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INTRA-CYCLIC ANALYSIS OF THE BACKSTROKE SWIMMING TECHNIQUE WITH AN INERTIAL MEASUREMENT UNIT

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ABSTRACT

Over the past decades, the use of video to monitor and analyze the performance in swimming has become the gold standard of motion analysis. Due to the high cost of a professional video system as well as the time and expertise required to evaluate performance relevant parameters, these systems are only available to athletes at international level.

To enable training analysis also for athletes at national level, more cost-effective systems such as Inertial Measurement Units (IMU) are becoming more and more important. The advantage of these systems is that they are easily accessible and offer the possibility to automatically analyze the movement of a swimmer.

The current study addresses backstroke swimming and transfers the knowledge gained through video analysis to the data measured with an IMU. The focus is on intra-cyclic characteristics such as the body's side-to-side roll, angular velocity and forward acceleration. Ten athletes from regional to national level swam 100 m backstroke with an IMU positioned on the lower back and were simultaneously recorded on video. The IMU data obtained was linked to the video to identify key positions during a swimming stroke cycle and to find similarities and differences between the swimmers. The findings are the basis for the development of an automatic pattern recognition system that provides coaches and scientists with direct, real-time feedback on the execution of swim movements. In addition, it provides information on which parameters should be specifically trained to improve performance.

Keywords: IMU, intra-cyclic analysis, Backstroke, Swimming, Movement Technique, acceleration

INTRODUCTION

The understanding and interpretation of intra-cyclic characteristics in competitive swimming is a prerequisite for coaches to refine the execution of the athletes' movement technique during training and finally to improve overall swimming performance. The observation and evaluation of the swimming technique by sports scientists during regular training sessions and performance tests plays an important role. Such analyses are mainly recorded on video and are then interpreted with the athletes. This procedure is time-consuming and requires at least a semi-professional video system (i.e. several connected cameras with high resolution and sampling frequency). Furthermore, the evaluation is limited by the subjective view of the observer. There is a lack of objective and measurable performance relevant global parameters such as stroke length and frequency as well as intra-cyclic parameters such as the duration for each arm stroke, speed variation, etc. which can be directly communicated to the coach in real-time.

Recent studies have shown that the use of inertial measurement units (IMUs) has provided coaches and scientists with direct feedback on key parameters of the swimming movement (2, 3, 7, 9, 16, 21, 22, 31). Information was obtained on the swimmers' stroke frequency, time per lap and number of laps. In addition, an increasing number of studies using IMUs (24, 27) promise a wider application of IMUs in the near future. Moreover, the use of IMUs is likely more affordable not only for major clubs or training centres but also for a number of smaller competitive clubs. So far, the use of such sensors during regular training sessions has been perceived as disruptive and still requires the assistance of an expert (1, 8, 14, 17, 18, 32, 36, 37, 38). In addition, the sensors currently available on the market are mainly designed for recreational swimmers and therefore lack the accuracy relevant for elite athletes (28).

More recent studies by Engel et al. (10, 11, 12) extracted intra-cyclic parameters from the measured data of IMUs (attached to the lower back of the swimmer) for butterfly, breaststroke and front crawl swimming. In general, backstroke swimming has been investigated relatively few compared to the other three competitive strokes in scientific studies. According to Mooney et al. (27), only 33 studies using an IMU considered backstroke, as opposed to butterfly with 34 studies, breaststroke with 44 studies and freestyle/front crawl swimming with 90 studies. Maghalaes et al. (24) found that backstroke was investigated in seven studies, while breaststroke was investigated in 12 studies and freestyle/front crawl in 20 studies. Only butterfly was examined even less in five studies.

The present paper therefore firstly aims to complete the intra-cyclical analysis of all four competitive strokes and to examine the backstroke swimming technique, as well as secondly, to fill the gap with the comparison of the theoretically described motion technique of backstroke swimming with the measured data of an IMU. Finally, the results should provide a basis for the development of an automatically executable intra-cyclic cycle analysis to support coaches and sports scientists in their daily work.

BACKSTROKE SWIMMING TECHNIQUE

The main difference between backstroke swimming and the other three competition strokes is the swimmer's body position in the water during movement execution: in back or supine rather than prone position. According to the rules of the World Swimming Federation (Fédération Internationale de Natation, FINA), the athlete is allowed to perform any movement during backstroke swimming throughout the competition as long as it is not performed in a prone position.

The only exception is the turn, if the swimmer approaches the wall, where the rules allow a short turn in prone position. After each lap, the swimmer must touch the wall with any part of his body. Furthermore, a part of the swimmer must be above the water surface during the whole competition. Again, the only exceptions are the start and the time after the turn and turnaround, when the rules allow the swimmer to stay under water for a maximum of 15 m (13).

TECHNIQUE OF THE ARM STROKE

Even though the FINA rules allow every possible kind of motion to move forward in the water, a similar motion has established internationally among athletes of all levels. The arms move separately, and shifted by half of a swimming stroke cycle. The legs kick alternately up and down as in front crawl. This makes the movement of the arms suitable for dividing the swimming cycle into different phases in the movement analysis.

Counsilman (6) was the first who described three phases of the arm stroke: the entry phase ("first part" - beginning with the fingertips diving into the water until the elbow is maximally flexed), the underwater phase ("second part" - from the maximally flexed elbow to the complete extension of the arm below the body line) and the "release and recovery" (beginning with the fully extended arm under water until the fingertips break through the surface overhead).

Schramm (33) divided the underwater phase of the arms described by Counsilman (6) into three further sub-phases. The first part of the main phase (beginning with the catch until the elbow is maximally bent), the second part of the main phase (from the maximally bent elbow until the hand is on the thigh) and the transfer phase (from the moment the hand is on the thigh until the arm is fully stretched). He agreed to the beginning of the cycle as the entry phase and the end of a cycle with the release and recovery of the arm.

Maglischo (25) modified both movement descriptions by dividing the arm movement into five phases. The entry phase is here described as the first downsweep (the fingertips dive into the water until the catch is made), followed by the first upsweep (from the catch until the hand is close to the surface). This is followed by the second downsweep (where the hand is pressed down and back until the arm is fully stretched and below the thigh), followed by the second upsweep (fully stretched arm until the thumb is lifted out of the water). The arm stroke cycle ends with the recovery when the fingertips touch the water surface again. This movement pattern has long been considered the gold standard, but seems to be obsolete in the near future, as world-class athletes, especially in the shorter disciplines, tend to pull their arm through the water in a straight line, as if they were grabbing a handful of water and throwing it to their feet, performing a kind of side crunch. This movement is described by Mark (26) and while not excluding the more specific pattern described by Maglischo (25), it allows more flexibility in the execution of the movement.

Mark (26) divides an arm stroke cycle into four phases: Entry and catch, mid-pull (from the moment the hand is at the shoulders to the hip), finish (from the hip position to the full extension of the arm), and release and recovery. Thus, the model proposed by Mark (26) includes all other movement descriptions and will therefore be considered here as the gold standard. Table 1 gives an overview of the different phases and their interaction.

Table 1. Overview over the different phases of the arm stroke cycle as described by Counsilman (6), Maglischo (25), Mark (26) and Schramm (33).

Author	Phase Structure					
Counsilman(6)	Entry	Underwater Phase			Recovery	
Maglischo(25)	1st downsweep	1st upsweep		2nd downsweep	2nd upsweep	Release & Recovery
Schramm(33)	Entry & Catch	1st part of main phase	2nd part of main phase	Transfer phase	Recovery	
Mark(26)	Entry & Catch	Midpull		Finish	Recovery	

Entry and catch

All authors mentioned describe the beginning of the arm stroke cycle with the entry of the fingertips into the water. At this point, the little finger enters first with the palm of the hand pointing outwards (6, 25, 26, 33). Then the wrist bends first, followed by the elbow (26, 33), while the arm begins to move down and backwards (33).

According to Maglischo (25), the hand is 45-60 cm below the water surface and 60 cm from the body. During the catch, the elbow is bent by 140°-150°. Counsilman (6), on the other hand, describes that the hand is moved 20-30 cm below the water surface and the elbow is bent by a maximum of 90°-100°. This corresponds to the description of Mark (26), who defines the position of the hand at about 10-30 cm below the water surface and sets the angle of the elbow at 110°-120°. When the palm of the hand and the forearm are pointing backwards, the catch is completed and the entry phase ends (6, 25, 26, 33). At this point, the hand is at its lowest and outermost point of the cycle (25). As long as the catch is not completed, Maglischo (25) notes that no propulsive forces are acting.

Midpull

During the midpull, when the arm passes the shoulder, it should have the same height or depth as the shoulder and should then move in a straight line towards the feet (medulla). The arm and elbow move through the same plane throughout the entire pull. According to Maglischo (25) this is the first propulsive phase. When the hand passes the elbow, it begins to move backwards and upwards (25), while the elbow is stretched slightly to 90°-100° (6, 25, 33). The speed of the hand increases in this phase, so that it is comparable to the insweep in front crawl swimming (25). Schramm (33) describes the underwater trace of the hand as an S-shape. According to Mark (26), the midpull ends when the hand passes the hip.

Finish

In contrast to the straight-line movement described by Mark (26) for the midpull, the hand in the finish phase moves towards the thigh (inwards-backwards) and downwards (26, 33). If the underwater path of the hand is more S-shaped, as described by Schramm (33), Maglischo (25) and Counsilman (6), the end point or finish is at the highest point of the hand (6, 25). During the entire midpull and finish (underwater phase), the fingertips point outwards (25). Maglischo (25) emphasizes that the hand should not be pushed too close to the thigh so that the forearm can generate propulsion over a longer period. At the end of this phase the arm is fully extended (6, 25, 26, 33) and the hand is lower than the body line, meaning the hip (26) or the thigh (25), with the palm pointing inwards (26) or downwards (25).

Release and recovery

Maglischo (25) compares the release phase (in his words the second upsweep) with the upsweep that is performed in the front crawl and butterfly. The palm of the hand is pointing backwards, the fingertips are pointing downwards and athletes with a hyperflexible elbow are able to generate propulsion in this phase because the forearm is pointing backwards and the hand is moving backwards-upwards-inwards (25). Mark (26), Schramm (33), Counsilman (6) and Maglischo (25) agree that the thumb should leave the water first and with the elbow fully extended, followed by a recovery of the straight arm. The palm rotates from inwards to outwards when the hand passes the highest point during the recovery (26). The entire recovery is in one line with the body, in projection of the shoulder width (6, 25, 26) and the arm enters the water overhead, shoulder width (6, 25, 26, 33).

TECHNIQUE OF THE KICKING MOTION

The kicking motion in backstroke swimming is very similar to that in front crawl swimming (7, 25, 26, 33). The legs are constantly moving up and down alternately, with the upkick being propulsive and the downkick being non-propulsive (6, 25, 26). Mark (6) emphasizes three main purposes of the kick. Firstly, a good kick supports the pulling motion of the arms and thus minimizes the workload. Second, proper timing supports the rotation of the body around its transverse axis. Third, an efficient kick stabilizes the body and lifts the lower part of the body to the surface, minimizing water resistance. The kick not necessarily has to be performed in a vertical plane, at the highest point, near the surface, the feet can cross each other (26). The alternating kick (6, 23, 25, 26) should be narrow (26), and the flexibility of the ankle joint is essential for an effective kick (6). Counsilman (6), Maglischo (25), Schramm (33) and Mark (26) agree when dividing the kick into two phases -the downbeat and upbeat- and how they should be performed.

The upkick is best performed with the knee flexed and relaxed (6, 25, 26, 33) with the foot pointing downwards-inwards (25). The feet should not break through the water surface to maximize propulsion at the upper turning point.

During the downkick the leg is fully stretched by the water resistance (23, 25, 26, 33), which is less effective for anatomical reasons (26). The feet thereby sink deeper into the water than the hips (26).

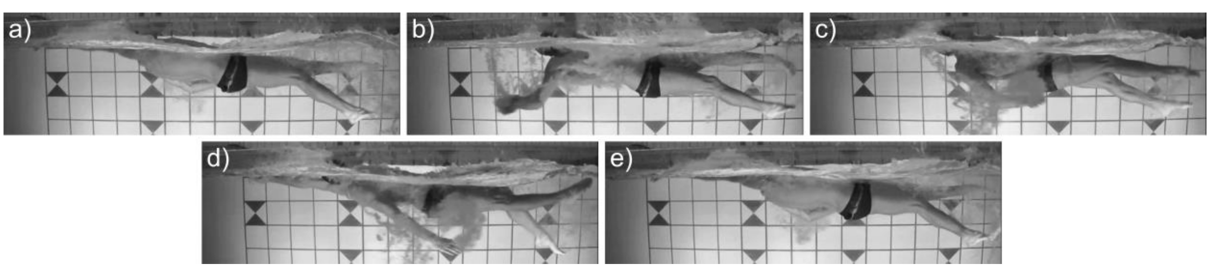

Figure 1. Key positions of the right arm stroke cycle.
Figure 1a: entry of the finger tips, which marks the beginning of the catch,
Figure 1b: right hand is at shoulder height, which corresponds with the beginning of the midpull,
Figure 1c: the hand is at hip height, this is where the finish begins,
Figure 1d: the arm is fully extended and the release and recovery begins,
Figure 1e: the right finger re-enter the water and one stroke cycle is finished.

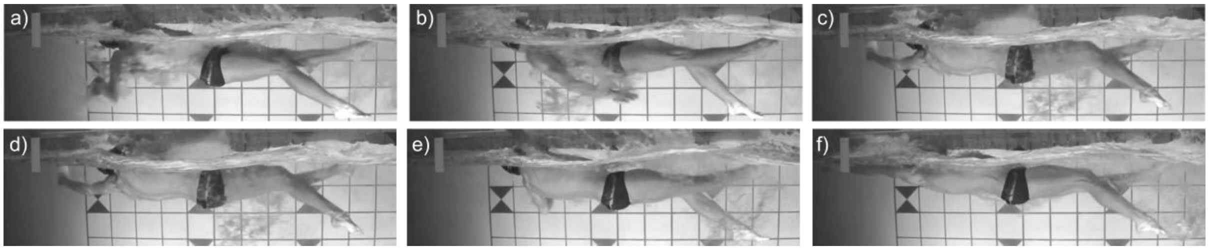

Figure 2. Key positions of one kick cycle of a junior athlete at national level.
Figure 2a: upper turning point of the left leg (start downbeat) and lower turning point of the right leg (start upbeat);
Figure 2b: lower turning point of the left leg (start upbeat) and upper turning point of the right leg (start downbeat);
Figure 2c: upper turning point of the left leg and lower turning point of the right leg;
Figure 2d-f: the beginning of the next cycle.

BODY ROTATION

Mark (26), Maglischo (25), Counsilman (6) and Schramm (33) all agree that body rotation is crucial for an efficient backstroke swimming. Schramm (33) makes some general statements on rotation, such as its supportive character for the pulling motion of the arms. More specifically, the catch is facilitated and the recovery benefits from body rotation (33) by reducing the water resistance through lifting the shoulder above the water surface (6, 26). The athlete should rotate 35°-40° to each side (33). This is in accordance with Maglischo (25) and Counsilman (6), who specify a maximum rotation of 45° to each side. They also specify the arms as the starting point for the rotation (25), which begins when one arm enters the water until the first upsweep, i.e. when the athlete finishes the catch. Subsequently the swimmer remains on the side until the second downsweep, which is identical to the finish and supports the swimmer when turning to the opposite side (6, 25).

Mark (26), on the other hand, indicates a rotation maximum of 30°, which is completed before the catch is initiated. The swimmer remains turned to the side during the entire arm stroke, with the rotation angle varying between 20° to 40°. The entire rotation takes place during the arm stroke completion, therefore it must be fast and precise and timing is crucial (26).

Maglischo (25) is the only author to emphasize the head should remain stable, although this view is generally accepted today.

TIMING OF THE ARM STROKES

While the overall movement of the arms and legs in backstroke swimming is in many ways similar to that in front crawl swimming, there is no variation at the beginning of an arm stroke as observed for different velocities in front crawl swimming (4).

Schramm (33) emphasizes the importance of coupling the propulsive motions of the arm stroke and leg kick to minimize intra-cyclic velocity fluctuations. This is further supported by a symmetrical stroke movement of the right and left body side. He also describes that the entry and catch of one arm takes place while the other is in the finish phase (33). This is consistent with Maglischo (25), who observed the first downsweep (entry and catch) of an arm during the second upsweep, which is technically assigned to the release and recovery phase. However, the arm is still under water.

We are not aware of any study that examines the timing of the arm stroke as a function of velocity or distance. We therefore assume that there is no difference.

KEY POSITIONS OF THE BACKSTROKE SWIMMING CYCLE

In summary, the descriptions of the backstroke swimming technique together show a clear division of the arm stroke cycle into four different phases. These phases are suggested by Mark (26) and described by Maglischo (25), Schramm (33) and Counsilman (6) with different names. We think that Mark's description is the most general and actually covers all variations of movement execution (26). Table 2 provides a detailed description of the phases and key positions of the arm stroke and leg kick and their propulsive character.

This paper therefore aims to answer the following questions: do athletes of different skill levels show the same characteristics in their IMU data with regard to lateral rolling (side-to-side roll) and forward acceleration when swimming with their individual speeds and stroke rates? What approach might be suitable for an automatic intra-cyclic analysis of backstroke swimming?

METHODS

The data was collected during regular training sessions with athletes at national and regional level. 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

Ten swimmers (six females (14.8 ± 0.9 years), four males (16.0 ± 0.7 years)) participated in this study. Seven athletes took part in the national junior championships and achieved an average of 430 ± 58 FINA Points at this event. Each of them swam 100 m backstroke and together they completed 270 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 backstroke with moderate intensity. The data was recorded with an IMU sensor placed on the lower back of the swimmer and video recorded as well.

Table 2. Phases and key positions of the arm stroke and leg kick in backstroke swimming: division of one cycle into different sub-phases.

Cycle Part	Phase	Key position at the beginning	Character
Arm stroke Cycle	Entry & Catch	Entry of the finger tips	Non-propulsive
	Midpull	Hand at shoulder height	Propulsive
	Finish	Hand at hip height	Propulsive
	Recovery	Arm fully extended	Non-propulsive
Kick Cycle	Downbeat 1	Right foot at its highest point	Non-propulsive
	Upbeat 1	Right foot at its lowest point	Propulsive
	Downbeat 2	Left foot at its highest point	Non-propulsive
	Upbeat 2	Left foot at its lowest point	Propulsive

Data acquisition

The sensor unit (BeSB GmbH Berlin, Germany) consists of a 3D-acceleration sensor (range: ±2g, resolution: 0.01 m/s²) and a 3D-gyroscope (range: ± 250°/s, resolution: 0.01°/s) with a sample frequency of 100 Hz. The unit also stores the measured data for later processing on a PC. The data was smoothed using 4 Hz Savitzky-Golay filter.

All trials were video recorded (sample rate 24 Hz) and the software jBeam (19) was used to link and synchronize the footage with the measured data. 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 provided a distinct acceleration peak in the IMU data and facilitated the linking to the video afterwards.

Sensor position

Maghalaes et al. (24) 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 (14), wrist (5), leg (4), forearm (3), head and upper back (2).

Based on this work and the work from Pansiot and colleagues (30), who 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, the sensor was placed on the lower back in a pocket sewn to a belt.

RESULTS

Arm stroke

Figure 3 shows exemplarily the time-normalized mean values of 31 backstroke swimming cycles of a junior athlete at national level for the roll angle (upper graph), forward acceleration (middle graph) and angular velocity (lower graph).

The different phases of an arm stroke are further explained using this example shown in Figure 3. T_1 describes the phase in which the hand dives into the water and the opposing arm is about to finish the underwater stroke. During these two phases, neither the arm stroke nor the leg movement generates any acceleration. Also, the hip does not move at all, so the angular velocity is close to zero. During the following phase P_1 the right arm dives deeper into the water, the elbow bends and the palm of the hand starts to point backwards. This leads to a rotation of the hip to the right, which is clearly shown by the increase in angular velocity and roll angle. The entry and catch phase is finished when the hand is at shoulder height (t_2). Subsequently, the midpull begins (P_2), during which the body is accelerated as seen in the course of forward acceleration. The hip remains almost stable to stabilize the body against the pushing movement of the arm. When the hand reaches the hip (t_3) the finish phase begins (P_3). Although this phase is

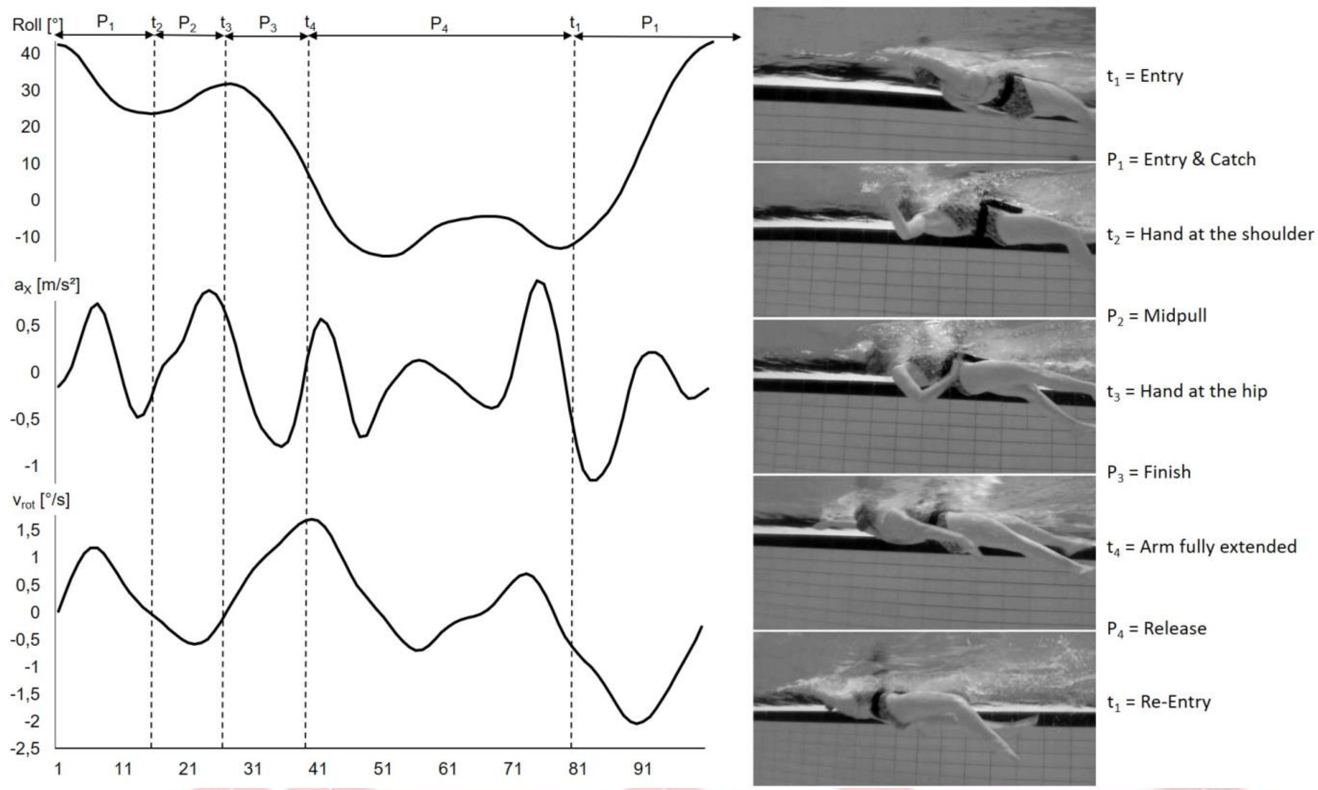

Figure 3. Arm stroke of the right arm of a junior athlete at national level.
t_1 shows the entry of the fingertips and the corresponding point in the IMU data,
t_2 shows the moment when the hand is at shoulder height,
t_3 is the moment when the hand is at hip height,
t_4 is characterized by a fully stretched arm and
t_1 then shows the re-entry of the right hand into the water.

supposed to be propulsive, there is a distinct deceleration peak in the data, which will be discussed later. During this phase the hip begins to move to the other side to support the release and recovery of the right arm und the entry and catch phase of the left arm. The release and recovery phase starts at t_4 when the arm is fully stretched and lifted out of the water (P_4).

The movement of the left arm in Figure 4 shows the same characteristics as described in Figure 3 for the right arm.

Both arm strokes in combination with the body rotation support and facilitate the execution of the overall movement. Figure 5 shows both arm strokes in one graph to illustrate which phases overlap. The black labels show the key positions and corresponding stroke phases for the right arm stroke, and the grey labels mark the key positions and corresponding stroke phases for the left arm stroke. Both arms show approximately the same pattern of body roll, forward acceleration and angular velocity.

The entry is in the finish phase of the opposing arm and is followed by a decrease in acceleration, due to the two non-propulsive phases of entry and catch and recovery, which overlap. During the entry and catch almost the complete rotation takes place.

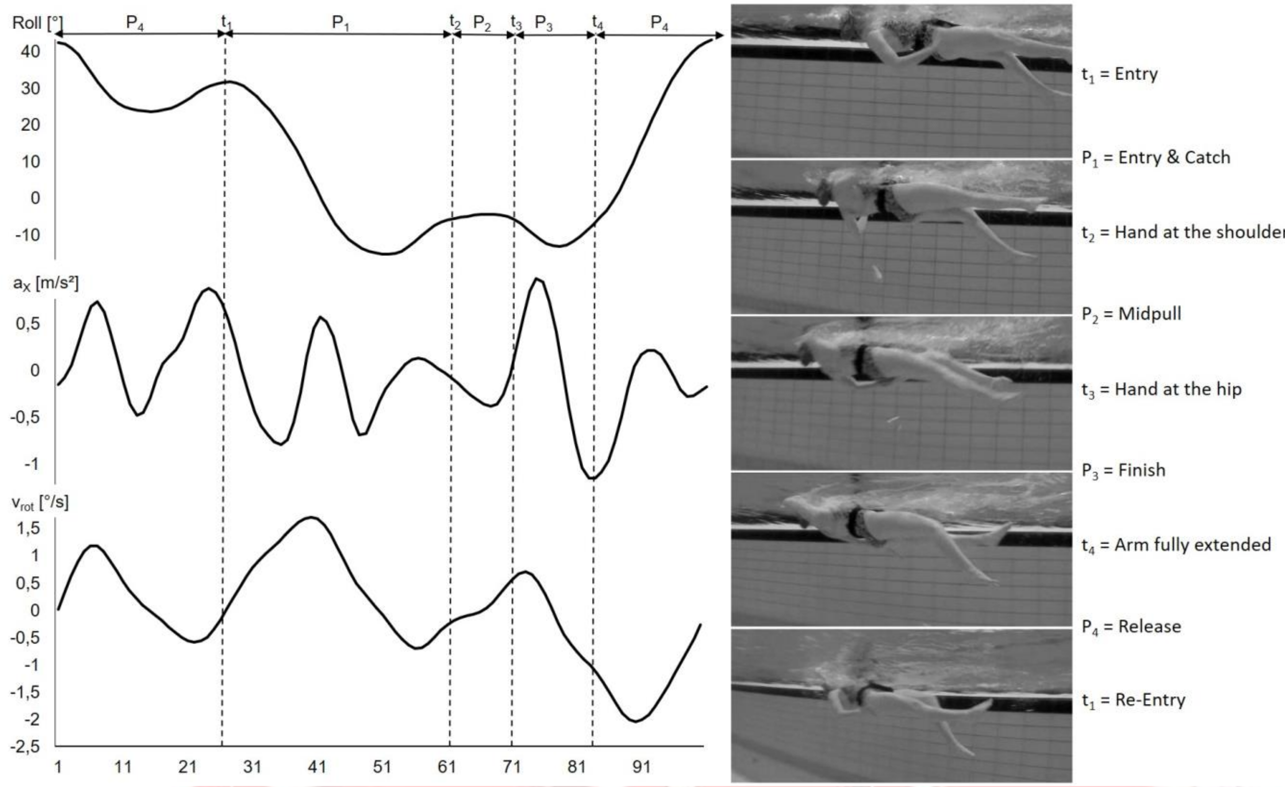

Figure 4. Arm stroke of the left arm of a junior athlete at national level.
t_1 shows the entry of the fingertips and the corresponding point in the IMU data,
t_2 shows the moment, when the hand is at shoulder height,
t_3 is that moment, when the hand is at hip height,
t_4 is characterized by a fully stretched arm, and then
t_1 shows the re-entry of the left hand into the water.

Bringing all athletes together

Figure 6 now shows the time-normalized and summarized data for all 10 athletes and their 270 stroke cycles. The upper graph depicts the rolling motion of the hip, the middle graph shows the forward acceleration and the lower graph shows the angular velocity during one stroke cycle. The bold line represents the average value, while the upper and lower black lines represent the maximum and minimum values respectively. The four boxes each mark the beginning of the corresponding phase for the arm stroke. The width represents the variance of the beginning of the phase among all athletes.

For all athletes, the entry phase correlates with a decrease in forward acceleration. As already shown, this is because the entry phase corresponds to the finish phase and the following recovery of the opposing arm, so that two phases of non-propulsive character occur simultaneously. Together with the entry and catch, the body rolls to the side, as can be seen in the course of the roll angle. Maximum lateral rolling is achieved just before the midpull begins.

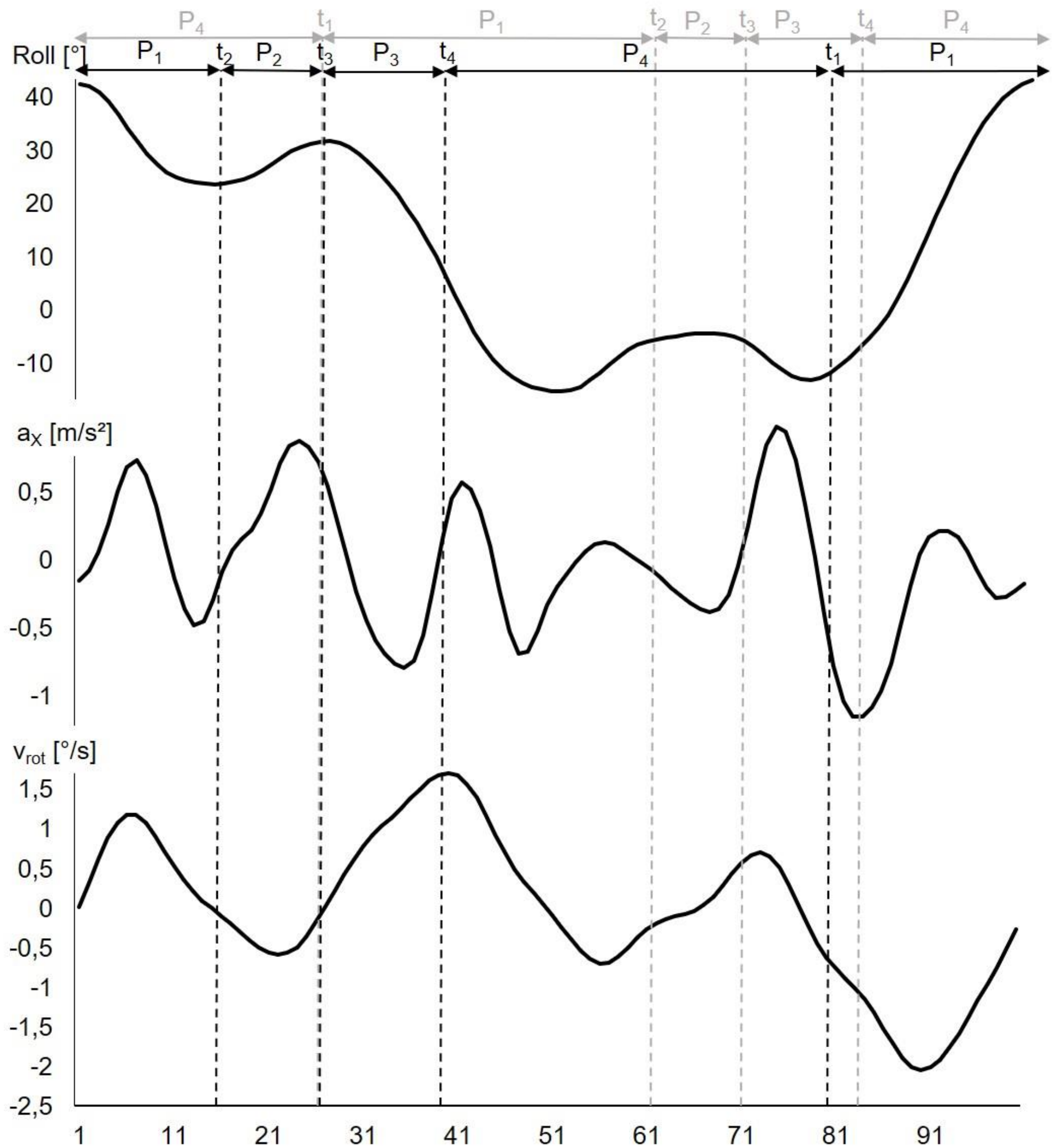

Figure 5. Combination of the left (grey labels) and right (black labels) arm stroke phases to emphasize the congruence of both movements and the overlaping of the different phases.

During the midpull there is almost no rotation in the hip. The angular velocity is about zero and the body roll remains at the same value. This changes with the beginning of the finish phase when the hand is pushed under the thigh and then released out of the water. At this point the hip starts rolling to the other side to facilitate the entry and catch movement of the opposing arm.

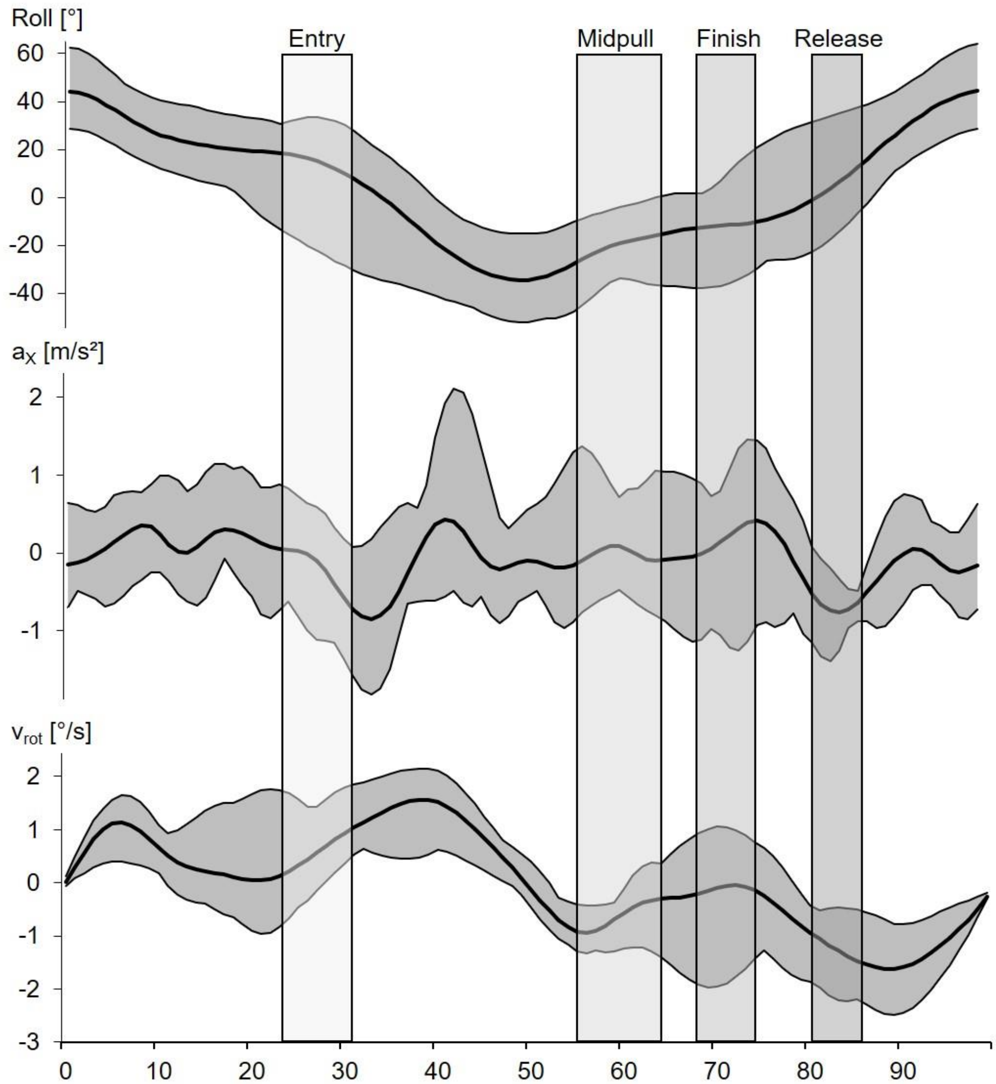

Figure 6. Time-normalized graphs over all 10 athletes and 270 stroke cycles The boxes mark the beginning of the different arm stroke phases, while the width of the boxes represents the variance among all participants.

DISCUSSION

The purpose of this paper was to answer the following questions: Do athletes of different skill or performance levels show the same characteristics in their IMU data in terms of side-to-side roll, forward acceleration and angular velocity? What might be a suitable approach for an automatic intra-cyclical analysis of backstroke swimming?

The structure and course of the three parameters body roll, forward acceleration and angular velocity can be considered as a model for the development of an algorithm for the detection of certain performance relevant parameters in backstroke swimming. Regardless of skill level, the same characteristics were observed in the data structure.

The body roll shows an almost sinusoidal behavior with a clear maximum and minimum within each cycle. This is not the case for the angular velocity, which tends to oscillate more strongly within a swimming stroke cycle and has three minima and three maxima. As expected, the zero values for angular velocity correspond to a minimum/maximum for body roll. In particular, the zero crossing in v_{rot} is the point in the cycle with the least variation and further divides a swimming stroke cycle into two halves.

As shown in Figure 6, there is no relevant hip rotation during midpull, which is consistent with the theoretically proposed model (6, 25, 26, 33). An automatic analysis could be able to detect the beginning of the propulsive phase of the arm stroke (midpull) when the angular velocity is at its local minimum, and the end of the finish phase when the hand is released and forward acceleration is minimal. In this way, differences between novice and elite athletes could be detected.

Another important observation in the data analysis was the forward acceleration curves, which seem to be dominated by the leg kick. While the pulling motion of the arms produces an almost homogenous propulsion, the leg kick is responsible for six acceleration peaks, which can be seen in Figure 5. In contrast to front crawl swimming, where the leg kick only dominates during sprint events, backstroke swimming relies more on a steady kicking regardless of swimming speed to prevent the legs from sinking down. Thus, the acceleration data is more influenced by the kicking motion and that is the reason for the acceleration and deceleration peaks in the data. Therefore, an intra-cyclic analysis of forward acceleration is rather unsuitable here. The two distinct minima that occur in all athletes are due to the simultaneous presence of the non-propulsive phases of the release and entry of both arm strokes.

In accordance with the theoretically proposed model (6, 25, 26, 33), the propulsive phase is located in the midpull and finish phases. The data presented also confirmed the statement that the rolling action is during the finish, recovery and entry phase (6, 25, 26). Values for body roll between 30° to 60° and -10° to -50° were measured. This is confirmed by literature values (6, 25, 26).

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

The results presented in this paper extend previous work in which global parameters such as stroke rate (15, 22, 29, 34, 35), number of strokes per length (15, 29, 34) and time (15, 20) were calculated from IMU data. For the first time an IMU positioned on the lower back was used to extract intra-cyclic parameters for backstroke swimming, as shown by Engel et al. for butterfly, breaststroke and front crawl swimming respectively (10, 11, 12).

It was demonstrated that athletes with different skill levels share the same characteristics in their IMU data, which is crucial for the development of an algorithm to detect intra-cyclic parameters such as time between arm strokes, body roll angle and roll amplitude. This gives both athletes and coaches an objective view of performance-enhancing parameters to help them make progress in training and competition.

Follow-up studies should focus on investigating differences in backstroke swimming data as a function of swimming speed (distance) in terms of time spent in each phase, as well as the level of the athletes in terms of quantitative parameters such as roll amplitude or decrease in forward acceleration.

All these parameters can be analyzed automatically, since the basis for such programming was established with the application in the present paper.

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Conflict of interest declaration

The authors have no conflict of interests.

Ethics

University of Hamburg Institutional Ethics Research Committee approval was obtained for the study procedure. The study conformed to the provisions of the Declaration of Helsinki.

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