Original Article

Intra-cyclic analysis of the front crawl swimming technique with an inertial measurement unit

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ABSTRACT

Sports scientists and coaches strive to identify and analyse performance relevant parameters and to optimize them in the training practice. In swimming, this process is time-consuming and requires expensive and professional video equipment, which is currently considered the gold standard. Since inertial measurement units (IMUs) are increasingly interesting for athletes, are more easily accessible and are less disturbing to wear, they offer an ideal alternative to classic video-supported motion analysis. In addition, IMUs provide further data of interest to scientists and trainers. The present study aims to transfer the findings from the video analysis data to the data measured with an IMU. The focus is on the frontal crawl and its key movements, body roll, angular velocity and forward acceleration in relation to their intra-cyclic variations. Ten athletes from regional to national level swam 100 m front crawl and the video recording was combined with the IMU to analyse the key positions and find similarities and differences between the swimmers. The findings are the basis for an automatic pattern recognition system to provide coaches and scientists with immediate feedback on the execution of movements and to decide which parameters should be specifically trained to improve performance.
Keywords: IMU; Freestyle; Swimming; Movement technique; Acceleration; Biomechanics.

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INTRODUCTION

Background and objectives

To improve athletes' overall performance in competition, it is essential to identify and optimize the performance relevant parameters in movement execution. Especially cyclical movements such as swimming, where the same motion is repeated extensively, require high stability in the movement patterns. Many studies investigated and revealed such relevant parameters, mainly via video analysis. Unfortunately, video analysis requires at least a semi-professional video system (i.e., several connected cameras with high resolution and sample frequency). Furthermore, direct feedback in real-time is missing, as the relevant parameters such as stroke length, frequency, stroke duration, intra-cyclical velocity variation have to be analysed manually and afterwards by a sports scientist.

The increasing number of studies conducted with inertial measurement units (IMUs) (Magalhaes, Vannozzi, Gatta et al., 2015; Mooney, Corley, Godfrey et al., 2015) promises to facilitate the process of obtaining certain parameters. Recent studies have already shown that it is possible to obtain information about the swimmers' stroke frequency, time per lap, number of laps and other global parameters with an IMU (Bächlin, Förster & Tröster, 2009; Chakravorti, Le Sage, Slawson, Conway & West, 2013; Dadashi et al., 2013; Davey, Anderson & James, 2008; Hagem, O'Keefe, Fickenscher & Thiel, 2013; Le Sage et al., 2010; Le Sage, Bindel, Conway et al., 2011; Peiwei, 2012). This gives coaches the opportunity to keep track of more than one or two athletes at the same time. Despite the promising approaches, the use of IMUs still lacks a broader practical application. This may be because the sensors are perceived as disturbing during swimming and their use requires the assistance of experts (Bächlin & Tröster, 2012; Daukantas, Marozas & Lukosevicius, 2008; Fulton, Pyne & Burkett, 2009; Hagem, Sabti & Thiel, 2015; James, Davey & Rice, 2004; Puel, Seifer & Hellard, 2014; Stamm, James & Burkett, 2013; Staniak, Buśko, Górski et al., 2016; Ungerechts, Cesarini, Hamann et al., 2016). In addition, the sensors available on the market are mainly designed for recreational swimmers and therefore do not consider relevant parameters with an accuracy that is relevant for elite athletes (Mooney, Quinlan, Corley et al., 2018). Studies by Engel, Schaffert, Ploigt and Mattes (in print) demonstrated the possibility to extract intra-cyclic parameters during butterfly and breaststroke swimming with an IMU on the lower back.

The majority of the studies conducted with an IMU so far have focused on the freestyle, the so-called front crawl, (75 of 83 studies according to Mooney and colleagues (2015)); 20 of 27 according to Maghalhaes and colleagues (2015), as this is the most commonly performed stroke among professional swimmers. Although front crawl is well understood, the studies lack a detailed view of intra-cyclical parameters and fail to compare theoretical and world-class athlete-derived stroke patterns with the inertial data obtained. Therefore, the present paper aims, first, to compare movement theoretically proposed in the literature and movement performed in practice with the corresponding IMU data, and second, to compare elite swimmers participating in national championships with athletes at regional level with respect to their intra-cyclical movement patterns. The findings from this will form the basis for an automated intra-cyclical stroke analysis to support coaches and sports scientists in their daily work.

Technical background of the freestyle swimming technique

The rules of the World Organization for swimming (Fédération Internationale de Natation, FINA) allow to swim in any style at a freestyle swimming event. The only regulations merely state that the swimmer must touch the wall with any part of the body after each lap and that some part of the athlete must break the surface during the entire race. The only exceptions are the start and the time following the turn, where the rules allow the athlete to stay under water for a maximum of 15 m (FINA, 2020).

Technique of the arm stroke

In swimming practice, a homogeneously executed movement of the arms is established, which is known as front crawl. This is similar to the technique applied in butterfly swimming, with the difference that here both arms are moved separately and not simultaneously.

The arm stroke was first described by Counsilman and Wilke (1980) and divided into three distinct phases: the entry phase, the underwater phase and the recovery phase. A more detailed phase classification was provided by Maglischo (1993), who emphasized the extension of the arm during the entry phase (entry and stretch) and further divided the underwater phase into three sub-phases based on the direction of the hand movement: beginning with the downsweep and catch (non-propulsive), followed by the insweep (propulsive) and ending with the so-called upsweep (propulsive). The underwater stroke ends here, and the release and recovery (non-propulsive) ends an arm stroke cycle, resulting in a total of five phases. Madsen and colleagues (Madsen, Reischle, Rudolph et al., 2014) named four phases, which are also based on the movement of the hand and can be translated from German as follows: outsweep-downsweep, insweep, backsweep. These four phases are then summarized by the authors into a phase of release, recovery and entry. Sanders and McCabe (2015) named four phases of the arm stroke, which are very similar to those from Maglischo (1993). They begin the stroke cycle with the entry and reach (according to the stretching aspect), followed by the catch and insweep, which leads to the upsweep and then to the recovery. In studies, the arm stroke is often simplified and divided into four phases, which were exemplarily presented by Chollet, Chalies and Chatard (2000). These phases are the entry and catch phase, the pull phase, the push phase and the recovery phase.

Since Maglischo's (1993) description of the phase classification had a considerable influence on the descriptions of all subsequent authors which also provides information on the movement of the hand, the analysis of the freestyle swimming technique in the present paper is based on the phases proposed and described by Maglischo (1993). However, an adjustment was in the classification in this paper in which the entry and the stretching was integrated into one phase with the downsweep as the entry and catch. Especially when the stroke rate increases, the aspect of stretching is more and more neglected and is often not executed correctly by the athletes. For this reason, these two phases were combined, resulting in a total of four phases, which are shown in Table 1.

Table 1. Overview over the different phases of the arm stroke as named by the authors listed below.

Author	Phase Structure				
Counsilman & Wilke	Entry	Underwater Phase			Recovery
Maglischo	Entry & Stretch	Downsweep & Catch	Insweep	Upsweep	Release & Recovery
Madsen, Reischle, Rudolph	Outsweep-Downsweep		Insweep	Backsweep	Release, Recovery, Entry
Sanders & McCabe	Entry & Reach	Catch & Insweep		Upsweep	Recovery
Chollet, Chalies, Chatard	Entry & Catch		Pull	Push	Recovery
Engel, Schaffert, Ploigt, Mattes	Entry & Catch		Insweep	Upsweep	Release & Recovery

Technique of the arm stroke

The first phase of the freestyle arm stroke involves the entry of the fingertips into the water at the level between the head and shoulders (Maglischo, 1993; Madsen et al., 2014). Counsilman and Wilke (1980) define the position of the hand as 45° flexed to the surface to avoid any bubbles, so that the thumb leads the hand into the water. Maglischo and Colleagues (1988) as well as Madsen et al. (2014) emphasize that the elbow is still flexed when the fingertips break through the water surface and the arm is actively stretched under water.

When the arm is fully extended, the palm of the hand points down (Maglischo, 1993) and initiates the downsweep. There is a difference between the disciplines in freestyle; with Sanders and McCabe (2015) emphasizing that in distance events there is a gliding phase, while in sprint events it is important to position the hand and forearm quickly to achieve a fast and strong catch. This catch is the final position of the downsweep, where the hand first moves outwards (initiated by flexing the wrist), then by flexing the elbow downwards backwards (Counsilman & Wilke, 1980; Maglischo, 1993; Madsen et al., 2014). Flexing the elbow is essential for an economical pulling movement, as the lever becomes more effective (Counsilman & Wilke, 1980; Maglischo, 1993; Madsen et al., 2014; Sanders & McCabe, 2015). Maglischo and colleagues (1988) state that the hand is 40 - 60 cm below the surface in this phase, in which the elbow is flexed by 140° according to Maglischo (1993). When the catch is finished, the hand and forearm are in a straight line and the palm of the hands points backwards.

The insweep

During the first propulsive phase of the arm stroke, the insweep, the hand performs a semi-circular motion, in which, in combination with a further flexion of the elbow (over 40° - 60°), the hand moves downwards, inwards and upwards until it has reached its furthest position under the body (Maglischo, 1993). During this motion, the upper arms turn inwards and the palm of the hand slowly turns inwards until it is aligned diagonally to the path of the hand (Madsen et al., 2014). The hand accelerates from 1.5 m/s up to 3 m/s according to Magalhaes and colleagues (2015). Maglischo (1993) distinguishes three different types of insweeps, depending on the width of the catch, which has the same width as the insweep. Thus, during the insweep, the hand (a) remains outside the swimmer's line; (b) is located between the shoulder and the middle of the torso or (c) moves to the other side of the body. Counsilman and Wilke (1980) indicate that the upper arm is perpendicular to the body and the elbow is flexed by 90° when the insweep is completed.

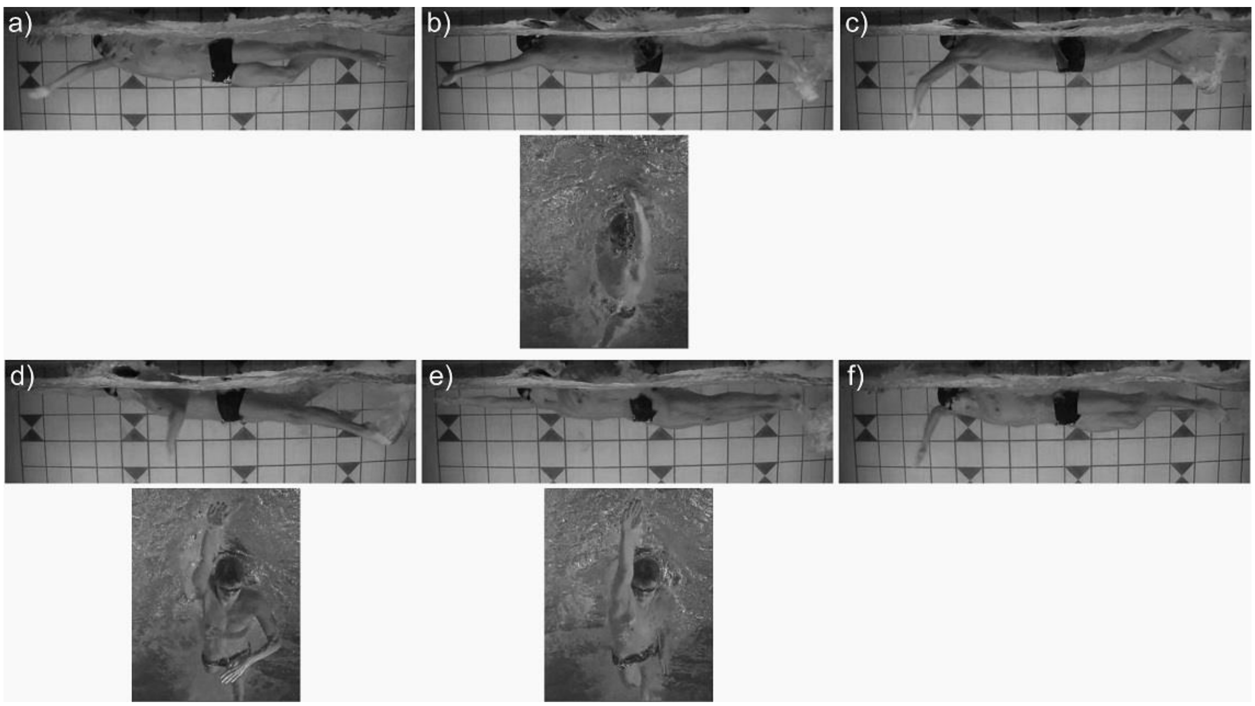
The upsweep

The upsweep begins when the hand reaches its furthest point below the body and ends when the hand is on the thigh (Maglischo, 1993). Sanders and McCabe (2015) emphasize that the term could be misleading because there is no active upward movement. The main motion of the hand is semi-circular backward (Maglischo, 1993; Sanders & McCabe, 2015) the elbow is stretched (Counsilman & Wilke, 1980; Madsen et al., 2014; Sanders & McCabe, 2015), with the palm of the hand pointing diagonally to the arm motion (Maglischo, 1993; Madsen et al., 2014). This coincides with an upward movement of the hand. During the transition from insweep to upsweep, the speed of the hand decreases and increases rapidly up to 6 m/s (Mooney et al., 2108; Counsilman & Wilke, 1980; Maglischo, 1988). The hand remains aligned with the forearm as long as possible. As soon as the elbow is almost fully extended and the hand is moved beyond the hip, the centre of gravity is more on the palm of the hand, which is still pointing backwards (Maglischo, 1993).

The recovery

Counsilman and Wilke (1980) emphasize the uncertainty about when exactly the recovery begins and recommends observing the hand movement. When the palm of the hand begins to turn inwards instead of backwards, this is the moment when the recovery begins. This usually occurs when the hand is on the thigh and the elbow is still slightly flexed. When the arm, guided by the elbow, is lifted out of the water, the palm of the hand points to the thigh, so that the little finger comes out of the water first (Maglischo, 1993).

In the past the elbow had to be the highest joint during recovery (Counsilman & Wilke, 1980; Maglischo, 1993), which is neglected by Sanders and McCabe (2015) and is performed differently by sprinters at world-class level. This leads to the assumption that the recovery must take place close to the bodyline (Counsilman & Wilke, 1980; Maglischo, 1993; Madsen et al., 2014; Sanders & McCabe, 2015) to avoid any torque in the body (Maglischo, 1993), with the shoulder of the recovering arm above the water surface (Sanders & McCabe, 2015). The recovery ends when the fingertips touch the water surface and the next stroke begins (Figure 1).



1a: entry of the fingertips which marks the beginning of the catch; 1b: the left arm is fully extended, midway through the catching motion; 1c: end of the catch with the palm facing backwards; 1d: point where the hand is at its furthest point beneath the body and begin of the upsweep; 1e: end of the upsweep with the palm facing the thigh and the beginning of the recovery; 1f: the left hand re-entering the water, finishing the recovery.

Figure 1. Key positions of the left arm stroke of a junior athlete at national level.

Technique of the kicking motion

In contrast to butterfly and breaststroke swimming, where the kicking action is crucial for overall performance, the kicking action in front crawl swimming is more supporting. As it was emphasized, the main purpose is to stabilize the body and therefore does not necessarily require the execution in vertical plane (Sanders and McCabe (2015). The alternating kick should be narrow and the flexibility of the ankle joint is essential for an effective kick. Counsilman and Wilke (1980), Maglischo (1993) and Madsen et al. (2014) agree when they divide the kick into two phases, the downbeat and upbeat, and how to execute them.

The downbeat should be performed with a flexed and relaxed knee (Counsilman & Wilke, 1980; Maglischo, 1993; Madsen et al., 2014) with the foot pointing downwards-inwards (Maglischo, 1993). As the leg passes the body, the movement reverses and the upbeat begins to avoid further frontal resistance. Due to the water resistance the leg is fully stretched (Counsilman & Wilke, 1980; Maglischo, 1993; Madsen et al., 2014), but knee and shank are free of tension (Maglischo, 1993; Madsen et al., 2014). The upper turning point where the downbeat starts should be close to the water surface (Maglischo, 1993).

According to the butterfly kick, the body accelerates when the feet are at the lower turning point when the downbeat ends (Engel et al, in print; Colman, Persyn & Ungerechts, 1998) (Figure 2).

2a: upper turning point of the left leg (start downbeat) and lower turning point of the right leg (start upbeat); 2b: lower turning point of the left leg (start upbeat) and upper turning point of the right leg (start downbeat); 2c: upper turning point of the left leg and lower turning point of the right leg and thus the beginning of the next cycle.

Figure 2. Key position of one kick cycle of a junior athlete at national level.

Body rotation
All agree and emphasize the importance of body rotation to support the pulling motion of the arms, so that an effective arm stroke is possible (Sanders & McCabe, 2015; Counsilman & Wilke, 1980; Maglischo, 1993; Madsen et al., 2014). Therefore, the rotation should be symmetrical to each side, as well as cyclic, rhythmic and independent of breathing (Sanders & McCabe, 2015). While Maglischo (1993) (30° - 40°) and Counsilman and Wilke (1980) (35° - 45°) use the shoulder as reference, Sanders and McCabe (2015) also consider the hip and notes that the rotation is less extensive than that of the shoulders, although he claims that rotation up to 60° is tolerable. Both movements produce a sinusoidal wave-like behaviour, independent of the stroke rate, which does not apply to the degree of rotation. The higher the stroke rate, the tighter the body rotation must be, which is mainly caused by the faster kicking, which hinders the hip from rolling widely. In addition, Sanders and McCabe (2015) state that at a lower stroke rate the hip roll occurs later than at high stroke rates.

Timing of the arm strokes
Maglischo (1993), Sanders and McCabe (2015) and Chollet and colleagues (2000) looked closer at the timing of the alternating arm strokes and answered the question of when an arm enters the cycle of the opposing arm. They distinguished between different swimming speeds and thus stroke rates, ranging from stroke rates for sprint competitions (50 m) to distance competitions (800 m). This means that a slower stroke rate is applied when swimming over longer distances than in sprint competitions. Since this is unfortunate, it is obvious that the timing of both arms is different.

Maglischo (1993) describes the arm stroke for distance swimmers as follows: The entry is when the opposing arm finishes the insweep and remains in a stretched position until the upsweep is completed. Sprinters, on the other hand, shorten the stretching phase, while the entry is earlier in the cycle during the insweep of the opposing arm. The catch follows immediately during the upsweep to avoid the deceleration that would result from a different execution.

Sanders and McCabe (2015) quantify the different stroke phases as follows: In distance competitions, the athletes spend 40% of the cycle in the entry phase, 17% in the pull phase (insweep), 16% in the push phase (upsweep) and 27% in the recovery phase. In contrast, sprinters spend 31% in the entry phase, 20% in the pull phase, 19% in the push phase and 31% in the recovery phase.

Chollet and colleagues (2000), on the other hand, developed the Index of Coordination (IdC) for the front crawl, which distinguishes between three different styles. The opposition style means that one arm begins the pull phase when the other arm finishes the push phase, which corresponds to an IdC of 0%. The catch-up style means that the pull phase of one arm is during the push phase of the other arm (IdC < 0%). Thirdly, the superposition is when the propulsive phases (insweep and upsweep) of the arm stroke overlap (IdC > 0%). A negative IdC can be found at low stroke rates (distance competitions) and a positive IdC is correlated with high stroke rates (sprint competitions).

Key positions of the front crawl swimming cycle

In summary and in addition to the various front crawl swim executions, which vary according to distance and stroke rate (Maglischo, 1993; Sanders & McCabe, 2015; Chollet et al., 2000), one stroke cycle can be divided into four phases based on the arm stroke (entry and catch, insweep, upsweep, recovery) with four key positions. Table 2 provides a detailed description of the phases and key positions of the arm stroke and leg kick and their propulsive character.

Table 2. Phases and key positions of the arm stroke and leg kick in front crawl (freestyle) swimming: division of one cycle into different subsections.

Cycle Part	Phase	Key position at the beginning	Character
Arm stroke Cycle	Entry & Catch	Entry of the fingertips	Non-propulsive
	Insweep	Forearm perpendicular to surface	Propulsive
	Upsweep	Elbow maximally flexed, Hand maximally beneath the body	Propulsive
	Recovery	Hand at the thighs	Non-propulsive
Kick Cycle	Downbeat 1	Right foot at its highest point	Propulsive
	Upbeat 1	Right foot at its lowest point	Non-propulsive
	Downbeat 2	Left foot at its highest point	Propulsive
	Upbeat 2	Left foot at its lowest point	Non-propulsive

This paper therefore aims to answer the following questions: do athletes of different skill levels show the same characteristics in their IMU data regarding the side-to-side roll and forward acceleration when swimming at different swimming speeds and stroke rate? What might be a suitable approach for an automatic intra-cyclical analysis of front crawl swimming?

METHODS

Ethics

Ethics approval was granted by the University of Hamburg (AZ2017_100). All athletes gave their informed consent before participating in this study and reported no injuries or other impairments.

Participants

The data was collected during regular training sessions with athletes at national and regional level. Six female (14.8 ± 0.9 years) and four male (16.0 ± 0.7 years) swimmers participated in this study. Seven athletes took part in the national junior championships and achieved an average of 517 ± 56 FINA Points at this event. Each of them swam 100 m front crawl and together they completed 289 stroke cycles.

Test design and procedures

The athletes were introduced into the handling of the system and the purpose of the study. Each swimmer was asked to swim 100 m front crawl with moderate intensity. The trials were also filmed and the data was recorded with an IMU sensor placed on the lower back of the swimmer.

Data acquisition

The IMU sensor (BeSB GmbH Germany, Berlin) combines a 3D-acceleration sensor (range: ± 2g, resolution: 0.01 m/s²) and a 3D-gyroscope (range: ± 250°/s, resolution: 0.01°/s). The sample frequency is 100 Hz and the data is stored on the sensor and later transferred to the PC via Bluetooth. The data was smoothed using 4 Hz Savitzky-Golay filter.

All trials were video recorded (sample rate 24 Hz) and the footage was linked and synchronized with the measured data using the jBeam software (jBeam AMS, 2020). For synchronizing the video with the measured data, the sensor was filmed while being moved out of a rest position prior to the swimming trial. This led to a distinct acceleration peak in the IMU data and facilitated the linking to the video afterwards.

Sensor position

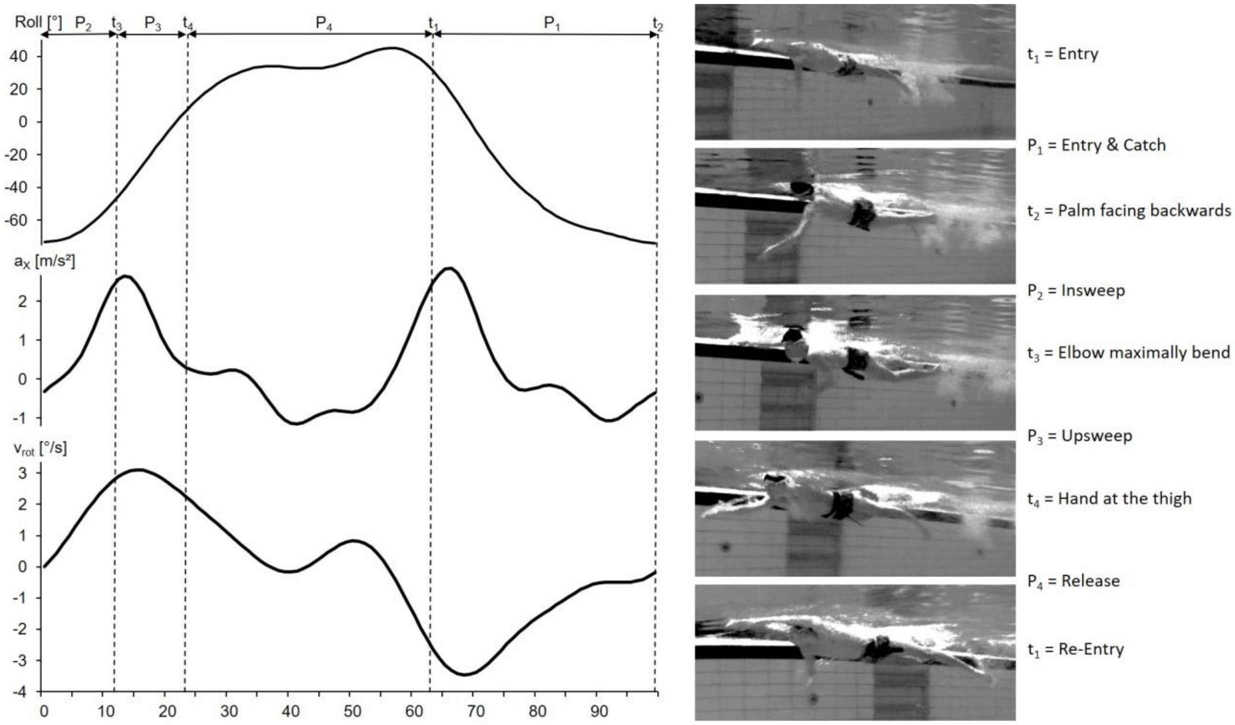
Pansiot, Lo and Yang (2010) examined the potential of different sensor positions in terms of timing, lap and stroke count as well as overall momentum in all four competitive swimming techniques and found these parameters best identifiable with the sensor placed at the lower back. Accordingly, Maghalaes et al. (2015) listed 27 studies in which swimming movements were investigated with IMUs and found that most of the data was obtained with a sensor attached to the lower back. Some studies used more than one IMU, resulting in exactly 33 measurements, divided as follows: lower back (Fulton et al., 2009), wrist (Colman et al., 1999), leg (Chollet et al., 2000), forearm (Chakravorti et al., 2013), head and upper back (Bächlin et al.,2009). Therefore, the sensor was placed on the lower back in a pocket sewn to a belt in the current study.

RESULTS

Arm stroke

Figure 3 shows the time-normalized mean value of 33 front crawl cycles performed during a 100 m swim by a junior athlete at national level, who achieved 454 FINA points in the 100 m freestyle in 2020. The upper diagram represents the roll angle (roll) of the hip, the middle diagram represents the forward acceleration (ax); the lower diagram represents the angular velocity (vrot) of the hip.

A complete single-arm stroke cycle is as follows: At the entry (t1), when the fingertips enter the water, the opposite arm moves from insweep to upsweep, resulting in an increase in forward acceleration. In addition, the hip begins to move from one side to the other, represented by a decreasing roll angle and an angular velocity that passes through a global minimum due to direction of movement. After the entry, there is a gliding phase of the left arm until the right arm recovers above water. To facilitate this recovery movement, the athlete rolls to the side and reaches his maximum roll angle at t2 with an angular velocity of zero. When the catch is performed during P1 (phase 1) the frontal area is maximized without generating propulsion forces, resulting in a minimum of forward acceleration.



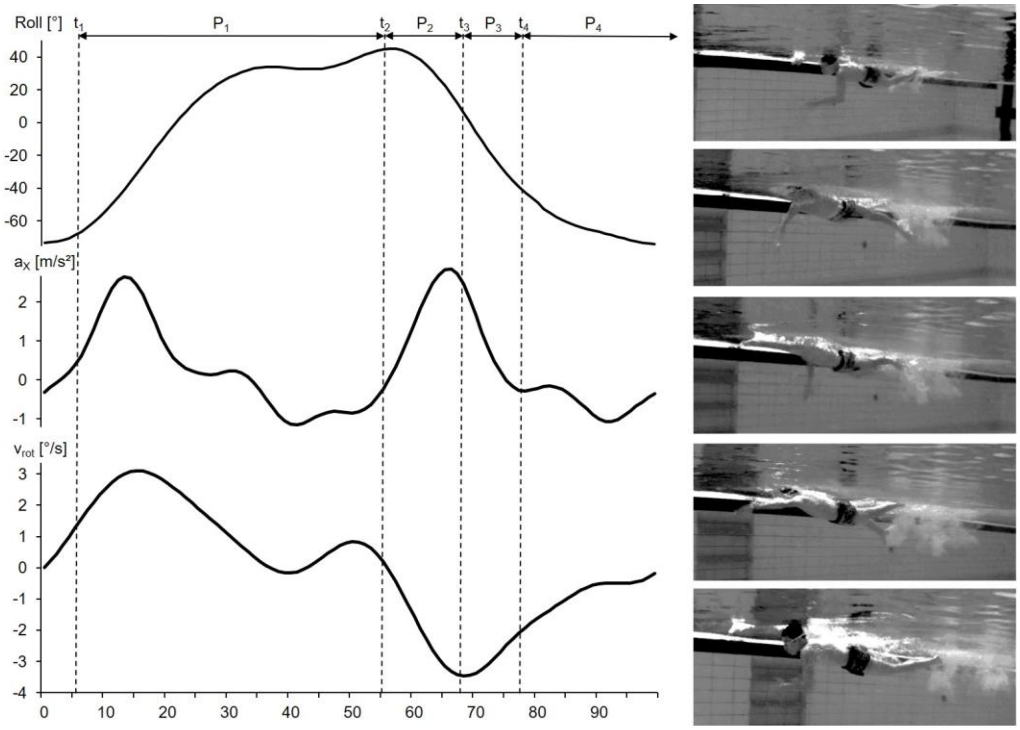
Note: t_1 shows the entry of the fingertips and the corresponding point in the cycle; t_2 shows the moment when the forearm is most likely perpendicular to the surface and the palm is facing backwards; t_3 is characterized by the hand being under the body at its outermost; t_4 shows the release of the left arm.

Figure 3. Arm stroke of a junior athlete at national level.

This turns during the insweep (P2), when generating propulsion with the arm stroke and the body begins to roll to the other side for supporting the execution of the insweep and the following upsweep. This roll motion results in an increase in the roll angle and angular velocity. At t3, when the elbow is flexed to the maximum and the hand is at its outermost point under the body, the hip is close to a horizontal position, resulting in maximum angular velocity and the roll angle exceeds zero degrees. During the upsweep (P3) the forward acceleration reaches its maximum.

When the underwater arm stroke is completed, the hip still rolls to the side to support recovery and the roll angle reaches its maximum during the arm recovery, while the angular velocity decreases towards zero until the hip reaches its turning point (maximum roll angle). As observed during right arm recovery, forward acceleration decreases to its minimum value as the left arm moves above the surface. The same characteristics described in Figure 3 for the left arm were also observed for the right arm as shown in Figure 4.

For a better understanding of how the two arm strokes mutually support each other, the combination of both graphs shows Figure 5. The black labels of the positions and times at the top of the graph represent the right arm stroke and the grey labels describe the left arm stroke. Both arms have nearly the same course structure. The entry takes place during the insweep, followed by a long glide phase until the catch. During the catch and transition into the insweep, the roll angle is maximum. The angular velocity is maximum during the insweep and upsweep, and during the recovery, the forward acceleration runs to a minimum.



Note: t_1 represents the entry of the fingertips and the corresponding point in the cycle; t_2 represents the moment when the forearm is most likely perpendicular to the surface and the palm is facing backwards; t_3 is characterized by the hand being at its outermost point under the body; t_4 represents the predicted release of the right arm.

Figure 4. Arm stroke of the same stroke cycle and athlete as in Figure 3.

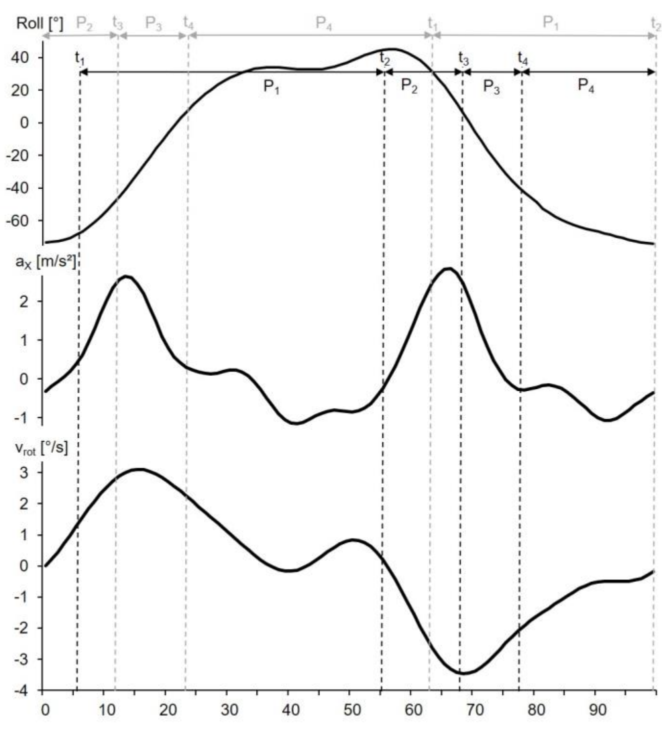


Figure 5. Combination of the left (grey labels) and right (black labels) arm strokes to emphasize the congruence of both movements, which show the same characteristics.

Bringing all athletes together

Figure 6 shows the time-normalized graphs for the roll motion (upper graph), forward acceleration (middle graph) and angular velocity (lower graph), averaged over all athletes and cycles. The bold line represents the mean value at the corresponding point in the cycle and the grey area represents the minimum or maximum value.

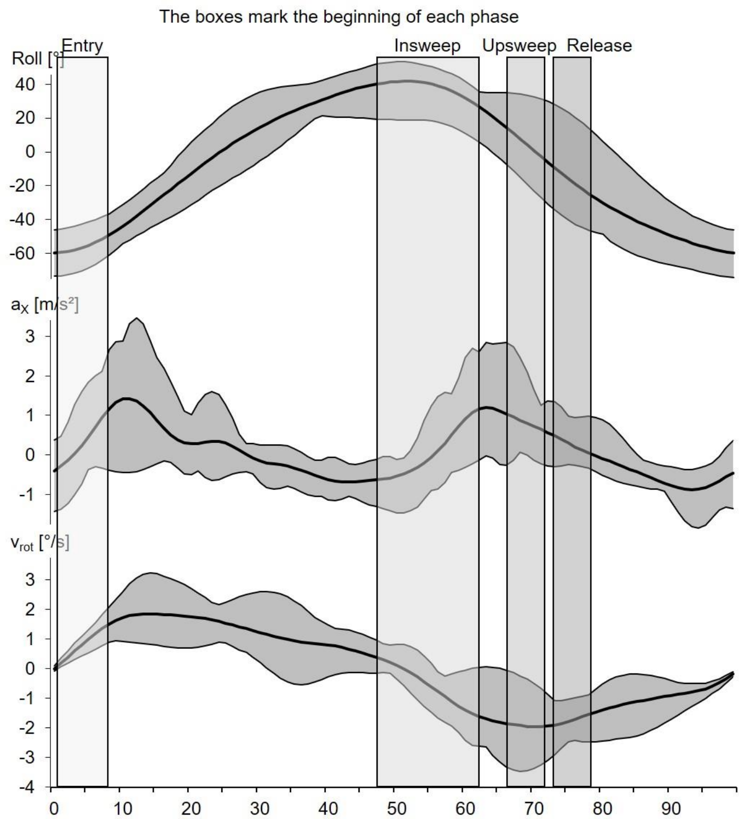


Figure 6. Time-normalized graphs over all 10 athletes and 289 arm strokes. The four vertical boxes mark the beginning of each phase, with the width of the boxes representing the variance among all participants.

Each of the four vertical boxes marks the beginning of the corresponding arm stroke phase, shown here for the right arm stroke. The width of the boxes represents the variance among all athletes.

The entry is when the roll angle passes its extremum (minimum for the right arm) and the insweep begins at the opposite extremum (i.e., maximum). Immediately after the beginning of the upsweep, the release takes place due to a high velocity of the hand and a very short distance to overcome underwater. Thus, both phases are at the extremum of the angular velocity (for the right arm it is the minimum).

DISCUSSION

This paper aimed at answering the following questions: do athletes of different performance levels show the same characteristics in their IMU data regarding side-to-side roll and forward acceleration when swimming at different speeds and stroke rate? What might be a suitable approach for an automatic intra-cyclical analysis of front crawl swimming?

The progression structure and characteristics of the mean curves shown in Figure 6 are considered as a model for the development of an algorithm for the detection of certain parameters of the front crawl swimming stroke. Regardless of fatigue (whether the first or last lap is considered), the same characteristics were observed in the three channels shown. Both the roll angle and the angular velocity show a sinusoidal behaviour with a global maximum and minimum within each cycle, as confirmed by several authors (Callaway, 2015; Davey et al., 2008; Rowlands, James & Lee, 2013; Stamm & Thiel, 2015) for the hips and Kudo, Sakurai, Miwa and Matsuda (2017) for shoulder roll. Furthermore, the zero value in vrot is linked to the extreme value in the roll angle. Note in particular that the zero crossing in vrot is that point in the cycle with the least variation and divides the stroke cycle into two halves. Thus, every zero crossing could indicate the beginning of a new arm stroke. Correspondingly, the time interval between the zero crossings should be identical if no asymmetries occur during the execution of the arm strokes. Such asymmetries could be the result of fatigue or individual breathing patterns. Thus, an automatic analysis of the time interval between arm strokes could reveal an individual athlete's deficit and contribute to training control.

As implied by Maglischo (1993) and Chollet et al. (2000), it was here shown that the main propulsion is generated during the insweep and upsweep phase of the arm stroke, while the recovery phase decelerates and slows the athlete down. This leads to two different acceleration peaks within each cycle and two deceleration phases each. The target of each athlete is therefore to minimize the intra-cyclical variation of acceleration and deceleration, which can be calculated as the amplitude of forward acceleration (ax). We have found that some athletes had different values for the acceleration maximum depending on the arm they used. This is of great practical interest as it indicates a muscular or motor imbalance and should be considered in the training practice. The goal here should be to correct the imbalance.

According to a study by Callaway (2015) the beginning of the propulsion action (insweep) coincides with the extreme value of the roll motion of the upper body (Figure 3 and 4). This has been confirmed in the present paper and it was possible to locate the beginning of the upsweep (push phase), which occurs in the area around the zero crossing of the roll of the upper body. This is also confirmed by Callaway (2015). In contrast to the above-mentioned agreements, the point of entry and the release of the arm in relation to the roll motion of the body has been defined to occur at an earlier time. This could be due to a different stroke rate used in both studies, which was not reported by Callaway (2015). The data structure presented is congruent with that of Stamm and Thiel (2015).

Referring to Figure 5, the athletes mostly swam the catch-up style, with one arm executing the insweep while the other arm recovers. This implies, according to Chollet and colleagues (2000), that the stroke rate is comparable to distance events. An average stroke rate of 32.4 ± 1.3 strokes per minute is in good agreement with the findings of Chollet et al. (33.9 ± 3.6; 27; Chollet et al., 2000) for their 800 m front crawl pace. Although the stroke rate and sinusoidal behaviour is identical for all athletes, large interpersonal differences are observable in forward acceleration (Figure 5). This was expected as the main purpose is to swim effortlessly while maintaining a high velocity per stroke. To distinguish between different skill levels, stroke efficiency should therefore be calculated automatically by dividing the difference between the maximum and minimum acceleration value (acceleration amplitude) over the cycle duration as with the formula:

$$SE = \frac{t_{cycle}}{a_{amplitude}}$$

In extreme cases, the athlete would have a small acceleration amplitude and could maintain his or her speed and therefore keep a low stroke rate.

To further validate the results of the present study, the synchronization process between video and measurement data should be improved by increasing the sampling rate of the video. In fact, this limitation led to an error of 0.06 s in key position detection. In addition, athletes of a broader skill level should be measured to confirm the results of the present study.

CONCLUSIONS

In this paper, for the first time an IMU positioned at the lower back was used to investigate the intra-cyclical characteristics of front crawl swimming. The results extended previous work which focused more on global parameters such as stroke rate (Le Sage et al., 2011; Ganzevles, Vullings, Beek et al., 2017; Ohgi, Kaneda & Takakura, 2014; Siirtola, Laurinen, Röning & Kinnunen, 2011; Slawson, Justham, West, Conway, Caine &Harrison, 2008), number of strokes per length (Ganzevles et al., 2017; Ohgi et al., 2014; Siirtola et al., 2011) and time (Ganzevles et al., 2017; Jensen, Prade & Eskofier, 2013).

It was shown that athletes with different skill levels show the same characteristics in their IMU data, which is fundamental for the development of algorithms for the analysis of the front crawl swimming stroke not only considering frequency and number of strokes, but also for the access to intra-cyclic parameters, e.g., time between each arm strokes, roll angle, roll amplitude, acceleration amplitude. It is important for coaches and athletes to have access to these performance-enhancing parameters to make progress in training and competition.

Future studies should focus on the evaluation of crucial parameters such as maximum acceleration, acceleration amplitude, time ratio of the two arm strokes as well as body roll, angular velocity and their respective amplitudes to learn more about the quantitative differences between expert and novice athletes. All these parameters can be automatically analysed, since the basis for such programming was established with the application in the present paper.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial intellectual contribution to the work and approved it for publication. AE conceived and drafted the first version of the manuscript. NS contributed to the writing and revision of the manuscript. RP supported the data analysis. NS and KM supervised and revised the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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