, the times of propulsion of the propulsive phases increase and differs neither in the percentage variations of the maximum and minimal speed, nor in the coefficient of variation of the speed (1). The aim of this study is to establish a model of changes of intracycle speed in freestylers in efforts of maximum intensity with and without fatigue and its relation with swimming coordination.

METHODS
Sample: 17 national level swimmers (10 males and 7 females) aged between 14 and 16. Equipment: In order to record the intracycle speed, a JLML MV-30m speedmeter was worn by the swimmers through a belt and wire. The sample frequency was 1000Hz. Such record was synchronized to an underwater video camera. The image registered to a frequency of 50 Hz. The synchronization of both signs is marked by a common base of times generated by the measuring computer. The video camera was located at 15 meters off the start line, and in a perpendicular way at a distance of 5 meters to the swimmer's movement. Intracycle velocities record protocol: swimmers performed two series at maximum speed. The first over a distance of 25m was considered "without fatigue" condition (A), while the second one over a 100m distance was as "with fatigue" condition (B). There was a break of about 10 seconds between the first 75m and the last 25m so as the swimmer could have the belt attached. There was a 10 min rest between first and second conditions. A complete cycle of the swimmer was selected as he was passing in front of the camera, about 15 meters from the start in both series ("with fatigue" and "without fatigue"). Data report: Each cycle was divided in four phases from the video pictures (table 1). The cycle was divided on the basis of the propulsive actions performed, so the insweep of an arm does not coincide with the propulsive action of the other arm. However, the upsweep and the downsweep do coincide in some instants with the opposite arm propulsive actions. Therefore, phase 1 coincides with the right arm insweep and phase 3 with the left arm insweep. Phases 2 and 4 start with the upsweep of one of the arms and finish with the downsweep of the opposite arm. The index of coordination (IC) was used for the evaluation of the coordination. This index is a percentage value on the total time of a complete cycle and there is zero when the end (purpose) of the propulsion of an arm with the beginning of another one coincides. IC is negative in case of a delay (dead time). It is positive if there exists overlapping of the actions of both arms (3). The dependent variables were: cycle length (CL), cycle frequency (CF), cycle index (CI), speed of cycle (V) and index of coordination (IC) as well as the average speed, and the speed of each one of the phases (Sph1, Sph2, Sph3 and Sph4). The statistical analysis was with the statistical package SPSS 11.5 and consisted of a descriptive analysis (comparison of related samples and independent samples) and of a correlational analysis (Pearson correlation coefficients) for the variables above mentioned.

Table 1. Phases selected for the analysis intracycle.

	phase 1 (insweep right arm)	phase 2	phase 3 (insweep left arm)	phase 4
Start phase	Final of the downsweep right arm	Start of the upsweep right arm	Final of the downsweep left arm	Start of the upsweep left arm
Final phase	Start of the upsweep right arm	Final of the downsweep left arm	Start of the upsweep left arm	Final of the downsweep right arm

RESULTS
The table 2 shows the differences between the dependent variables CF (cycles/minute), CL (meters/cycle), CI (CL*V), V (meters/Second) and IC (%). According to the type of series, both male and female swimmers obtain significant differences in CF, V and CI. According to gender, in A series the significant differences are obtained in the CL, V and CI. In the B series only significant differences are obtained in V and in CI between genders.

Table 2. Differences between the dependent variables CF, CL, CI , V and IC.

		Male				Female			
	Set	N	Mean	sd	p	N	Mean	sd	p
CF	A	10	56.87	4.29	0.000	7	54.75	6.78	0.002
CF	B	10	48.89	4.85		7	45.37	7.29	
CL	A	10	1.78*	0.12		7	1.60*	0.26	
CL	B	10	1.76	0.12		7	1.60	0.23	
S	A	10	1.68**	0.07	0.000	7	1.43**	0.09	0.001
S	B	10	1.42**	0.09		7	1.19**	0.13	
CI	A	10	3.02**	0.33	0.000	7	2.32**	0.36	0.001
CI	B	10	2.54**	0.23		7	1.85**	0.28	
IC	A	10	4.84	2.48		7	6.34	2.41	
IC	B	10	5.47	4.05		7	8.44	3.85	

Differences male-female * $p<0.05$ ** $p<0.01$

The intracycle analysis shows the differences between the average speeds in each of the phases (table 3 and graph 1). Thus, when the different speeds are compared between genders, only the Sph4 in the B series does not show significant differences. There are only significant differences between the Sph1 and the Sph2 in the B series from the analysis of the evolution of the speeds of the different phases in swimmers. In female swimmers, there are significant differences in both Sph1 and Sph2, as with Sph2 and Sph3 and between Sph3 and Sph4 in the A series. The differences found in the average speeds by phases in the A series with regard to the series B are significant in both genders.

Table 3. Statistics of the average speeds in each phase.

							Same gender and set			Same gender and set B			
							Sph2	Sph3	Sph4	Sph1	Sph2	Sph3	Sph4
	Set	Gender	N	Mean	sd	p	p	p	p	p	p	p	p
		M	1	1.68	0.09					0.000			
Sph1	A	F	7	1.42	0.10	0.000	0.004			0.001			
		M	1	1.71	0.10						0.001		
Sph2	A	F	7	1.55	0.03	0.000		0.004			0.002		
		M	1	1.65	0.09							0.000	
Sph3	A	F	7	1.41	0.10	0.000			0.032			0.001	
		M	1	1.74	0.12								0.001
Sph4	A	F	7	1.52	0.09	0.001							0.004
		M	1	1.40	0.11		0.026						
Sph1	B	F	7	1.17	0.15	0.002							
		M	1	1.49	0.13								
Sph2	B	F	7	1.26	0.13	0.003							
Sph3	B	M	1	1.43	0.10	0.000							
		F	7	1.18	0.11								
		M	1	1.39	0.23								
Sph4	B	F	7	1.25	0.20								

The correlational analysis shows that, in A and B, S has a high and positive correlation ($r>0,8$; $p<0,01$) with Sph1 and Sph3 in both sexes. In B, Sph2 for the male swimmers ($r=0,8$; $p<0,01$) and Sph4 for the female swimmers ($r=0,9$; $p<0,01$) obtain a positive correlation. In B, IC shows a high and positive correlation ($r=0,9$; $p<0,01$) in female swimmers with Sph4.

Table 4. Relationship average S and IC with S, Sph1, Sph2, Sph3 and Sph4 in female and male.

S	N	S phase 1	S phase 2	S phase 3	S phase 4	IC	S	S phase 1	S phase 2	S phase 3	S phase 4
$Male_A$	10	.84**	.55	.89**	.18	$Male_A$	0.14	0.41	-0.05	-0.13	0.02
$Male_B$	10	.84**	.77**	.96**	.24	$Male_B$	-0.02	-0.13	0.19	0.03	-0.23
$Female_A$	7	.96**	.67	.97**	.52	$Female_A$	-0.09	-0.01	0.27	-0.19	0.50
$Female_B$	7	.98**	.60	.99**	.92**	$Female_B$	0.79*	0.69	0.49	0.70	0.88**

* $p< 0.05$ ** $p<0.01$

DISCUSSION

The CL and the IC in fatigue do not differ with the values obtained without fatigue. CF, V and CI reduce their values in a significative way. This information contrasts with the reduction of CL and IC in other studies that analyze these variables at the beginning and at the end of a maximum effort (1). The difference between the results obtained with the present study can be caused due to the variability in which the swimmers response to the speed loss. The correlational analyses of these variables with the intracycle speed might facilitate information on how the best swimmers modify the CL and IC.

As for the speeds obtained in the different studied phases, the female swimmers obtain lower speeds that the male swimmers in all the phases and series, except in the phase 4 and in conditions of fatigue. Without fatigue, the speeds of the phases 2 and 4 are higher than the speeds of the phases 1 and 3. This is significant as for of the female swimmers is concerned. With fatigue, the differences between the speeds are not significant. According to these results, the changes of speed for phases that take are produced by female swimmers in the A series can only be emphasized as a repetitive pattern.

Also the losses of speed obtained in the different studied phases do respond to repetitive pattern in both genders. Concerning the changes of speed in the described phases in this study, it would be necessary to do new studies with more swimmers to determine, if so, the patterns of change of the best swimmers.

The results allow determining that the best swimmers obtain the highest speeds in the phases 1 and 3 in both series. This distinguishes the importance of these phases in the performance of both male and female swimmers. Contrary to this, only the best male swimmers have higher speeds in the phase 2 in situation of fatigue, as well as the best female swimmers obtain the higher speeds in the phase 4 in situation of fatigue. These relations in the phases 2 and 4 may occur because the best swimmers have a better balance between the propulsive forces and the resistance forces. As well as the fatigue in the worst swimmers might impede the coordination body/arms/legs in a few phases where the body rolling is maximum (4 and 5).

In this study, the IC does not change when the swimmers are fatigued. This fact contrasts with IC's decrease in other studies (1). Hereby, IC's increase obtained before diminishing speeds (3) cannot take place when the speed loss is due to a situation of fatigue as it is described in the present study. For this the IC cannot contribute with relevant information about the changes of coordination in situations of fatigue.

The correlational study of the IC with the average intracycle speeds and with the average speeds in the different phases shows that no relation exists between the best male swimmers and the type of coordination. On the other hand, in the female swimmers, the established relation indicates that the swimming improvements in situation of fatigue have a higher IC. Hereby, it is possible to indicate that the best female swimmers, with fatigue, reach major speeds due to a higher IC. Moreover, a high relation between the speed in the phase 4 and IC's values is obtained, which can emphasize the importance of supporting IC's high values in order to reduce the speed losses registered of Sf4 in conditions of fatigue. The speed of the phase 4 in conditions of fatigue does not obtain significant differences between male and female swimmers. This descriptive result might be justified by the increase of the IC in the female swimmers in conditions of fatigue and its high correlation with the speed in the phase 4.

CONCLUSION

1-When swimming without fatigue, Sph1 and Sph3 seem to be good indicators of the performance.
2-When swimming with fatigue, Sph1, Sph2 and Sph3 for the male swimmers and Sph1, Sph3 and Sph4 for the female swimmers ones are good indicators of the performance.
3-In the female swimmers, a high IC when swimming with fatigue is related to a better performance in S and Sph4. In conclusion, the whole analysis of the IC and of the Sph1, Sph2, Sph3 and Sph4, can contribute to relevant information about the most suitable type of coordination when swimming in different conditions of fatigue.

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THE RELATIONSHIP OF ANTHROPOMORPHOLOGICAL CHARACTERISTICS OF CRAWL SPRINT SWIMMERS OF BOTH GENDERS WITH CRITICAL SPEED AT 50 AND 100 M

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The aim of this work is to establish a relationship between the various anthropomorphological ($A_{nth}M_{orph}$) characteristics of crawl sprint swimmers of both genders in relation to critical speed at 50 and 100 meters (sprint distances). The research has been carried out over a sample of 13 male and 12 female swimmers in sprint crawl style. The given value of the critical speed at 50 and 100 meters was obtained by applying the mathematical modelling of Distance – Time ratio, calculated from the 15, 25, 50 and 100m distances covered in crawl style. The $A_{nth}M_{orph}$ characteristics of swimmers are evaluated over a set of eight variables: BMI, LBM, and percentage of fat, leg-length and arm-length index, the shape of the chest, the trunk and the body. With regards to men, a higher level of critical speed had those with a more pronounced rectangular shape of trunk (the same proportion of the width of shoulders and hips in relation the the body height) and a higher level of lean body mass – LBM. With regards to women, a higher level of critical speed had swimmers with a shorter arm length in relation to body height and a higher LBM.

Key Words: crawl sprint swimmers, critical speed, anthropomorphological characteristics.

INTRODUCTION

The elite results in swimming depend on a number of factors including the efficiency of the swimming technique, various functional and metabolic characteristics of swimmers and the level of training accomplishment. They also depend on a number of features of the swimmer's body (2, 8, 9). In general, besides an efficient swimming technique, that is the way swimmers move in the water, the body shape and/or the body size of a swimmer may help him to obtain a better position for a more efficient swim from the hydrodynamics standpoint. In this way, the body shape or the body size, i.e. the anthropomorphological characteristics, may contribute significantly to achieving better results. It is known that during the movement of the body in the water, the phenomenon of resistance appears. It has two basic characteristics, that is the active and passive drag forces. In general, the passive drag forces constitute themselves the hydrodynamic of the swimmer's body and could be more related to the gliding phase of swimming (2, 7, 9). On the other hand, active drag forces would be more closely related to the changes of the body position during swimming and they have three basic causes, namely: "pressure or form drag, frictional drag and wave drag" (6, 8, 10). It has been found that mean active drag force (Fd) is related to swimming velocity and demonstrates an approximately quadratic dependency on velocity. Besides, it is different for female and male swimmers (10). It is concluded that differences in the body structure, that is the body shape and size, may have a different impact on the results achieved. In other words, it can play a negative role or provide an advantage in achieving a higher level of performance.
The aim of this study is to initially establish a relation between the critical speed in swimming, as a simple indirect parameter to use in following the general efficiency in swimming (6, 8, 11) and a score of various, but not difficult for measuring and observation, antropomorphological characteristics defining the swimmer's body shape. The obtained results could also prove useful in perfecting the swimmers selection methods, and in certain aspects of the hydrodinamics of swimming.

METHODS

The research has been carried out over a sample of 25 swimmers (13 male and 12 female) in a sprint crawl style. The basic descriptive characteristics of the sample were: Male – Age=15.3±1.4 years, BH=1.754±0.079 m, BW=63.58±5.84 kg; Female - Age=14.8±1.2 years, BH = 1.612±0.064 m, BW = 49.48±7.19 kg. All of them were members of swimming clubs in Athens. The given value of the critical swimming speed (CSS) at 50 (V_{crit}50) and 100 meters (V_{crit}100) was obtained by applying the mathematical modelling of Distance – Time ratio, calculated from the 15, 25, 50 and 100m swim in crawl style (measured from the start up in one training session) (11).
The $A_{nth}M_{orph}$ characteristics of swimmers were evaluated over a set of eight variables (1):
— Morphological variables –
- body mass index-BMI (kg/m^2), lean body mass-LBM (kg), and percentage of body fat (%),
— Anthropometrical variables -

- leg-length index, calculated as a ratio between sitting height and body height,
- arm-length index, calculated as a ratio between front arm span and body height,

— Body shape variables –

- index of the chest shape, calculated as a ratio between chest depth and shoulder width (biacromial),
- index of the trunk shape, calculated as a ratio between hips width (bitrochanteric) and shoulder width (biacromial),
- index of the body shape, calculated as a ratio between hips width (bitrochanteric) and body height.

All anthropometrics and body shape variables are presented in the arbitrary units.
The results have been analyzed by applying descriptive and multiple regression analysis where the variables of the CSS represented the criteria and, the $A_{nth}M_{orph}$ characteristics represented the predictor system (5).

RESULTS

In Tables 1 and 2, the results of the descriptive statistical analysis of the sample variables are presented. In accordance with the values of the coefficient of variation (cV%) it is recognised that the all results are reliable because their variation ranges below the limit of 30% (5). For the male swimmers, the cV% is in the range at 2.65% as regards the variable of the arm-length index and 25.61% for the variable of the body fat, whereas for the female swimmers the values are from 2.55% to 25.61%, respectively.
The results of multiple regression analysis show that for male swimmers, the given $V_{crit}50$ is explained at the level of 56.85% ($AdjR^2$ = 0.5685), and statistically in a significant way (F = 4.95, p = 0.026). It was defined as a model structure by the following set of predictors: index of the body shape (t = 3.09, p = 0.015), index of the trunk shape (t = - 1.43, p = 0.188), LBM (t = 3.73, p = 0.006) and BMI (t = - 2.37, p = 0.045).
The $V_{crit}100$ is explained at the level of 57.79% ($AdjR^2$ = 0.5679), and it was defined in a significant way statistically (F=5.10, p=0.024) by the model structure of the following set of predictors: index of the body shape (t=1.32, p=0.224), index of the trunk shape (t= - 1.52, p=0.168), LBM (t=2.18, p=0.061) and the percentage of the body fat (t= -3.26, p= 0.012).

Table 1. The variable descriptive analysis of male swimmers.

MALE swimmers (N = 13)	$V_{crit}50$ (m/s)	$V_{crit}100$ (m/s)	BMI (kg/m²)	LBM (kg)	% of Body fat	leg-length index	arm-length index	Index of the chest shape	Index of the trunk shape	Index of the body shape
MEAN	1.656	1.572	20.70	59.05	7.13	0.5196	1.0429	0.5150	0.8102	0.1858
SD	0.106	0.084	1.73	5.62	1.83	0.0138	0.0349	0.0349	0.0288	0.0054
cV%	6.38	5.36	8.38	9.51	25.61	2.65	2.77	6.78	3.56	2.90
Min	1.477	1.462	17.29	52.28	4.02	0.5028	1.0056	0.4512	0.7750	0.1782
Max	1.786	1.715	23.95	72.18	10.19	0.5479	1.0847	0.5732	0.8750	0.1955

Table 2. The variable descriptive analysis of female swimmers.

FEMALE swimmers (N = 12)	$V_{crit}50$ (m/s)	$V_{crit}100$ (m/s)	BMI (kg/m²)	LBM (kg)	% of Body fat	leg-length index	arm-length index	Index of the chest shape	Index of the trunk shape	Index of the body shape
MEAN	1.516	1.445	18.97	41.37	15.23	0.5310	1.0402	0.5104	0.8119	0.1825
SD	0.076	0.074	2.17	4.70	3.71	0.0140	0.0245	0.0624	0.0809	0.0136
cV%	4.98	5.15	11.42	11.35	24.38	2.64	2.35	12.23	9.96	7.44
Min	1.387	1.319	14.74	31.84	8.35	0.5158	1.0127	0.4167	0.6857	0.1548
Max	1.623	1.529	21.57	47.24	22.59	0.5578	1.1056	0.6349	0.9841	0.1975

For female swimmers, the $V_{crit}50$ is explained at the level of 57.09% ($AdjR^2$ =0.5709), and it was defined in a statistically significant way (F=8.31, p=0.009) by the model structure of the following set of predictors: arm-length index (t= -3.21, p=0.011) and LBM (t =3.40, p=0.008).
The $V_{crit}100$ is explained at the level of 47.29% ($AdjR^2$ = 0.4729), and it was defined in a statistically significant way (F = 5.93, p = 0.023) by the same set of predictors, that is arm-length index (t = -3.03, p = 0.014) and LBM (t = 2.52, p = 0.033).

DISCUSSION

The results show that statistically there is a significant relationship between the crucial swimming speed in the sprint distances of 50m and 100m in sprint crawl style for both male and female swimmers and that there exist different anthropomorphological characteristics which affect a specific critical speed. In addition, the results demonstrate that there are significant differences between male and female swimmers with respect to the CSS.
As regards both critical speeds (at $V_{crit}50$ and $V_{crit}100$) for male swimmers, it was confirmed that a positive correlation between them and the body shape index and the LBM. This implies that swimmers who with a more pronounced rectangular shape of trunk (the same proportion of the width of shoulders and hips in relation the the body height) and a higher percentage of muscle mass, have a higher $V_{crit}50$ and the $V_{crit}100$. On the other hand, the negative relationship between the $V_{crit}50$ and $V_{crit}100$ and the index of the trunk (chest) shape, the BMI and % of the body fat was also confirmed. This mean that swimmers who have broader shoulders in relation to their chest depth (that is, who have a flattered shape of chest) and small BMI as well as a small percentage (%) of body fat (that is, who have a lesser body surface area) have a higher $V_{crit}50$ and $V_{crit}100$ in sprint crawl swimming.
As regards $V_{crit}50$ and $V_{crit}100$ for female swimmers the positive relationship concerning the value of the LBM was confirmed. That means that female swimmers who have a higher percentage of muscle mass have a higher $V_{crit}50$ and $V_{crit}100$. On the other hand, the negative relationship between the $V_{crit}50$ and $V_{crit}100$ and the arm–length index was also confirmed. This implies that female swimmers having short arms in relation to their body height, that is they are short-armed 0swimmers, and have a higher critical speed at 50m and 100m. In the past it was proved that female swimmers pulled deeper and narrower than male swimmers and had a lower propulsive force (4). It is well known that higher swimming velocities are mainly achieved by an increase of stroke frequency (10), especially at sprint distances (3).
It is possible, regarding the sample, that short-armed female swimmers were capable of achieving, in sprint distances, a higher swimming speed because they were managing to obtain a higher stroke frequency during the swimming.

CONCLUSION

The results have shown the existence of important differences between genders regarding the relationships between indices of $V_{crit}50$ and $V_{crit}100$ and $A_{nth}M_{orph}$ characteristics. As regards male swimmers from this sample, swimmers who attained faster critical speeds were those who had a more rectangular shape of trunk, a more flattened shape of the chest, higher LBM, lesser BMI and a lower % of the body fat. With regards to female swimmers from this sample, a higher level of critical speed at $V_{crit}50$ and $V_{crit}100$ was achieved by swimmers with shorter arms in relation to the body height, and by those who had and a higher level of lean body mass – LBM.

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CONSEQUENCES OF UNSTEADY FLOW EFFECTS FOR FUNCTIONAL ATTRIBUTION OF SWIMMING STROKES

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The purpose is to direct attention to the relation of unsteady approach and functional attribution of strokes. Swimming strokes can be executed with different modes per action, which require an answer what for is the function of a mode? The functional attribution of modes is closely related to the idea about flow conditions and its effects. Here flow is characterised by a mixture of steady and unsteady effects. In front-driven locomotion the momentum-transfer is related to effects from bound vortex (rotating water), shed vortex and the interaction between bound and shed vortex, called jet-flow which does not exist in stationary flow. Based on this, the functional attribution of actions are re-checked placing emphasis on common goals of motion mutual to all four swimming strokes, showing that appropriate flow-forms are created and organised by similar actions of the hand/arm.

Key Words: PIV-method, unsteady flow, vortex-induced momentum, action modes, jet-flow.

INTRODUCTION

Swimming strokes are means to propel the body into a desired direction. They are individual corporal motions according to men made rules, based on mental programs and powered by the organism with limited energy reservoirs. Counsilman (3) pointed out that swimmers have no alternative but to obey laws of nature. Appropriate laws will be found in the field of natural science including flow physics. Biomechanics of swimming is a field to bridge the gap between practise and science. It is the duty to give notice whenever the scientific view on motions in water changed and to provide some hints for the practise. The proceedings of the BMS-Series demonstrate the changes in understanding locomotion in water. Among others it became obvious that the unsteady nature of the flow demands more attention (to avoid misunderstandings concerning terminology: unsteady means non-stationary and steady flow means stationary flow). In an unsteady flow its effects are depending both on velocity and acceleration of the flow whereas in steady flow velocity is the only relevant parameter (again to avoid misunderstandings concerning terminology: unsteady flow is not equivalent to the notion "turbulence" and does not mean swimming in a flume). The question may arise to which extent the unsteady-flow-approach has consequences for the understanding of modes of motion, e.g. closed or spread fingers during of underwater action of arm-motion? The following approach is oriented on a theory called Functional Motion Analysis (4), emphasising that each action is closely connected to a function (this distinguishes the Functional Motion Analysis among others from motion analysis which prefers relation of action and success of the athlete). A major part of Functional Motion Analysis is called functional attribution which is the step to combine mode of action or sequences with a function. In swimming, the functional attribution of modes of actions is closely related to conception of flow conditions. A conception of flow can be "You need still water to gain more thrust" or "Apply different hand orientation to constant flow condition". Cyclic activity in water, however, creates flow which is characterised by a mixture of steady and unsteady effects. The purpose of this paper is to direct attention how the unsteady approach do affect the functional attribution of cyclic swimming strokes.

METHODS

In this chapter some aspects are presented concerning unsteady flow conditions and functional attribution, respectively. In water, corporal actions create flow conditions combined with generation of momentum (again to avoid misunderstandings concerning terminology the term momentum sometimes could mean swing or inertia when used in conjunction with the release of the hands from water like "allowing the momentum of upsweep to carry the hand upward"). Due to reciprocal interaction of body motion and motion of water momentum is created and transferred simultaneously which is called momentum-induced propulsion. Generating momentum coincides with momentum transfer (according to "actio = reactio). A problem is to produce more momentum to thrust the body ahead than momentum which slows the body down.
In unsteady flow conditions momentum generation/-transfer differs from steady flow conditions (1, 5, 6, 7, 10). Unsteady flow aspects can be studied in swimming of vertebrates somewhat easier due to the harmonic nature of body motions. Ungerechts (8) demonstrated that the spatio-temporal pres-

sure gradients (per cycle) varies locally, characterised by changing from negative to positive and vice versa which results in local flow acceleration (Fig. 1) which –in steady flow- would have disastrous effects.
In addition it was shown that the flow in the wake was set into rotation as vortex which are known as a very good means "for carrying as much momentum as possible in relation to their energy" (4). In this context we have to learn to understand the meaning that Fish create vortices, which are like teeny whirlpools, and the vortices create changes in water pressure that move the fish forward (9).

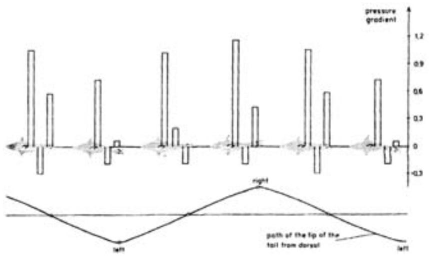

*Fig. 1. Intra-cyclic pressure gradient distribution (per cycle) of a shark model (Re = 9 * 105, Reduced Frequency Σ = 0,5).*

Unsteady flow effects found with vertebrate swimming can be in great part also applied or found to the human swimming according to Blickhan (1) as follows:— Reduction of total drag due to body undulation realised in human swimming during the underwater period after start and turns.
— Added mass supports thrust in periods of body deceleration realised in human swimming in breaststroke due to the intracyclic variation of velocity.
— Bound vortex start earlier realised in human swimming when turning action of hands are executed.
By using flow-visualisation techniques like PIV-Method in human swimming the existence of unsteady flow fields became obvious (7). Moreover it was demonstrated that propulsion is produced more effectively by vortex-induced momentum transfer. In front-driven locomotion (by arms/hands) the momentum transfer at the hand is related to effects from bound vortex (rotating water), shed vortex and the interaction between bound and shed vortex, called jet-flow; with pressure changing in time. In rear-driven locomotion (by legs and feet) vortex rings are created with the potential to create also jet-propulsion. Jet-flow related propulsion does not exist in stationary flow. The additional thrust due to jet-flow depends largely one the orientation of that jet-flow, the more the direction of the jet-flow is oriented opposite to swimming direction the more the body is pushed ahead.

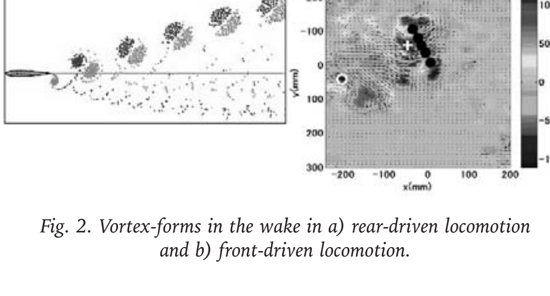

Fig. 2. Vortex-forms in the wake in a) rear-driven locomotion and b) front-driven locomotion.

In the context of competitive swimming, a consequent application of flow physics is nearly the only way to judge the solutions by transferring complex laws to functional attributions. Attributions which are applicable in human swimming should consider the change of view due to unsteady flow approach which provides some remarkable changes as a) sources of drag and thrust are not separable in self propulsion, b) the Wagner Effect deals with the circulation which rises in steady flow slowly whereas in unsteady flow the starting vortex at the beginning of a stroke rises rapidly, c) total drag becomes a relative issue since the mass of water "How many mass a body carries per meter?" may be much closer related to the feeling of being exhausted due to swimming locomotion than to the generally quoted drag forces and d) effects due to rotation of water masses are relevant.
Functional Motion Analysis offer a frame to examine nearly every locomotion by starting to answer the following questions: a) "Under which condition the motion takes place?", b) "What is moved?", c) "Who moves what?" and c) "In which surrounding the motion takes place?" Answering these questions for motions in aquatic space a unique situation arises. The answer to "What is moved?" is ambiguous because it could either be "water mass" or "body mass". The answer to "Who moves what?" could either be "Swimmer moves water" or "Water moves swimmer". One major aspect of Functional Motion Analysis, however, is the requirement to give explicit information to what end a mode of action (or sequence) is executed, simply to answer the question "what for". This steps is called functional attribution. The attributions can be derived from different sources, however, biomechanics offer best grounds.

Consequences
In an extensive study Ungerechts and colleagues (9) listed: 1st the actions, 2nd the modes of actions and 3rd the functional attribution of each (action) mode for all strokes.

Table 1 Example of three steps of Functional Motion Analysis applied to the beginning of the underwater sequence in butterfly arm-motion.

Action	Modes of action	Functional attribution
Arms/hands sweeping outwards below waterline and backwards rotation starts	• Stretched arms are rotated inwards (outward rotated elbow) to • Hands are sculled outwards and upwards; simultaneously to	…prepare a long path to "induce unsteady flow" …direct the flow on th e back of the hand(s) creating steady flow effects

In essence, hand/fingers disturb water, inducing a flow after a certain time lag for fetching and catching water mass creating micro-vortices. During sweeping sequences, *steady* flow effects the momentum transfer whilst during the transition of the hands *unsteady* flow effects a marked increase of momentum.
Finally, as a result it turned to be out that some mutual actions exist in all four strokes. Each of these actions as such are functionally alike (irrespective to the stroke considered) in two respects: anatomical-morphological and flow-related. For the arm/hand motion (upper limb) these mutual actions were as follows: a) starting the cycle with stretched arm and outward rotated elbow position, b) fingers slightly spread, c) rotation either around the long axis in crawl- and backstroke or rotation around the short axis in breast- and butterfly-stroke, d) supination of the hand (before bending elbow) in breast- and butterfly-stroke,

e) pronation of the hand (before extending elbow) in crawl- and butterfly-stroke, f) sweeping action (outward, upward, inward sweep), g) slicing action before leaving water.
In any of the four swimming strokes appropriate flow-forms are created and organised by similar actions of the hand/arm:
— Goal: creating flow around the hand(s) and arms at the beginning of the arm cycle by: fully stretched arm, fingers slightly spread, thumb abducted, shrugging shoulder(s).
— Goal: creating long path to induce unsteady flow supported by body rotation: sculling hands with nearly stretched arm, fingers slightly spread (outward and upward scull in breast and butterfly-stroke, downward sweep in crawl- and back-stoke).
— Goal: creating jet-flow by: transition motion of the hand, either supination in breast- and butterfly-stroke, followed by inward scull of hands and/or pronation in butterfly, back- and crawlstroke followed by slicing hand (extending arm during upward scull).
Irrespective of the stroke it is valid that the rotation around body axes are modulating relative velocity (at the hands) and thus influencing momentum generation. While interacting with water mass hand/arms transfer momentum to the centre of body mass (propelling the body) as follows: a low pressure in the back of the hand refrains the hand from being moved *back*wards - the body is moved *for*ward instead while self-propulsion in water means that the "propelling limbs" allow for motion on each side of the limb resulting in momentum-production and in reaction to that the proximal end is moved as well and the swimmer's body is pushed ahead.

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MOTION ANALYSIS OF FRONT CRAWL SWIMMER'S HANDS AND THE VISUALIZATION OF FLOW FIELDS USING PIV

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Flow fields around a swimmer are extremely unsteady. Top swimmers are expected to swim by using effectively unsteady flow force. A motion analysis can evaluate the unsteady motion quantitatively. In addition, PIV (Particle Image Velocimetry) can visualize the unsteady flow field. With this method, the vortex motion around a hand can be evaluated quantitatively. Our study is to clarify the relationship between the vortex behavior and the motion of a hand in crawl swimming by using the motion analysis combined with PIV. The analysis is made for two subjects; one is a male with no competitive career (subject 1) and the other a female Olympic swimmer (subject 2). It was found that the hand motion in swimming was closely related to the vortex generation.

Key Words: PIV, motion analysis, front crawl, propulsion, unsteady flow, circulation.

INTRODUCTION

Schleihauf (1) evaluated a force exerted on a hand in swimming using a quasi-steady analysis. However, swimmer's motion cannot be evaluated quantitatively by the quasi-steady analysis, because of extremely unsteady characteristics. Unsteady lift force is generally greater than steady one. Top swimmers are expected to swim by using effectively the unsteady flow force. Counsilman (2) found S-shaped pull as a result of the motion analysis for top swimmers and proposed it as an efficient one. We paid our attention to a phase turning from In-sweep to Out-sweep of S-shaped pull. Fig. 1 shows a palm trace in a horizontal plane. The flow direction is in the positive X-direction. The palm of the swimmer reverses the orientation of the circulation in the two places denoted by (α) and (β) in Fig. 1 (a). In these places, a hand gains larger propulsion by shedding a strong and large vortex by the conservation law of circulation.
A motion analysis can evaluate the unsteady motion of swimmers quantitatively on digitizing the motion of the swimmer. Fig. 1 (b) shows the definition of the angles using in the motion analysis. Let $\vec{v}$ and $\vec{u}_0$ be the hand velocity and the forward velocity of a swimmer. The velocity of hand relative to water is written as $\vec{v}+\vec{u}_0$.
We defined a palm inclination angle (θ) as an angle between the palm and the flow direction. We defined an attack angle (α) as an angle between the palm and the relative velocity, $\vec{v}+\vec{u}_0$ (3).
In addition, PIV (Particle Image Velocimetry) was used to visualize the unsteady flow field around a swimmer (4, 5). With this method, vortex motion around the hand can be evaluated quantitatively. We referred the vortex rotating clockwise to positive and the one rotating counter clockwise to negative. Our study is to clarify a relationship between the vortex behavior and the motion of the palm in crawl swimming by using a motion analysis combined with PIV.
Table 1 shows the data of the subjects. The flow velocity of a flume is set at their top speed for the subjects. The flow velocities are 0.8 m/s for subject 1 and 1.5 m/s for subject 2.

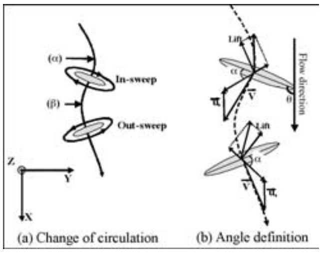

Figure 1. (a) : the position where the hand reverses the orientation of the circulation in (α) and (β). (b): the definition of the angle for the motion analysis.

Table 1. Data of the subjects.

Subject	Sex	Flow velocity(m/s)	Stature (cm)	Weight (kg)
1	Male	0.8	168	72
2	Female	1.5	166	55

METHODS

Motion analysis

Fig. 2 shows the experimental configuration of the motion analysis. It determines the geometry of the palm in space viewed from the bottom and the side of the flume installed at Tsukuba University with two synchronous high-speed cameras. Let the camera installed at the bottom and at the side of the flume be camera 1 and camera 2, respectively. The camera 1 was used in combination with a mirror inclined at 45deg. Our system can get 250 planes per second.

Several points on the hand are digitized using a video motion analysis system Frame-DIAS 2 version 3. For the image captured by camera 1, we digitized the tips of a thumb and a little finger, because we regard a segment joining the two points as a palm. For the image captured by camera 2, we digitized the tip of a third finger and a wrist, because we regard a segment joining the two points as a palm. A trajectory of the palm is calculated by connecting the digitized points at each time. The palm inclination angle was calculated from the coordinates of the thumb, the little finger and an arbitrary point drawn from the little finger parallel to the flow direction (see Fig. 1(b)) using the cosine theorem. The magnitude of the hand velocity is calculated as the average of the velocity of the middle point of the palm. The attack angle (α) is determined by the angle between the palm viewed from camera 1 and the direction of the relative velocity ($\vec{v}+\vec{u}_0$).

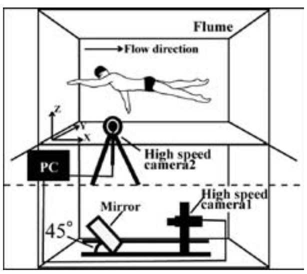

Figure 2. Experimental configuration of the motion analysis.

PIV (X-Y plane)

PIV system measures the flow velocity from the movement of tracer particles irradiated with YAG laser sheet. The laser sheet is set in the horizontal plane located at a depth of 0.6m below the free surface. The image of the tracer particles is reflected by a mirror and captured by a CCD camera set at the bottom of the flume and then the image is transferred to a computer for the determination of the velocity. The interval of the laser pulse is controlled using a pulse generator. The measurement region is set 0.5_0.5 m. Our PIV system can get 15 planes per second. Fig. 3 shows the experimental configuration for the PIV.

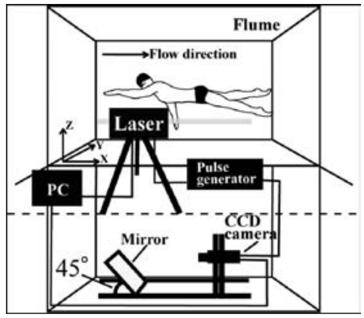

Figure 3. Experimental configuration of PIV.

RESULTS AND DISCUSSION

Motion analysis

Fig. 4 and 5 show the change of palm and palm inclination angle (θ) of the subjects 1 and 2, respectively. The left shows the digitized points of the tips of the thumb and the little finger every 4 ms. The right shows the digitized points of the tip of the third finger and wrist at the same instants as the left. The angles shown in both figures are the palm inclination angle. The flow is in the X-direction. The trajectory of the palm of the subject 2 was in somewhat S-shaped motion while that of the subject 1 was almost straight. From the palm inclination angle, we confirmed that the palm of the subject 2 reverses the orientation of the circulation in the phase turned from In-sweep to Out-sweep. From these observations, it is supposed that the subject 1 generates no vortex pair.

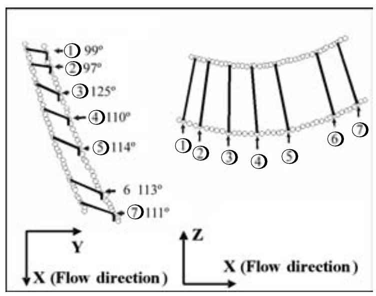

Figure 4. Change of palm and palm inclination angle of subject 1 (left: camera 1, right: camera 2).

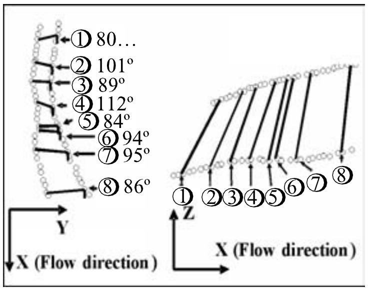

Figure 5. Change of palm and palm inclination angle of subject 2 (left: camera 1, right: camera 2).

PIV (X-Y plane)
From the data of particle positions we calculated the velocity. Fig. 6 and 7 show the velocity and vorticity distributions of the subjects 1 and 2, respectively. The gray scale on the right column of these figures denotes the vorticity measured in 1/s. In the velocity vectors shown in Fig. 6 and 7 the mean velocity have already been subtracted to clarify the vortex behavior. Two ovals denoted by dotted line show the position of the palm at the previous two planes. Fig. 6 shows that the subject 1 does not shed any clear vortices. In contrast, Fig. 7 shows that the subject 2 generates two vortex pairs after the phase turned from In-sweep to Out-sweep. In addition, the shed vortex pair produces a jet flow in the direction of the flume velocity. Hereafter, we designate the left vortex pair as vortex pair 1, the right vortex pair as vortex pair 2. Table 2 shows the characteristics of the vortex pairs. In the table, the values of the induced velocity and momentum predicted by supposing the pair as a vortex ring are listed in comparison with the experimental data. Γ, b, Ve, Vt(=Γ/b) and M(=ρbΓ) are the circulation of vortex pair, the diameter of the vortex ring, the value of jet flow velocity determined by the experiment, the values of jet flow velocity and momentum predicted as a vortex ring. These values of the vortex pair 2 are greater than those of the vortex pair 1. The increase in the diameter (b) and the circulation (Γ) resulted in the great increase of the momentum (M) from 15.6 kg/s to 22.6 kg/s

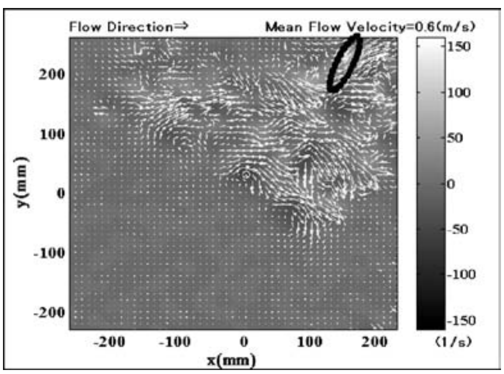

Figure 6. Distribution of velocity vectors and vorticities (subject 1).

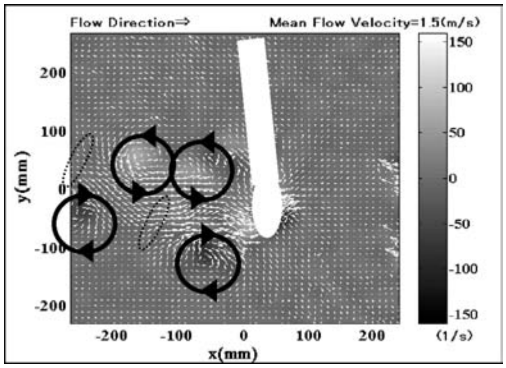

Figure 7. Distribution of velocity vectors and vorticities (subject 2).

Table 2. Characteristics of vortex pair shed by subject 2.

Vortex pair	Γ(m^2/s)	b(m)	Ve(m/s)	Vt(m/s)	M(kg/s)
1	0.13	0.12	1.0	1.0	15.6
2	0.15	0.15	1.0	1.0	22.6

CONCLUSION
We could evaluate the hand motion of crawl swimmers by the trajectory and the palm inclination angle using the motion analysis method. PIV could visualize and see the pair vortex suggested by the variations of the palm inclination angle.
We concluded that the subject 2 swam by using effectively the unsteady flow force by changing the palm inclination angle. From the motion analysis combined with PIV, it was found that the hand motion in swimming was closely related to the vortex behavior and momentum generation.

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