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

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ABSTRACT

Inertial measurement units (IMU) are becoming increasingly relevant to motion analysis among scientists as they become more accessible and less annoying for athletes. They are also a promising alternative to time-consuming video analysis. Current research in swimming focuses on the analysis of global parameters for the four competing strokes, such as stroke frequency, number of cycles and timing, and fails to look at intra-cyclical parameters that are known to have an important impact on overall performance. The aim of this study was to analyze the intra-cyclical breaststroke patterns of 10 athletes of different performance levels who swam 100 m each with medium effort and performed a total of 357 swimming strokes. The data obtained were linked to the video to extract previously described key positions and and their corresponding data points in order to explore similarities in the data structure between all athletes and for different performance levels. The results were pretty clear, that regardless of the athlete's level, certain global patterns in the data structure exist, which allow for an automatic intra-cyclic analysis of the breaststroke. This enables sport scientists to detect mistakes in movement performance, objectify the technical analysis and help coaches improve their training load and adapt it to the fatigue and specific needs of each athlete.

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

INTRODUCTION

The use of inertial measurement units (IMUs) in swimming has increased considerably in recent years (18, 13) as they offer clear advantages over conventional methods. First, the use of IMUs is less time-consuming and requires less personnel than video analysis (2), with the latter having some other disadvantages. One can only observe a few swimming cycles or have to connect several cameras together to observe a greater distance, which increases costs (2). On the other hand, tachometers (or velocity meters) are widely used where a cable is attached to the hip of the swimmer like a belt. Puel and colleagues (21) describe the disadvantage of this method, which is primarily due to its design. Inside the speedometer there is a generator that measures the speed at which the wire attached to the swimmer unwinds. To obtain a value independent of gravity, a torque must be applied to the wire, which results in a less sensitive measurement of velocity changes compared to IMUs (4, 21, 23).

In contrast to these traditional methods, IMUs offer many advantages. They have become affordable in recent years (17) and are easier to set up and use than video systems or speedometers. However, these systems lack a simple analysis that meets scientific requirements (18). Performance relevant parameters that have to be analyzed are e.g. number of strokes, frequency, stroke duration, intra-cyclical velocity fluctuations. Puel and colleagues (21) showed an IMU in breaststroke can measure velocity as accurately as a speedometer and that even small changes in velocity can be observed. Unfortunately, the authors neither performed an intra-cyclical analysis nor assigned the data to the different phases and key positions of arm stroke and leg kick movement. This was done by LeBlanc and colleagues (10), who used a velocity-meter to measure speed and linked the minima and maxima to the respective key position during a swimming cycle. In addition, they compared the 50 m, 100 m and 200 m times of elite swimmers and non-elite swimmers with respect to various intra-cyclical parameters. Dadashi and colleagues (5) investigated the intra-cyclic characteristics of the breaststroke, using two IMUs positioned on the forearm and the tibia.

For the analysis and evaluation of a movement technique, it must be possible to distinguish between appropriate and inappropriate movements. Acceleration data are indispensable for this because they can provide information about intra-cyclical speed changes (14). Due to the few findings on this topic so far, this study aims to analyze the IMU data collected in a study intra-cyclically and to assign them to the key positions in breaststroke. The normalized acceleration curves of swimmers with different performance levels will be evaluated and aspects for an automated intra-cyclical analysis of the breaststroke technique will be discussed.

BREASTSTROKE TECHNIQUE

The International Swimming Federation FINA (30) defines the rules for the technique of breaststroke in competition. The swimmer must to be in a prone position throughout the race and a stroke cycle is defined as an arm stroke followed by a leg kick. The movement of arms and legs must be simultaneous and in a horizontal plane without alternating movements. The head must break through the water surface at least once on every cycle and both hands must touch the wall simultaneously.

The arms must not pass the hip and must be pushed forward starting from the chest. The elbows cannot break through the surface of the water. The movement of the legs is defined in such a way that the feet must be turned outwards during the propulsion phase and no downward kick (comparable to the butterfly kick) is permitted.

TECHNIQUE OF THE ARM STROKE

Due to the strict rules described above, there are not many differences in the description of the arm stroke technique of breaststroke by several authors. It consists mainly of a semicircular underwater movement without sharp direction changes (22, 15, 16) to generate propulsion and a straight forward recovery. Maglischo (15, 16) mentioned three phases: The outsweep, the insweep and the recovery. Other authors such as Counsilman and Wilke (3), Madsen and colleagues (12) or Riewald and Rodeo (22) did not explicitly describe the phases; only Schramm (24) named four phases: Initiation, main phase, transition and preparation, whereby the transition phase today is not performed by world-class athletes and the very general description of Maglischo (15, 16) remains the basis for the description of the movement. In contrast to the other three competitive strokes, the breaststroke arm stroke is more of a sculling movement with a diagonal of 70° to 85° compared to a much stronger backward movement as in the front-crawl or in the butterfly with a diagonal of 30° to 60° (15, 16).

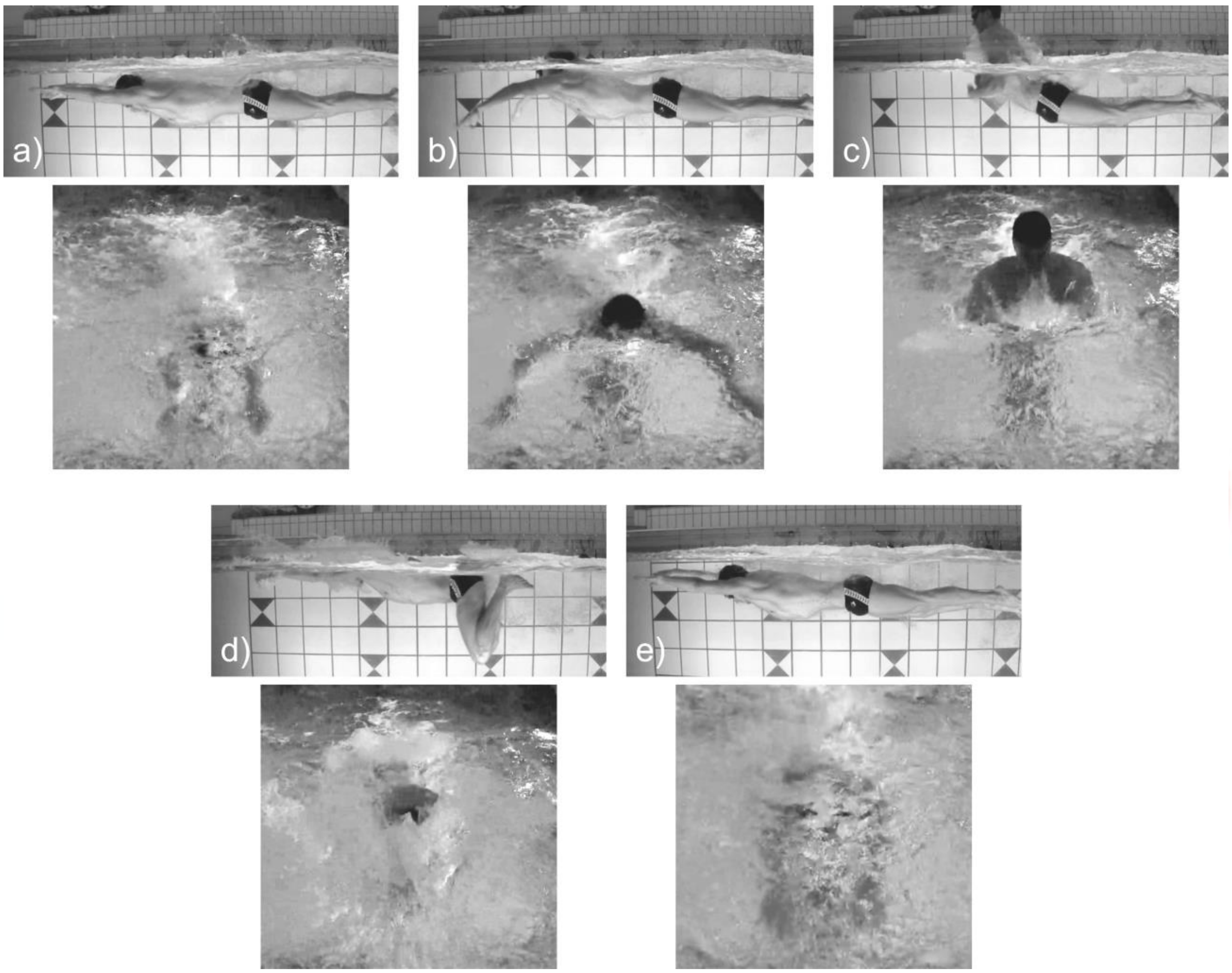

Figure 1. An arm stroke cycle of an athlete at international level;
Figure 1a: the beginning of the outsweep;
Figure 1b: the moment, when the palms turn backward and the insweep begins;
Figure 1c: begin of the recovery;
Figure 1d: begin of the gliding phase;
Figure 1e: begin of the outsweep and the next swimming cycle.

The outsweep

The Outsweep begins with the arms stretched in front of the body and with a movement of the palms turning from facing the bottom to the outside and a spreading of the arms (3, 14, 22, 24). It is unclear whether this movement is performed with the arms stretched (3, 14, 24) or bent (12, 22). Counsilman and Wilke (3) determines a 45° angle of the outer palms and initially positions the hands at a depth of about 15-25 cm.

If the hands exceed the shoulder width (3, 24), the elbows are bent (3, 12, 14, 22) at around 30° to 40° (3) to perform the catch with a high elbow. The palms and forearms are directed from the outside to the back (14). Finger and forearms are aligned (14) and point downwards (22) when the outsweep is finished. Riewald and colleagues (22) emphasizes that the widest point (2-2.5 width of shoulders (24)) of the stroke is reached in front of the shoulders.

The insweep

The Insweep begins when forearms and palms point backwards and is characterized by a semicircular movement (14, 24), in which the hands are accentuated and quickly (12, 22) move sideways inwards (22, 24) whereby the shoulders are also moved inwards (14). The upper arms turn inward (3, 12), palms are diagonal to direction of movement (22, 24) and produce propulsion by lift-forces (24) and vortices (14). To maximize propulsion, it is necessary to place the forearms in line with the hands. It is unclear whether the elbows must be above the hands (14) or whether the forearm inclined 40-60° to the surface (24). The elbow is bent continuously throughout the Insweep - from 120° (24) to 80° (14).

Propulsion stops when the palms are opposite at the end of the insweep (14), so it is necessary to keep the palms and forearms back, even if the circular motion brings the forearms closer.

There is no consensus between the authors as to whether the elbows must remain in front of the shoulders (12, 22) or whether the arm stroke is still effective when the elbows pass the shoulder line (14). However, Maglischo (14) emphasizes that the recovery is not negatively influenced when performed correctly, but that the propulsive phase is extended.

At the end of the insweep the upper arms rest on the side of the body (14, 22, 24) and the palms of the hands face each other (3). Riewald and Rodeo state that the forearms are horizontal, which is not confirmed by the other authors, and Maglischo (14) merely notices that the hands are led to the surface.

Recovery

Recovery begins when the elbows and upper arms are on the side or under the upper body (14) and the palms of the hands are facing each other (3). The hands move towards the water surface (14, 15, 16, 22) or above (14, 15, 16), while the palms of the hands are directed inwards and upwards (14, 15, 16, 22). The hands are not on top of each other, the elbows remain close (14, 15, 16), but separate from each other and lower than the hands during the entire recovery (22). While the arms are stretched forward in streamline position (14, 15, 16), the palms of the hands rotate downwards (14, 15, 16, 22) and the hands break through the water surface just before the arms are fully stretched (22). At the end of the recovery it is inevitable that the head and upper body touch the water (14, 15, 16). The recovery ends when the arms are fully stretched (12, 14, 15, 16).

ENTRY AND GLIDE

The recovery is followed by the entry and gliding of the arms, which is mostly ignored. World-class athletes, especially in the 100-meter and 200-meter races, have a clearly observable gliding phase with every arm stroke. The arms remain in a streamlined position (12, 14, 15, 16, 22) to minimize drag until the leg kick is completed and then the palms turn outwards, initiating the next stroke cycle.

TECHNIQUE OF THE BREASTSTROKE KICK

Like the arm stroke, the kicking movement is also subject to very strict regulations, with the position of the feet (turned outwards) serving as the main factor for a unique movement. Maglischo (14, 15, 16) described the kick phases explicitly in complete analogy to the arm stroke. The kick begins with the recovery and is followed by the outsweep, the insweep and the leg lift and glide.

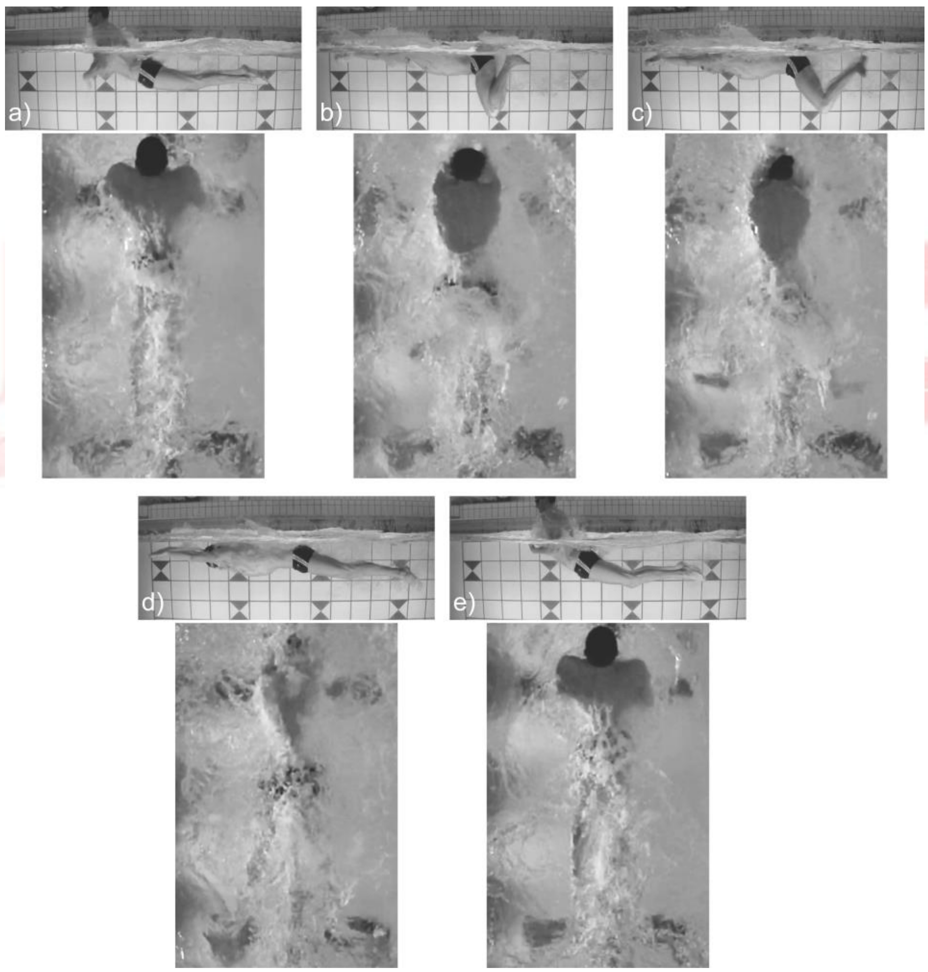

Figure 2. A kick cycle of an athlete at international level;
Figure 2a: begin of the leg recovery;
Figure 2b: begin of the outsweep;
Figure 2c: widest point in the leg kick and begin of the insweep;
Figure 2d: begin of leg lift and glide phase;
Figure 2e: begin of the recovery of the next swimming cycle.

Recovery

The recovery begins when the knees begin to bend and ends when the feet are as close as possible to the buttocks (3, 14, 22, 24). Maglischo (14) states that the hips remain in line with the upper body and are not bent, but fall deeper into the water. This is in contrast to Counsilman and Wilke (3), who mention a bent hip, but in agreement with Madsen. During this movement the knees remain close, hip-width (24) or shoulder-width (12, 14, 22) apart, while Riewald and Rodeo (22) explicitly emphasize that the feet are further apart than the knees. Nevertheless, when describing the position of the feet, the authors agree that the feet are pointing outwards with the toes pointing to the side (3, 22, 24). The sole of the foot is directed backwards (22) and the angle between the feet is 140° (24).

The authors disagree on the determination of the angle between hip and thigh. Schramm speaks of 135°, Counsilman and Wilke (3) mention a minimum of 110° and Riewald and Rodeo (22) observed angles up to 90°. To minimize the effect of the deceleration due to the large frontal resistance of the thighs, Riewald and Rodeo (22) as well as Maglischo (14) emphasize that the movement should be performed quickly.

The outsweep

According to the arm stroke the next phase can be termed outsweep. The outsweep begins when the feet are on the buttocks, the soles of the feet are directed backwards and the toes point outwards (14, 22). The path of the feet can be best described as a semicircular movement (12, 24) with bent feet (12, 14). Madsen and colleagues (12), Riewald and Rodeo (22) as well as Maglischo (14) divide the kick into an outward movement (Outsweep) followed by an inward movement (Insweep) during which the legs are stretched. The outward movement ends when the feet are as far apart as possible.

The insweep

The Insweep is characterized by the legs sweeping downwards, backwards and inwards, while the feet are turned downwards and inwards (14). According to Schramm (24), propulsion is generated by vortices and frontal drag and Maglischo (14) states that the Insweep is the only propulsive phase of the breaststroke kick. More precisely, Riewald and Rodeo (22) attribute the main propulsive effect to pressing the lower legs and feet against each other. Schramm emphasizes here that the purpose of the leg kick is to maximize the propulsion in the shortest time possible.

The inward movement ends when the legs are fully extended and the feet are close together with the soles of the feet facing each other (14). Normally the legs at this point are not in a horizontal position, which leads to an upward movement of the feet. Therefore, Maglischo (14) labels the next phase leg lift and glide.

LEG LIFT AND GLIDE

The leg lift and glide begins when the legs are fully extended and the feet are almost together (14) as described above. The legs move upwards until they are in line with the body (12, 14) and the gliding phase begins (14). The duration of the glide depends on the stroke frequency and is characterized by fully stretched legs and a pigeon toe position of the feet to reduce drag and maintain a high velocity (14) throughout the glide phase in the overall movement and during the propulsive phase of the arm stroke (14, 15, 16). The higher the stroke frequency the shorter the glide time. The leg lift and glide ends when the knees begin to bend, marking the start of the next kick cycle and thus the recovery.

TIMING OF THE KICK AND ARM STROKE FROM CYCLE TO CYCLE

The main factor for timing the start of the next stroke cycle is the stroke frequency. Maglischo (14) distinguishes between three styles, namely glide, continuous and overlap. When performing the gliding style, the athlete shows a short interval between the end of the kick and the start of the next arm stroke, as mentioned above (14). This style is less effective than the other two, regardless of the velocity loss during the glide phase that the world class 200-m-breaststroke swimmers achieve.

The continuous style is performed when the athlete begins the arm stroke immediately after finishing the kick and shows less deceleration from one stroke to another compared to the gliding style (14). The athlete can minimize the inter-cyclical velocity fluctuations by performing the overlap style, which is characterized by starting the arm stroke even if the propulsive phase of the kick is not yet finished (14). Schramm (24) and Madsen and colleagues (12) agree by saying that the outsweep of the arms can begin, even if the leg kick is not finished, but a high stroke frequency is necessary. Thus, the athlete skips the leg lift and glide in the kick phase and goes directly to the recovery.

Riewald and Rodeo (22) showed that the time required to perform the arm stroke is independent of the stroke frequency, but the time required for the recovery and glide phase of the legs becomes shorter with increasing stroke frequency.

TIMING OF THE KICK AND ARM STROKE WITHIN A CYCLE

Due to the above described connections, the timing for the start of the leg recovery during the arm stroke is independent of the style performed. Madsen determines the start of the recovery of the legs parallel to the start of the recovery of the arm, while Riewald and Rodeo (22) as well as Counsilman and Wilke (3) determine the recovery of the leg parallel to the Insweep of the arms. Therefore, Madsen and colleagues (12) describe the beginning of the kick when 2/3 of the arm recovery is completed. In contrast, Counsilman and Wilke (3) describe the leg kick as simultaneous with the recovery of the arms and Riewald and Rodeo (22) state that the leg kick begins when the head dives between the arms, which do not necessarily have to be fully stretched. Riewald and Rodeo (22) also emphasize the need to take care of the propulsion phases and minimize drag.

Table 1. Phases and key poses of the arm stroke and leg kick in breaststroke swimming to divide a cycle into different parts.

Cycle Part	Phase	Key pose at the begin	Character
Arm stroke Cycle	Outsweep	Stretched arms, Palms turn outward	Probably propulsive
	Insweep	Hands turn backwards and inwards, High elbow	Propulsive
	Recovery	Palms are opposite to each other, upper arms are at the side of the body	Non-Propulsive
	Entry & Glide	Arms fully extended	Non-Propulsive
Kick Cycle	Recovery	Knees begin to bend	Non-Propulsive
	Outsweep	Knees fully bent	Non-Propulsive
	Insweep	Feet maximally apart	Propulsive
	Stretch & Glide	Legs straight	Non-propulsive

Regardless of the concrete timing, a stroke cycle is characterized by two different propulsive movements, each followed by a non-propulsive and thus decelerating phase (1, 8). Thus, this study aims to answer the following questions: Do athletes of different skill levels show the same characteristics in their IMU data with respect to the different phases? How could an automatic analysis of the breaststroke cycle be designed?

METHODS

The data were collected with athletes of different skill level (regional to national) during regular training session. Ethics approval was granted by the University of Hamburg. All athletes gave their informed consent before participating in this study and reported no injuries or other impairments which would have excluded them.

Participants

Ten athletes (six females, 14.9 ± 0.9 years; four males, 16.0 ± 0.7 years) swam 100 m and a total of 357 breaststroke cycles. They reached an average of 444 ± 86 FINA points in the 100 m breaststroke.

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 breaststroke with medium intensity. The trials were filmed as well and data was recorded with an IMU sensor, placed on the lower back of the swimmer.

Data acquisition

The IMU sensor (BeSB GmbH Germany, Berlin) included a 3D-acceleration sensor (range: ±2 g, resolution: 0.01 m/s²) and a 3D-gyroscope (range: ±250°/s, resolution: 0.01°/s). The data were measured with 100 Hz and stored and transferred to the PC via Bluetooth. The data was smoothed using a 4 Hz Savitzky-Golay filter with the software Origin94, which was also used to generate the presented graphs. All trials were video-recorded (sample rate 24 Hz) and the footage was linked and synchronized with the measured data using the software jBeam (29) to extract videos of a predefined length. To synchronize the video with the measured data, the sensor was filmed while being moved out of a resting position before the swimming trial which produced a distinct acceleration peak in the IMU data and could easily be linked to the video. Data analysis was conducted descriptively.

Sensor position

According to Pansiot and colleagues (20), who found, that the best sensor position is the lower back to track timing, lap count, stroke count, the sensor was positioned on the lower back in a pocket sewed to a belt. In literature there is no consensus, whether the hip or the center of mass is an appropriate location to measure intra-cyclic characteristics in breaststroke (8) As both landmarks are located very close to each other, one could assume, that the acceleration shows the same behavior, regardless of which mark is used to calculate.

Gourgoulis and colleagues (8) found, that the velocity to time curves of the center of mass (CM) and the hip showed the same patterns. Those are two clear velocity maximums (whereas the one generated by the leg kick has a steeper increase) followed by a decrease in velocity and therefore minimal values. Though, they emphasize that the velocity calculated from the CM is more valid, the hip velocity can be used to give feedback to the swimmer. Additionally, they state, that the hip velocity overestimates the velocity variation throughout one cycle, as it delivers a greater maximum and a lower minimal value than the velocity calculated from the CM.

RESULTS

Arm stroke

According to the rules from FINA, one stroke cycle has to start with the pull of the arm stroke, which is why we start the analysis of the stroke cycle with the palms turning outward while the arms are still fully extended. Figure 3 shows a mean stroke cycle over 33 swimming strokes of an athlete at national level of a 100 m swim. The key positions of an arm stroke cycle are marked with t_1 to t_4 and the following stroke phases with P_1 to P_4. The upper graph shows the forward acceleration (a_{sx}) and the lower graph the vertical acceleration (a_{sz}) perpendicular to the swimming direction.

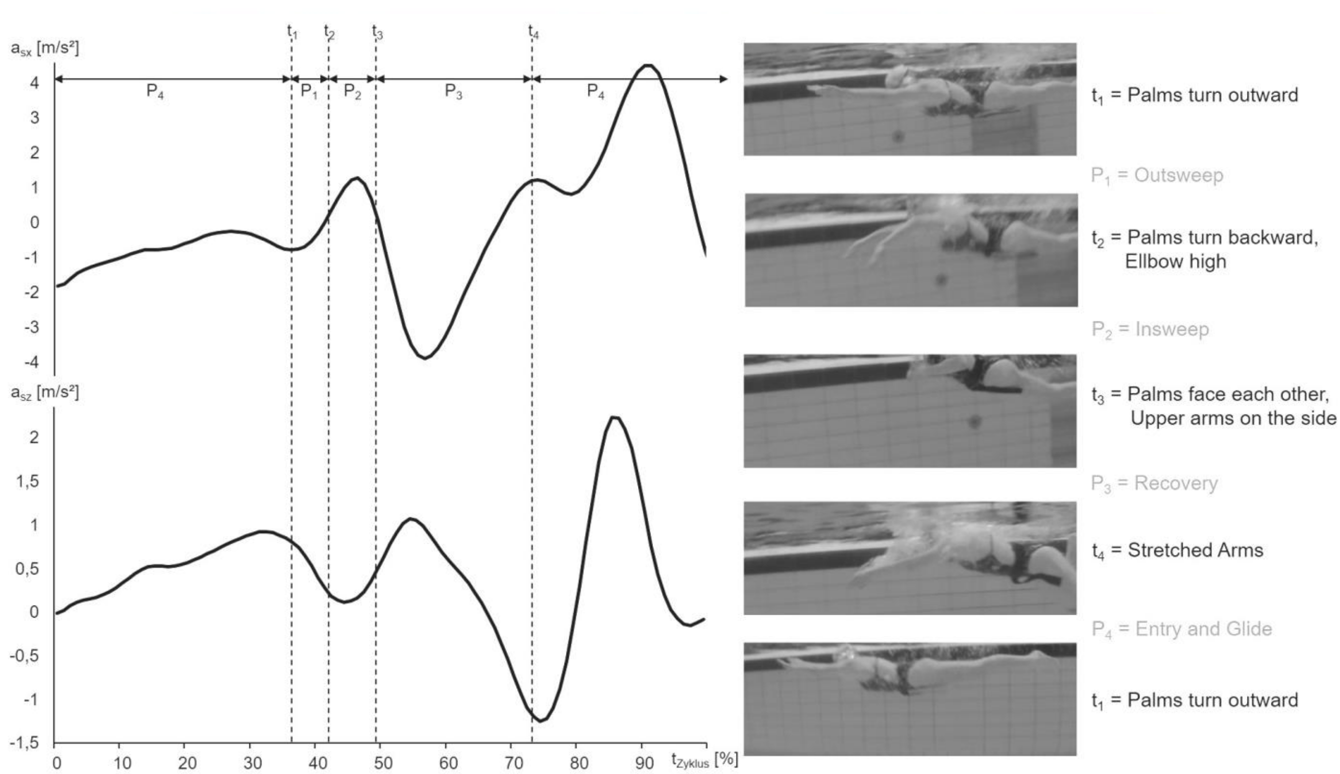

Figure 3. One arm stroke cycle with the corresponding forward acceleration of an athlete at national level.

At point t_1 the palms of the swimmer start to turn outwards and push some water to the side. During this movement the frontal resistance increases and the body decelerates, resulting in a small decrease in forward acceleration (a_{sx}). As the hands continue to move through the water, the elbows begin to bend and the palms are turned back. At this point (t_2), the swimmer accelerates until the palms are facing each other, the upper arms rest on the side of the body and the head lifts above the surface (t_3). In the following sequence (P_3), the body decelerates quickly when the arms are pressed against the water and returned to the streamline position (t_4).

Note the course of a_{sz} during the arm pull. During the insweep (P_2) there is a small break, followed by a maximum at the beginning of the recovery (P_3). This is caused by the upper body lifting over the surface during the insweep, pushing the hip down. The hip then lifts again, resulting in a small maximum of a_{sz}.

The breaststroke kick

As described in the technical model, the breaststroke kick begins when the knees begin to bend and one cycle is completed when the next leg recovery begins.

Figure 4 shows a kick cycle of the same athlete as shown in Figure 3. The key positions are indicated by t_1 to t_4 and the following phases by P_1 to P_4. The upper graph shows the forward acceleration (a_{sx}) and the lower graph the vertical acceleration (a_{sz}) perpendicular to the swimming direction.

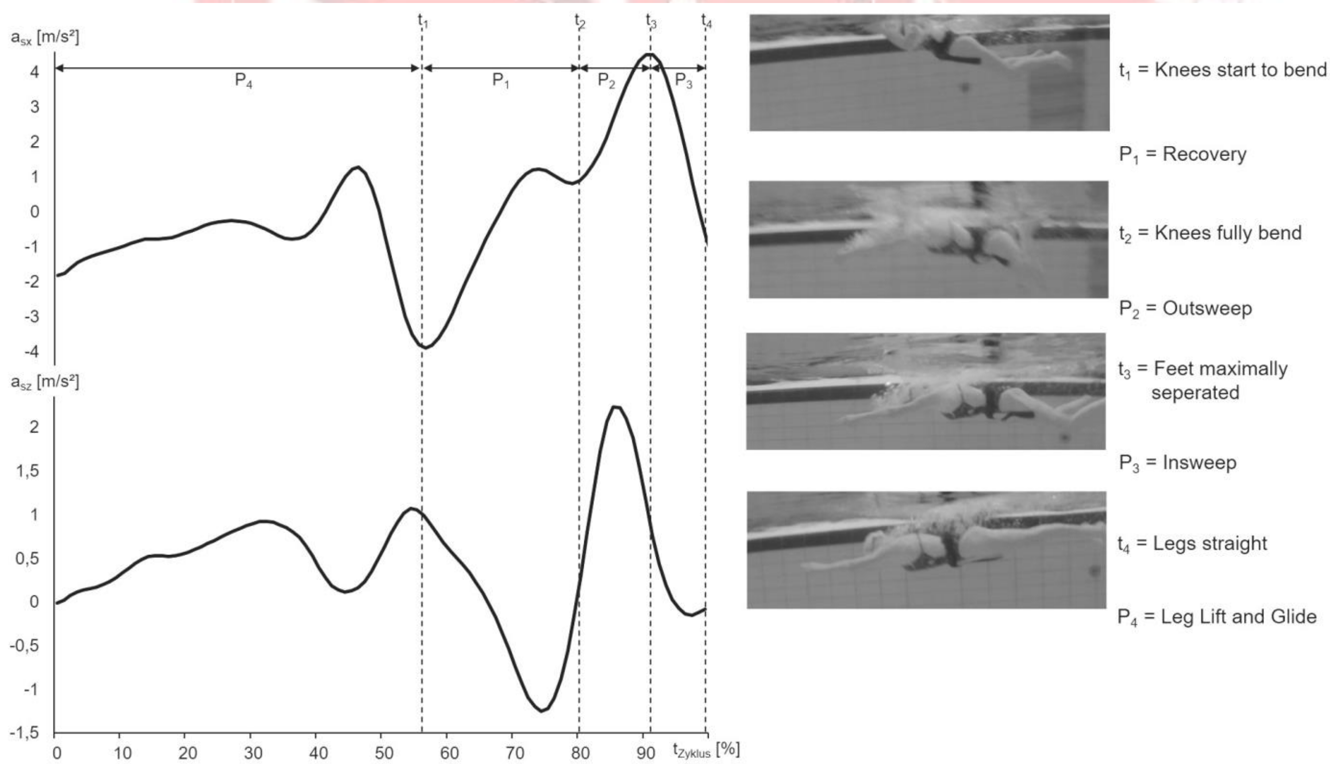

Figure 4. One kick cycle with its corresponding forward acceleration of an athlete at international top level.

At point t_1 the legs begin to recover and the knees begin to bend. This point correlates with the total minimum in a_{sx}. When the knees are fully flexed and the feet touch the buttocks, the driving phase of the leg kicks (t_2) begins. The body is accelerated quickly until the feet are maximum separated (t_3) and the insweep begins. When the Insweep is finished (t_4), the swimmer begins to glide and tries to maintain it.

The timing of leg kick and arm pull

Figure 5 combines the arm stroke shown in Figure 3 and the leg kick shown in Figure 4 to give an impression of the time of arm stroke and leg kick. Again, the upper graph (a_{sx}) shows the forward acceleration and the lower graph (a_{sz}) the vertical acceleration of the hip. In grey the key positions and the following phases of the leg kick are associated, while the black words are the key positions and the following phases of the arm pull.

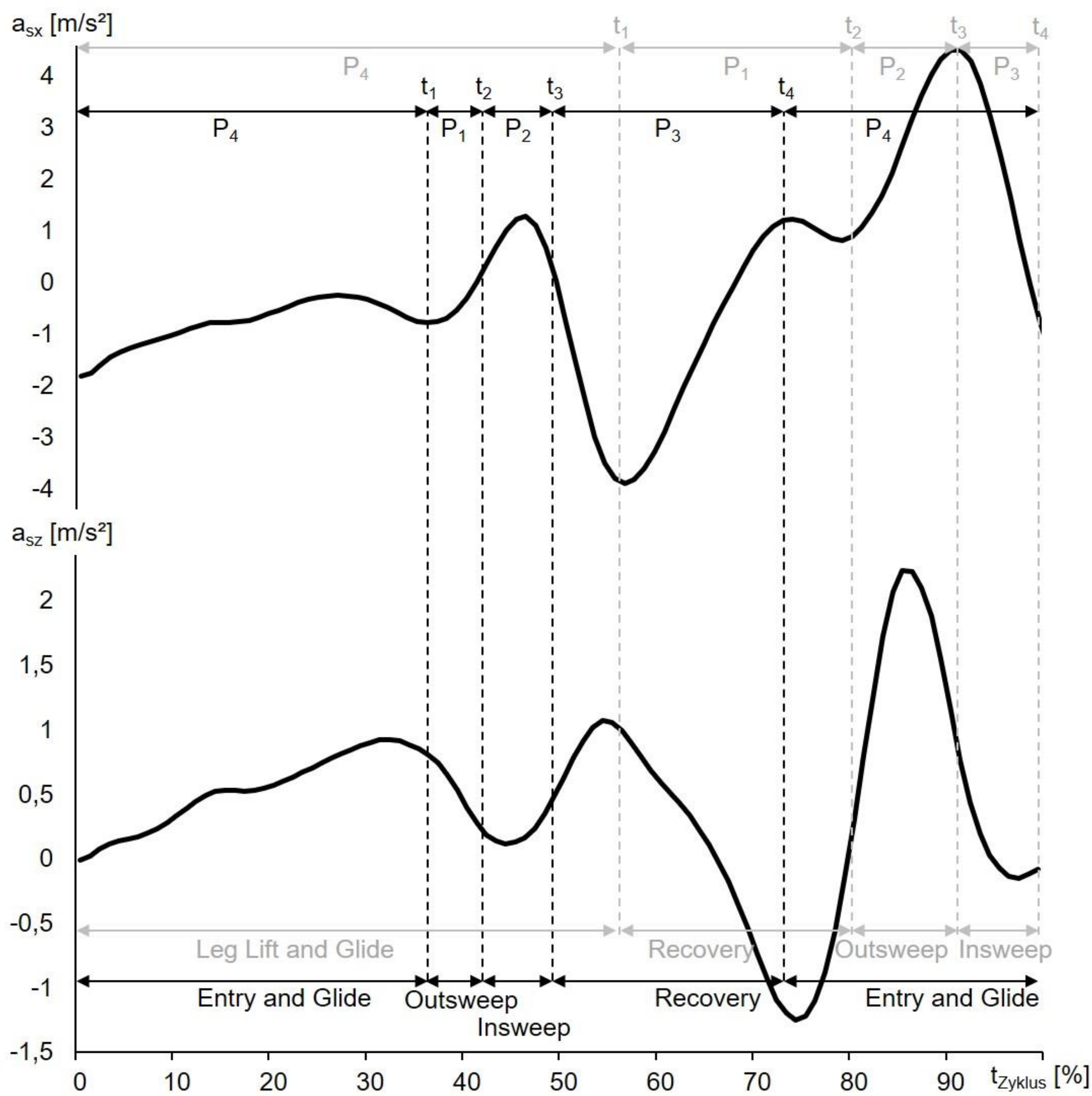

Figure 5. Combination of arm stroke and leg kick and thus the timing of the two.

It is clearly visible that the gliding phase of the arm stroke and the leg kick overlap strongly. This phase becomes shorter with increasing stroke frequency (14). It is also obvious that the propulsion phase of the leg kick begins when the arm stroke is finished and the swimmer is in a streamlined position. This is because the athlete wants to maximize the result of a powerful breaststroke kick. Therefore, it should be possible to automatically divide a stroke cycle into arm stroke and leg kick, as the two phases produce two different acceleration maxima.

Bringing all athletes together

Figure 6 shows the mean stroke cycle of all 10 athletes and 357 strokes. The middle black line represents the mean values, while the upper thinner black line represents the maximum value at this point of the cycle and the lower black line represents the minimum value at this point of the cycle. As a result, the grey background area indicates the range of values at a certain point during the swimming cycle. The boxes shown in the graphs mark the beginning of each phase of the arm stroke. The width of the box represents the variety with which the athletes begin the phase.

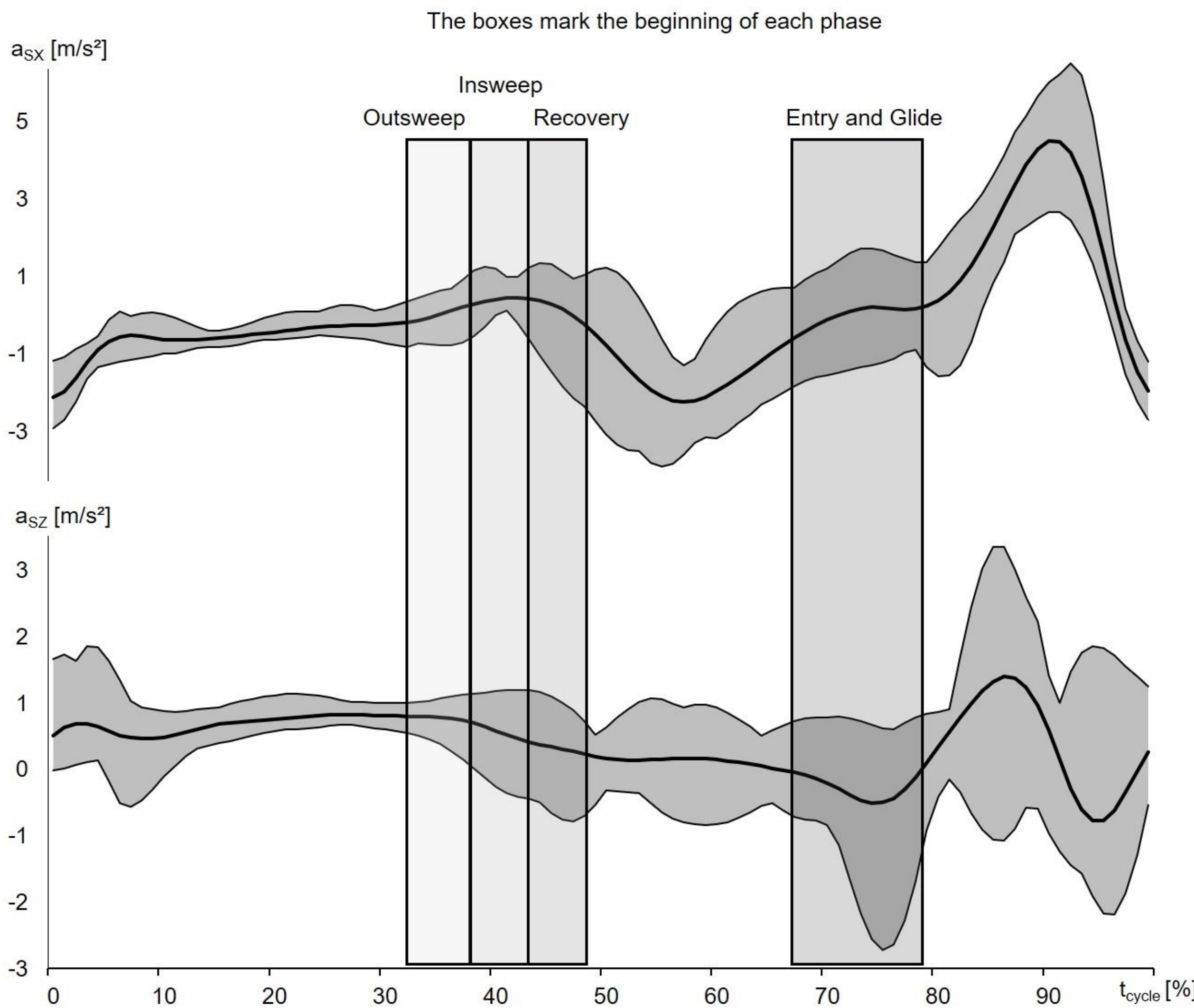

Figure 6. Beginning of each phase of the arm stroke, summarized over all participants and trials.

In the case of forward acceleration (a_{sx}) during the arm stroke, there is no large deviation in the values achieved by the athletes, nor is there a large deviation in the qualitative course of a_{sx}. There is a marked increase due to the outsweep and insweep of the arms, followed by a deceleration phase (global minimum) when the recovery begins.

The vertical acceleration of the hip (a_{sz}) shows no characteristic behavior during the arm stroke in mean across all athletes. This is surprising because we showed a clear minimum-maximum behavior in one athlete and associated it with the movement of the upper body. This movement is obviously not performed by all the athletes studied, which can be a criterion for distinguishing between different levels. Figure 7 shows the same diagrams for forward and vertical acceleration as Figure 6, but now concentrates on the different phases of the leg kick.

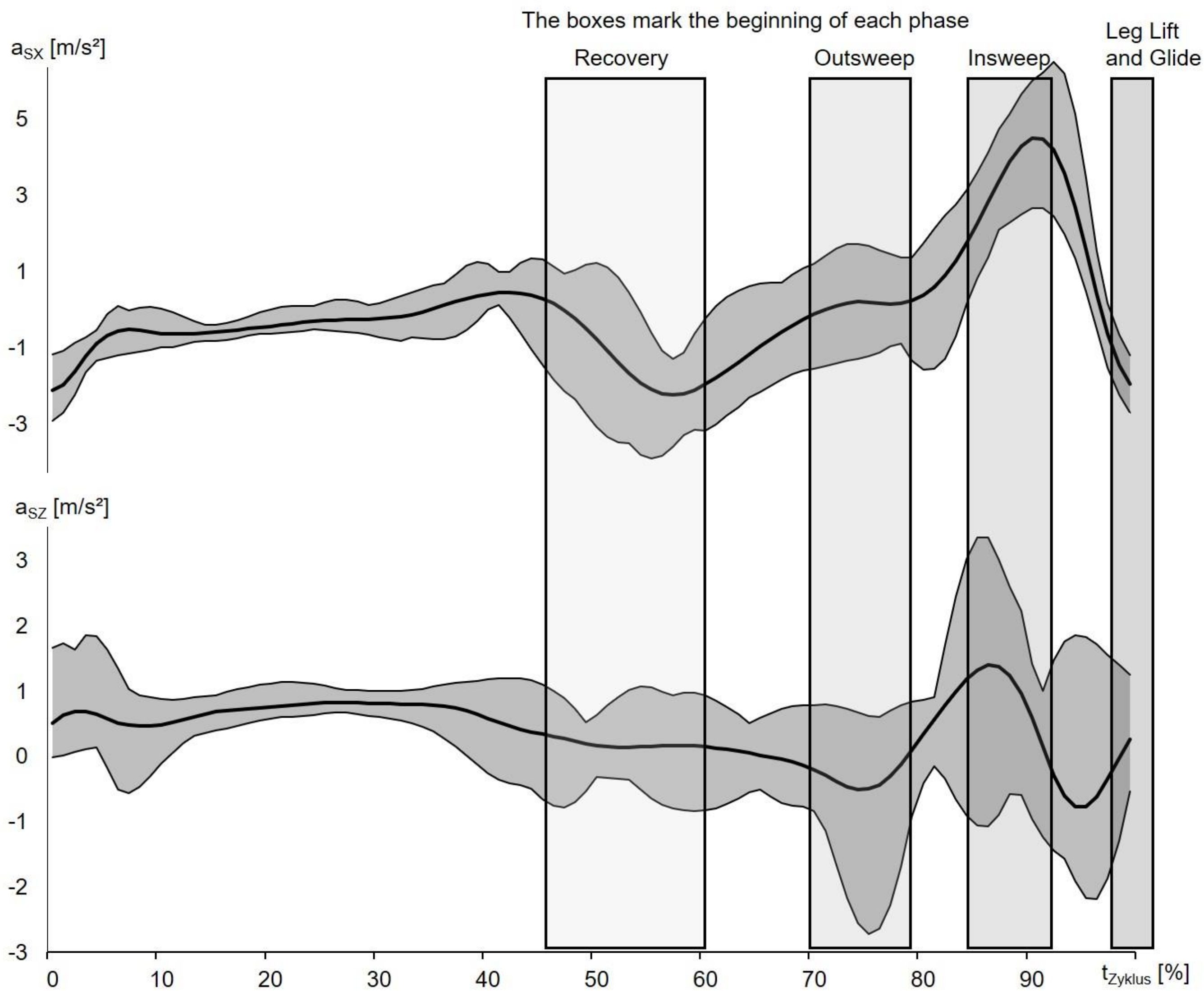

Figure 7. Beginning of each phase of the leg kick, summarized over all participants and trials.

The recovery begins when the forward acceleration decreases and reaches the global minimum. When the outsweep starts, the forward acceleration increases rapidly and distinctly, resulting in a high sharp peak. Just before the maximum in a_{sx}, the Insweep begins, which is less propulsive and therefore decreases to a minimum when the leg lift and glide begin. Especially in the Outsweep and Insweep there is a small variance in the values achieved by the athletes.

The vertical acceleration on the other side also shows a clear maximum associated with the Outsweep and Insweep. Note the high variance among all athletes, which is a clear indicator of how differently the kick action is performed.

DISCUSSION

This paper presents an approach for the automatic intra-cyclical analysis of the breaststroke swim cycle by going further than previous studies which used an IMU to extract global parameters such as stroke rate (7, 11, 19, 26, 27), number of strokes per length (7, 19, 26) and time (7, 9) without providing information on the movement technique performed. The data of 10 athletes swimming with the sensor positioned on the lower back were measured and summarized. Similarities between the movement and the IMU data structure were detected regardless of the performance level or fatigue of the athletes. It was shown that the theoretically described key positions of the breaststroke of several authors (3, 12, 22, 24) correlate with certain characteristics of the measured IMU data in terms of forward and vertical acceleration. The overall data structure is similar to that of Seifert and colleagues (25) and Staniak and colleagues (28).

At the beginning of a stroke cycle, the swimmer is in a streamlined position by compressing his arms and legs, minimizing frontal resistance, and taking advantage of the great acceleration achieved by a powerful breaststroke kick. This is represented by an almost horizontal course of forward and vertical acceleration. The vertical acceleration increases as both the hip and the whole body is lifted to the surface. This phase is followed by the outsweep and insweep of the arms, which initially leads to an increase in the frontal area and thus the frontal resistance, resulting in a slight deceleration during the outsweep, which is converted into an acceleration phase during the insweep. At the same time, the upper body is lifted above the surface, diving the hip deeper into the water. This results in a local minimum of vertical acceleration. The arms then recover and lift towards the surface, initiating a deceleration phase leading to the global minimum of forward acceleration. This slowing movement coincides with the recovery of the legs, forcing the thighs to press against the water. This leg recovery lowers the hip deeper into the water, resulting in a global minimum of vertical acceleration.

The hip of the swimmer accelerates again when the arms fully recover in the streamline position, throwing the upper body forward and thus also affecting the hip velocity. At the end of arm recovery (minimum front surface), the legs begin the outsweep and accelerate the athlete, resulting in the overall maximum forward acceleration. It is also possible to observe how the hip is lifted to the surface during this movement, resulting in a more effective kick. The retraction of the legs is less propulsive and leads to a deceleration of the swimmer. This is the case when the swimmer dives under water to get the most out of the propulsion phase as the resistance is minimized compared to the surface.

The data structure described was observed for athletes at regional and national level. The athletes differed in quantitative parameters such as absolute values for the minima and maxima of vertical and horizontal acceleration, which led to amplitude differences between minima and maxima. There are also differences in stroke duration (i.e. stroke frequency) between national and regional athletes. For example, although the qualitative data structure is congruent between different athletes and velocities, there are differences in the quantitative parameters that may be the reason for performance differences. Future research should focus on the differences to describe why elite athletes perform better than recreational athletes. Special attention should be paid to kick action, as it should be performed with narrow knees (3, 12, 14, 22, 24) and a fast outsweep and insweep to maximize the propulsion. The timing of the leg kick and arm stroke should be considered as well as the duration of the glide phase and the recovery of the legs to distinguish between different styles (14) and frequencies (22).

A limitation of the current study is the synchronization process between data and video. The resulting film material produced an inaccuracy due to the low sampling rate of the video, which led to an error of 0.06 seconds in recognizing the key positions and the corresponding data points. The next step should try to minimize this error in order to achieve a higher accuracy in the detection of key positions. To analyze the intra-cyclical characteristics for breaststroke, forward and vertical acceleration data should be used to evaluate fatigue or technical failures. The duration of the glide phase and the amplitude of forward acceleration of arm stroke and leg kick may be an indicator of fatigue. In addition, the length between the global minimum (leg recovery) and the global maximum (leg insweep) should be analyzed, as this movement should be performed quickly at all times. As Riewald and Rodeo (22) show, the duration of the arm stroke remains constant over different stroke frequencies, while the occurrence of the kick and the duration of the glide phase vary with different swimming velocities. For example, the duration of the arm stroke should be monitored and can be used as an indicator of fatigue or to explain differences in performance. An additional benefit when using the horizontal and vertical acceleration to intra-cyclically analyse the breaststroke is, that Oghi and colleagues (19) used these two parameters to distinguis between the four different competitive strokes.

In fact, all the parameters that influence performance are known, but it remains unknown to what extent an experienced breaststroke swimmer differs from a less experienced breaststroke swimmer and how different stroke rates affect the amplitudes of arm stroke and leg kick. The IMU data presented here offer the advantage of automatic analysis of intra-cyclical parameters and promise a powerful tool for sports scientists and coaches. The time interval between the propulsive actions can be easily calculated, as well as the amplitudes of forward acceleration associated with the actions of the arms and legs.

CONCLUSION

Automatic analysis of the swimming technique and immediate access to important performance-enhancing parameters is essential for progress in training and competition. The current approach has shown that athletes with different levels of breaststroke performance show the same characteristics in their IMU data. This provides the basis for the development of algorithms to analyze breaststroke frequency and number of strokes, as in previous studies (6, 11, 27), but also to access intra-cyclical parameters such as the duration of the gliding phase (between the end of the kick and the start of the arm stroke) as well as the pulling and kicking motion. Furthermore, the amplitude in forward acceleration of arm stroke and leg kick can be obtained. The propulsion generated during each swim cycle and its evolution over distance could be an indicator of fatigue, as could the duration of the glide phase and arm stroke separately.

Future work should focus on developing algorithms to develop an interface capable of providing the coach with the sensor generated data information. Thus, it should be possible to adjust the training load not based solely on time, but on technical performance to avoid overtraining and inadequate swimming technique. Finally, sports scientists should be able to objectively evaluate the swimming technique.

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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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