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ORIGINAL RESEARCH **OPEN ACCESS**

INTRA-CYCLIC ANALYSIS OF THE BUTTERFLY SWIMMING TECHNIQUE USING AN INERTIAL MEASUREMENT UNIT

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ABSTRACT

The use of inertial measurement units (IMU) has increased in swimming research as it is a promising alternative to the time-consuming traditional ways of performance analysis such as the manual video-analysis. Current research mainly focuses on freestyle (front-crawl) and breaststroke swimming whereas backstroke and butterfly are underrepresented. Also, the focus is on data analysis in terms of stroke count, frequency and timing without considering the movement in relation to the measured data.

This paper investigated the butterfly swimming stroke over 100 m with 10 athletes of different skill-levels (from regional to national level). Data were measured using an IMU in combination with video. Key positions of the butterfly swimming technique were analyzed and summarized across all athletes. Aim of this study was to identify the intra-cyclic characteristics of the butterfly swimming technique to find commonalities in the measured data independent of skill level.

The results may contribute to an automatic pattern recognition and detailed stroke analysis with separation into the different sub-phases (i.e. in- and upsweep, recovery). In addition, the two executed dolphin kicks per cycle can be analyzed with regard to timing and duration without using video recording.

Keywords: IMU, intra-cyclic analysis, Butterfly, Swimming, movement technique, acceleration, dolphin kick

INTRODUCTION

Analyzing technique and performance relevant parameters is essential in competitive sports to improve athletes' performance. In cyclic movements like swimming, parameters such as stroke frequency and stroke duration as well as the relationship between propulsive and non-propulsive phases, the coupling of propulsive movements and rhythmical features are essential to modify training plans and to adjust movement execution for performance improvements. Unfortunately, many of these parameters are difficult to access using conventional video analysis or stop-watches. Video-analysis performed with commercially available systems like the (semi-)professional system Dartfish can give the coach and athlete helpful insights into swimming technique by analyzing joint angles and highlighting the path of the hand under water. Moreover, video-analysis allows the coach to precisely measure time-related parameters (i.e. propulsive and non-propulsive phases and stroke duration), but this process is time-consuming and therefore lacks a direct real-time feedback. Moreover, parameters such as acceleration and deceleration are even more complicated to extract from any footage as this requires a precisely calibrated camera system and a certain point of the athlete must be tracked frame by frame.

The use of stop-watches to obtain data such as frequency or time per length is popular among coaches but has the drawback of being unprecise. A moment of inattention can falsify the time measurement. Also, measuring stroke frequency at the beginning or at end of the lap can make a great difference. Moreover, it is impossible for a coach to keep track of every athlete using only one or two stopwatches.That is why the use of inertial measurement units (IMUs) becomes more popular in swimming as the proper application can solve these problems. Changes in movement execution (technique) can be objectively evaluated by considering absolute values. Also no further expertise of the coach or any other subjective feeling is necessary. This allows the data obtained to be analyzed automatically and provides access to performance-relevant parameters much faster than is possible with video analysis. To date IMUs are mainly used in research and still lack a wide practical application. This may have different reasons. First, many of the devices used in scientific investigations are disruptive and require the assistance of experts (1, 2, 7, 9, 12, 13, 24, 31, 32, 34). Second, the main focus of current research is on freestyle swimming and rarely considers the other three competitive swimming strokes butterfly, back- and breaststroke.

Mooney and colleagues (20) reviewed 83 studies of which 75 investigated freestyle (or front-crawl), 44 considered breaststroke, 34 butterfly and 33 backstroke. Maghalhaes et al. (18) reviewed 27 studies using IMUs of which 20 investigated freestyle, 12 breaststroke, 7 backstroke and 5 butterfly. Taken together, butterfly and backstroke swimming have been considered the least compared to the other swimming strokes. This might be because most studies were conducted with recreational swimmers, who prefer front crawl and breaststroke over backstroke and butterfly, whereas the latter is ususally only performed by competitive swimmers. Moreover, 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 (21).

The focus of this paper is on the butterfly stroke, particularly on the effect of the arm stroke and dolphin kick on certain variables accessed by the IMU such as horizontal acceleration and vertical acceleration. We do not take a closer look on the underwater dolphin kick during starts and turns, which is one of the main determining factors for overall performance in swimming (4,5) The majority of studies investigating the butterfly stroke listed by Mooney (20) and Maghalhaes (18) lack a detailed view on the acceleration data. However, Daukantas and colleagues (7) as well as Silva and colleagues (29) offer a closer look on their measured data. Figure 1 shows the data of an athlete swimming over four laps butterfly. The sensor was positioned on the lower back. The up and down movement of the hip becomes clearly identifiable in the vertical acceleration (a_z) (lowest graph). Each maximum in a_z correlates with a maximum in forward acceleration (a_x). The two executed kicks during one stroke cycle produce two propulsive phases as a result of the downward kicking action.

In contrast, Figure 2 shows the data of 11 butterfly strokes obtained from Silva and colleagues (29). The sensor was positioned on the upper back; therefore, the vertical acceleration (ACC-Z) is more related to the action of the arms than to the two executed dolphin kicks during one arm stroke.

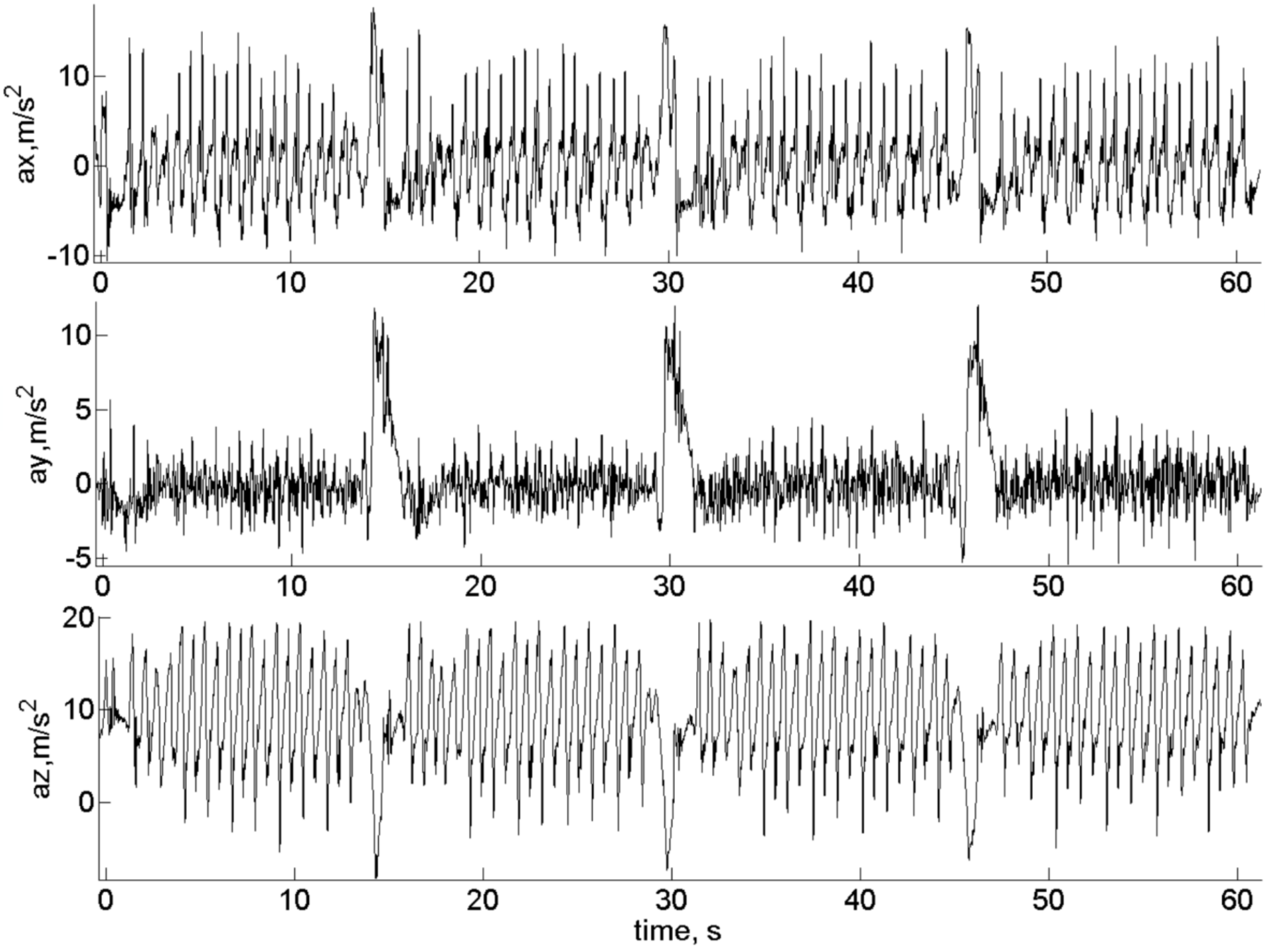

Figure 1. Acceleration data obtained over four laps from Daukantas and colleagues (7): ax represents the horizontal acceleration, ay the lateral acceleration (although not relevant for butterfly) and az the vertical acceleration.

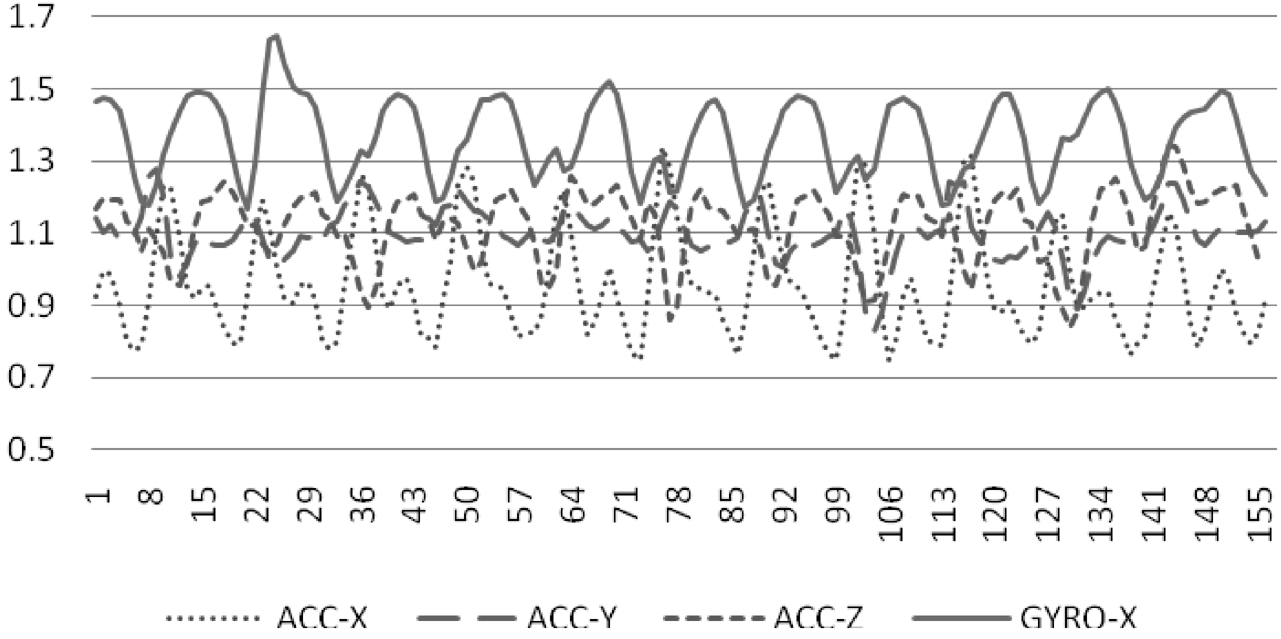

Figure 2. Acceleration data of the butterfly swimming technique from Silva and colleagues (15): ACC-X marks the forward direction, ACC-Y the horizontal acceleration, ACC-Z the vertical acceleration and GYRO-X the rotation along the transverse axis.

Both studies derived several global parameters from the data like stroke count, lap count, stroke duration and frequency but did not consider intra-cyclic parameters like the pause between the dolphin kicks during one stroke cycle. Moreover, none of the investigations using IMUs correlated the stroke phases as introduced from Maglischo (19) with the acceleration data, which is essential to discriminate useful from useless movements. Thus, this study aims at aligning theoretically described movement patterns from IMU data with respect to propulsive and non-propulsive phases of the butterfly swimming stroke by considering the vertical (forward) acceleration and horizontal acceleration of the hip. Furthermore, it is aimed to show, that swimmers of different skill level exhibit the same data characteristics. Finally, aspects for an intra-cyclic analysis of the butterfly swimming stroke are presented and discussed.

BUTTERFLY SWIMMING TECHNIQUE

There are some general principles, based on the rules provided from FINA (8). In the butterfly stroke the swimmer has to stay in a prone position and should move both arms as well as both legs simultaneously. The arms have to move backwards through the water and have to recover above the surface. The legs have to kick up and down in a vertical plane direction. It is not defined, how many dolphin kicks per arm stroke have to be executed, nor how many arm strokes – it has to be at least one per length (8). The key to describe a valid model for the most effective technique is to keep it as simple as possible to incorporate every variation performed by world-class swimmers, but at the same time to shape it as precise as necessary to include the basic fundamentals on propulsion.

TECHNIQUE OF THE ARM STROKE

Counsilman (6) simplified the arm stroke by dividing it into two phases: the recovery and the underwater phase. Maglischo (19) had a more detailed look and separated the underwater phase into three sub-phases, based on the propulsive aspects of the arm stroke: outsweep (non-propulsive), insweep (propulsive) and upsweep (propulsive), followed by the recovery (non-propulsive). In 2014, Madsen and colleagues (17) also named four phases which can be translated from German as follows: outsweep-downsweep, insweep, backsweep and recovery. As those from Maglischo, the names indicate the direction of the movement. Seifert et al. (27) divided the outweep into two separate movements, the entry and the pull, and combined the subsequent insweep and upsweep into the push phase. These underwater movements are followed by the recovery phase, resulting in four phases.

The most current description is from Sanders et al. (25), who named five phases of the arm stroke that are very similar to that of Maglischo (19). It starts with the entry, followed by the outsweep and catch, insweep, upsweep and recovery. Because Maglischo’s description had a considerable impact on all subsequent descriptions, our analysis of the butterfly swim technique is on the basis of the phases proposed by Maglischo (19). Noteworthy, already Counsilman’s (6) description of the stroke mechanics is similar to Maglischo (19), but without to name them explicitly.

The outsweep

The underwater arm stroke begins when the arms enter the water at shoulder width (17, 19), fully stretched or slightly bend. The palms are facing outward (6, 17, 19, 25) and move smoothly to the outside. At the end of the outsweep, the palms turn inward, the elbow is bend around 30 – 40° and the arms reach the catch position (19), while the hands are maximal seperated.

The insweep

Maglischo (19) describes the insweep by turning the palms inward and bending the elbow further up to 90 - 100° (6, 17, 19, 25). The whole insweep can be seen as a semicircular movement until the hands are beneath the body (19). The combination of the bent elbow, the inward rotation of the shoulder and the stretching of the arm leads to the first propulsion (27, 29) and therefore acceleration of the swimmer. The insweep ends when the hands are at the closest point towards each other (6, 19, 25).

The upsweep

When passing the closest point under the body, the hands and arms start the upsweep by turning the palms to the outside and move in a semicircular way to the side of the body (19). To generate propulsion and accelerate the body, it is necessary to push the water backwards, which is achieved by a high elbow position (25) and by keeping the hand in line with the forearm (19). During this phase the elbow extends until the hands pass the thighs (6, 17, 19, 25).

Recovery

The recovery starts when the hands pass the thighs with slightly bent elbow. The palms face inward to avoid unnecessary drag (6, 19) and turn upward at the beginning of the recovery and turn downward, when passing the shoulders (19). The stroke cycle ends, when the hands break through the water surface.

The aforementioned key positions of the butterfly arm stroke are shown in Figure 3. The pictures are screenshots from a video taken from a junior athlete at national level (kindly provided by the Olympic training centre in Hamburg).

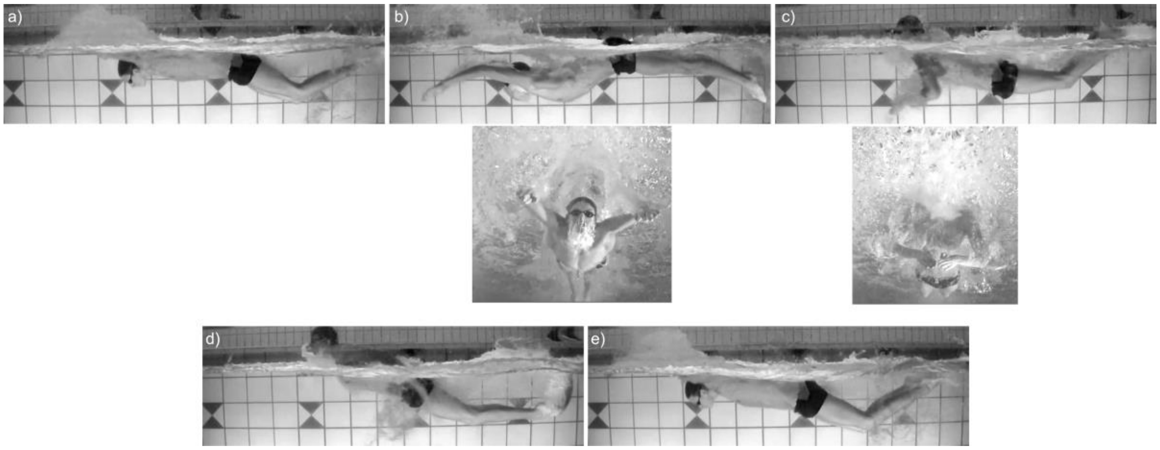

Figure 3. Key positions of one arm stroke cycle of a junior athlete at national level,
Figure 3a: entry of the fingertips and marks the beginning of the outsweep;
Figure 3b: maximum width of the hands, where the insweep begins;
Figure 3c: the closest position of the hands under the body and begin of the upsweep;
Figure 3d: the point when the hands pass the thighs and the recovery begins;
Figure 3e: end of the recovery and the beginning of the next cycle, when the fingertips break through the water surface.

TECHNIQUE OF THE DOLPHIN KICK

The dolphin kick is defined as a simultaneous, whip-like, up and down movement of both legs (8) and the hip. Maglischo (19), Counsilman (6), Madsen (17) and Sanders (25) name the same technical key points and divide the kick in two parts: down- and upbeat. The downbeat (downward kick) is characterized by bended knees and feet aligned with the calf. Colman (3) states, that the athlete accelerates and gets a great push forward during the downbeat, which is confirmed by Seifert et al. (27). The movement begins, when the feet reach their highest point and ends, when the feet are at the lowest point of the cycle (27).

Subsequently, the upbeat (upward kick) starts, which is performed with extended legs and relaxed feet. Schramm (26) points out, that owing to the disadvantageous lever, the upbeat takes more time than the downbeat and is non-propulsive, which is confirmed by Seifert and colleagues (27). There is no pause between these two phases; it is more of a rebound-like action.

TIMING OF THE DOLPHIN KICK AND BODY MOVEMENT

For a successful butterfly swimming stroke the correct timing of two dolphin kicks performed during one arm stroke cycle is crucial (25, 27). As the dolphin kick has its origin in the hip and can be highly supported by the upper body, one has to look at the arm stroke to find the correct timing. The exact beginning of the first downbeat is unclear, and may be individually different. In general, the first downbeat starts somewhere between the second part of the recovery and the arms entering the water. This is, when the upper body submerges and the hip breaks the surface of the water. That results in the feet being at their bottom point (6, 19, 25) shown in Figure 4 a) and b). Madsen (25) identifies the first downbeat during the outsweep, which might be correct for some athletes or especially when the athlete breathes and therefore lifts his upper body further out of the water. However, it might be difficult to distinguish between the entry and outsweep as both movements merge. Seifert and colleagues (27) describe this phase as characteristic propulsive due to the downward kicking action of the legs.

The first downbeat is followed by the first upbeat, which starts during the outsweep of the arms (Figure 4b). The definition of the exact timing differs. Maglischo (19) starts it with the beginning of the insweep whereas Sanders (25) starts it earlier during the outsweep. The beginning of the upbeat mainly depends on when the end of the downbeat is defined and the whole duration of the upbeat is non-propulsive (27). Nevertheless, during the transition from the out- to the insweep the upper body is lifted at around 15° (26), and therefore, has a decreased drag because of a better streamline position (19). The authors agree when defining the end of the upbeat as it coincides with the end of the insweep (6, 17, 19, 25; shown in Figure 4c).

The second downbeat begins with the upsweep. The upsweep moves the hands back and out and up. To keep the hips from falling to far in the water as it would be the case of the up-push of the hands, the downbeat pushes the trunk towards the surface and therefore helps the athlete to maintain a small front area (19). In addition, the downbeat supports the breathing movement as it pushes the upper body upward (25, 26). Maglischo (19), Counsilman (6), Madsen (17), Sanders (25), Seifert et al. (27) and Schramm (26) agree that the second downbeat takes place during the upsweep. As the transition from the upsweep to the recovery phase takes place, the second upbeat starts and continues throughout the first part of the recovery (19). This lifts the feet up and leads to a low drag position of the swimmer. Nevertheless, the athlete decelerates throughout this phase (27). During the second half of the recovery phase the swimmer begins the first downbeat.

Amongst coaches and experts there is a discussion about the first or the second downbeat being stronger and should therefore be emphasized. The power of each of the two kicks may be related to the athletes' stroke frequency. As Counsilman (6) states, during sprint butterfly the second downbeat is stronger than the first one and vice versa during longer distances. This may be the result of the lower frequency used in longer distances as the athlete has more time to dive deeper in the water at the end of the recovery and therefore can emphasize the first kick more. Schramm (26) for his part states that both kicks are of similar force.

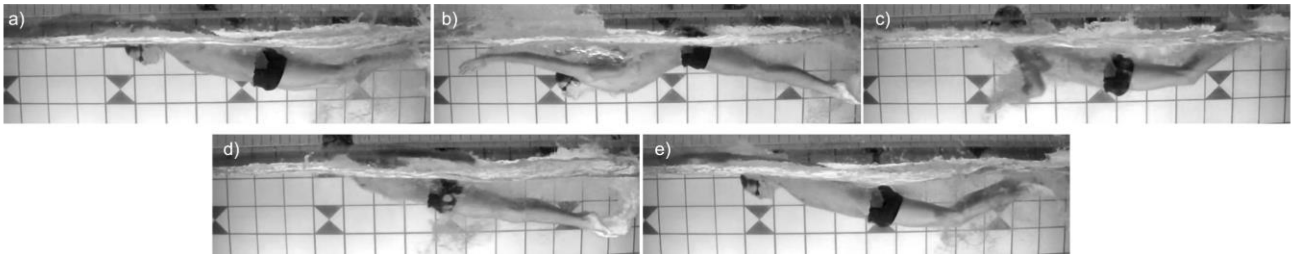

Figure 4a-e: Key positions of the dolphin kick during one arm stroke cycle of the same athlete and stroke as shown in Figure 3;
Figure 4a: begin of the first downbeat, where the hips are at the bottom turnaround point and the feet at their highest point;
Figure 4b: end of the first downbeat and the beginning of the first upbeat with the hips being at their highest point and the feet at the bottom point in the cycle;
Figure 4c and 4d: begin of the second down- and upbeat;
Figure 4e: end of one cycle, where two kicks are completed.

Table 1. Phases and key positions of the arm stroke and underwater dolphin kick in butterfly swimming: division of one cycle into different sub-parts.

Cycle Part	Phase	Key position at the beginning	Character
Arm stroke Cycle	Outsweep	Entry of the finger tips	Non-propulsive
	Insweep	Maximum width between hands	Propulsive
	Upsweep	Minimum width between hands	Propulsive
	Recovery	Hands at the thighs	Non-propulsive
Dolphin Kick Cycle	Downbeat 1	Hips low, feet high During Recovery and Outsweep	Propulsive
	Upbeat 1	Hips high, feet low During Outsweep and Insweep	Non-propulsive
	Downbeat 2	Hips low, feet high End of Insweep	Propulsive
	Upbeat 2	Hips high, feet low End of Upsweep, Beginning Recovery	Non-propulsive

KEY POSITIONS OF THE BUTTERFLY SWIMMING STROKE CYCLE

The butterfly swimming stroke cycle can be divided on the basis of the arm stroke into four phases (outsweep, insweep, upsweep and recovery) with four key positions or by the two dolphin kicks into four phases (downbeat 1, upbeat 1, downbeat 2, upbeat 2) with four key positions. Table 1 provides a detailed description of the phases and key positions of the arm stroke and dolphin kicks and their propulsive character.

Thus, this study aims to answer the following questions: Do athletes of different skill levels show the same characteristics in their IMU data? How could an automatic analysis of the butterfly swimming stroke be designed?

METHODS

Data was obtained during regular training sessions with national and regional level athletes. Ethics approval was granted by the University of Hamburg (AZ2017_100). All athletes were introduced about the purpose of the study and gave their informed written consent before participating in this study and reported no injuries or other impairments.

Participants

Ten athletes (six females, 14.8 ± 0.9 years; four males, 16.0 ± 0.7 years) swam 100 m butterfly and completed a total of 391 butterfly stroke cycles. Seven athletes participated in the national junior championship in 100 m butterfly swimming.

Test design and procedures

The athletes were introduced into the handling of the system and each swimmer was asked to swim 100 m butterfly 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 can be 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 software jBeam (14) 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.

Pansiot and colleagues (23) explored the potential of different sensor positions with regard to timing, lap and stroke count as well as overall momentum in butterfly, breaststroke, freestyle and backstroke and found, that these parameters are best identified, when the sensor is placed on the lower back. Hence, the sensor was positioned on the lower back in a pocket which was sewed to a belt.

RESULTS

Arm stroke

There is common sense that the swimming cycle begins when the arms begin to move out of the stretched position, independent of the swimming stroke cycle. This is why we begin the butterfly cycle with the entry of the fingertips and the following outsweep of the arms during which the body gets a great push forward from the downbeat of the first kick.

Figure 5 shows the key positions during one butterfly stroke cycle of an athlete at regional level and the time-normalized acceleration data of the same stroke cycle. . . The upper graph of the data represents the forward acceleration (a_{SX}); the lower graph the vertical acceleration (a_{SZ}) of the hip.

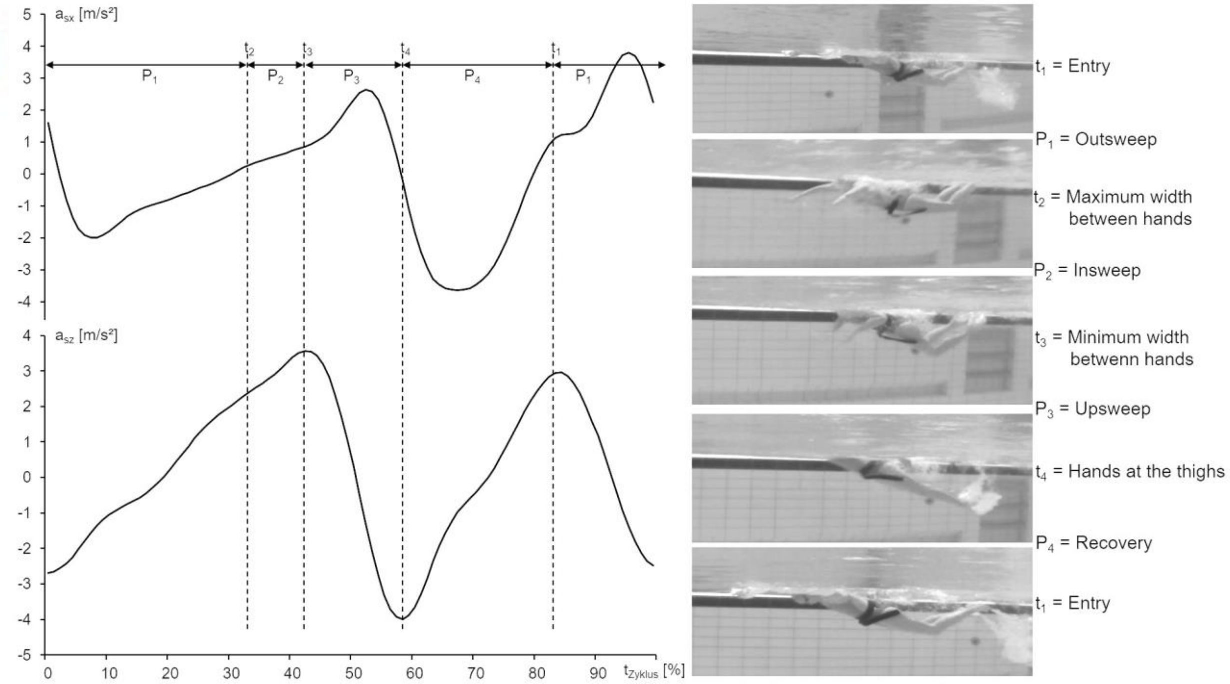

Figure 5: Key points of the butterfly arm stroke and their corresponding data point. Data and pictures are from the same athlete.

A closer look on Figure 5 reveals that the key positions of the arm stroke coincide with the extrema in vertical hip acceleration. The outsweep begins at the second maximum of a_{sz} as well as the upsweep starts at the first maximum and finishes at the vertical acceleration minimum. This is, when the recovery starts. Following the entry, the legs kick downward and therefore generate a major impulse resulting in a high forward acceleration peak. Subsequently an acceleration minimum occurs, due to the outsweep movement of the arms and a larger frontal drag. As the arms reach their maximum width under water (t_2), the insweep (P_2) starts. The insweep is finished at t_3, when the hands are close together and an uninterrupted transition to the upsweep (P_3) takes place. During the insweep (P_1) and upsweep (P_2) the legs complete the first downbeat and both movements combined push the body forward, resulting in an increased forward acceleration.

The upsweep (P_3) ends, when the arms reach the thighs and the legs finish the second downbeat. This marks the beginning of the recovery (P_4), where the athlete decelerates until the next maximum of a_{sz} is generated. The reason for this is: first there is no propulsive movement during the recovery and second, the legs are no longer aligned with the body and generate an additional drag due to a greater frontal surface area (i.e. water resistance).

The dolphin kick

Figure 6 shows the correlation between the inertial data and key positions of the same swimmer and stroke cycle as in Figure 5. The upper graph depicts the forward acceleration and the lower graph the vertical acceleration of the hip. One swimming stroke cycle includes two kicks and is framed by t_1.

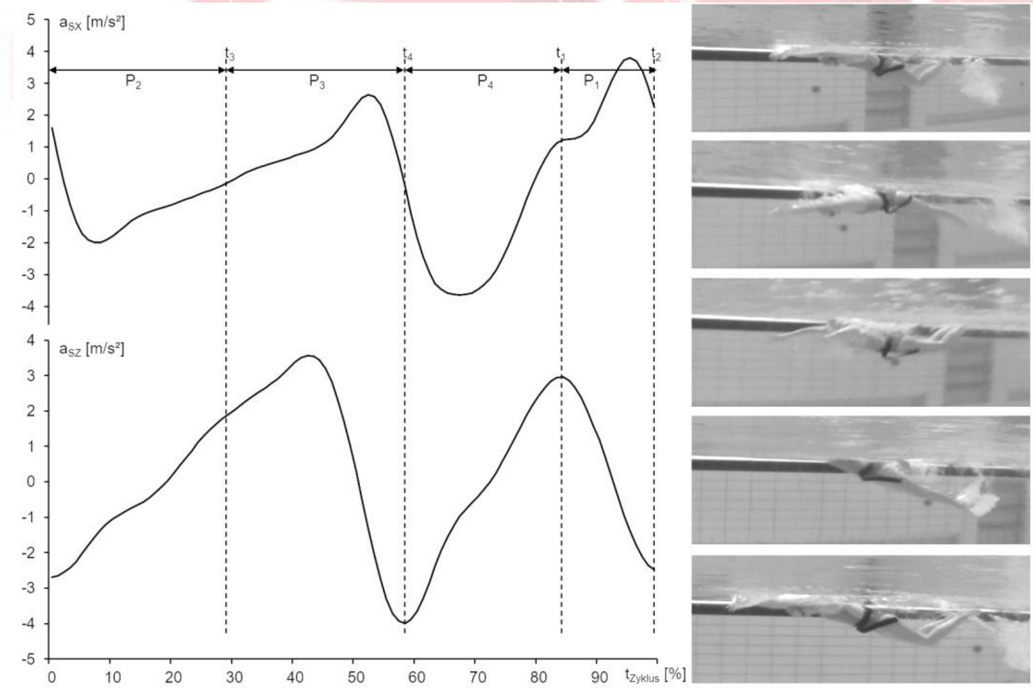

Figure 6: Key points of the butterfly (dolphin) kick and their correlating data point from the same athete: forward acceleration (upper graph) and vertical acceleration (lower graph) of the hip.

Hence, t_1 marks the beginning of the first downbeat, which results in a global maximum of vertical acceleration (a_{sx}) during P_1, which occurs when the hip is at its top turnaround point. This is, where the first upbeat begins, during which the athlete decelerates until the feet reach the highest point (t_3). Then the athlete accelerates again during the second downbeat (P_3) until the next maximum in horizontal acceleration (t_4). Finally, the second upbeat takes place which decelerates the athlete (P_4).

The hip-movement can be easily identified on the basis of the vertical acceleration. The top turn around point corresponds to the local maximum and the bottom turnaround point corresponds to the local minimum. Each vertical acceleration maximum (top dead center) is followed by a forward acceleration maximum, as the feet pass their bottom dead center and generate a high propulsive force.

Figure 7 combines the arm stroke and the leg kick and shows the overlap of the different movements.

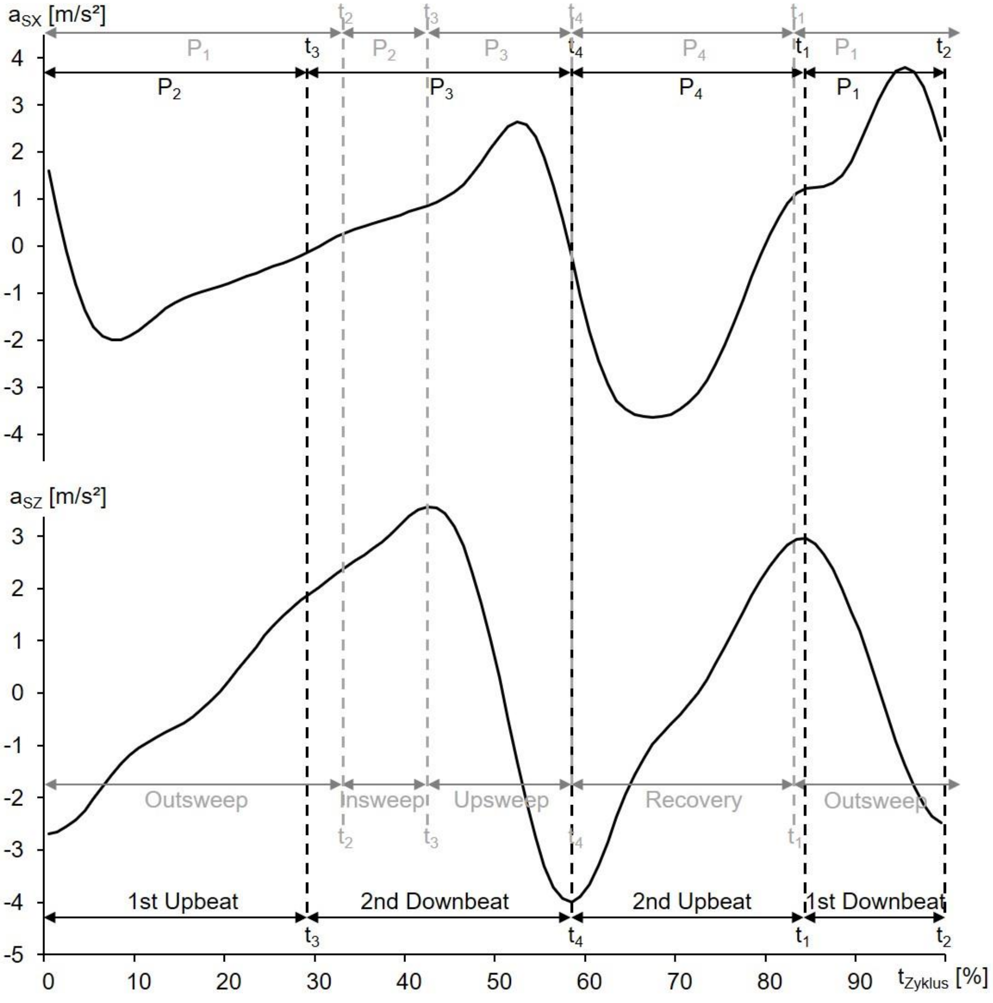

Figure 7: The overlapping phases from the arm stroke (upper graph) and butterfly kick (lower graph) for the same athlete presented in figure 5 and figure 6. The grey colored lines and words represent the arm stroke, whereas the black lines and words represent the leg kick.

The first downbeat takes place during the outsweep of the arms. Referring to the model proposed earlier, the athlete presented in Figure 5, 6 and 7 finishes the first upbeat (t_3) too early. That point should coincide with the end of the insweep (6, 17,19, 25) (t_3). Nevertheless, the second downbeat takes place during the insweep and the whole upsweep. As expected, the second upbeat occurs simultaneously with the recovery and the first downbeat takes place during the first part of the outsweep, more exactly right after the entry (t_1). This is in good agreement with the theoretical model.

Elite swimmer compared to non-elite swimmer

Figure 8 shows a comparison of the data of a non-elite athlete (grey line) with the data of an elite athlete (black line) with respect to forward acceleration (upper graph) and horizontal acceleration (lower graph).

Regardless of the athlete's skill level, the vertical acceleration shows a sinusoidal behavior that has two maxima and two minima per stroke cycle. The forward acceleration also shows two clearly visible acceleration peaks, each following the horizontal acceleration maximum. There are some differences between the two athletes in the absolute acceleration values and the timing of the two dolphin kicks, which appear to have a gap of 50% of the stroke duration in the elite athlete, while the non-elite athlete kicks more unrhythmically. In addition, the non-elite athlete appears to decelerate more than the elite athlete in terms of horizontal acceleration, while the elite athlete has an additional acceleration peak during the outweep.

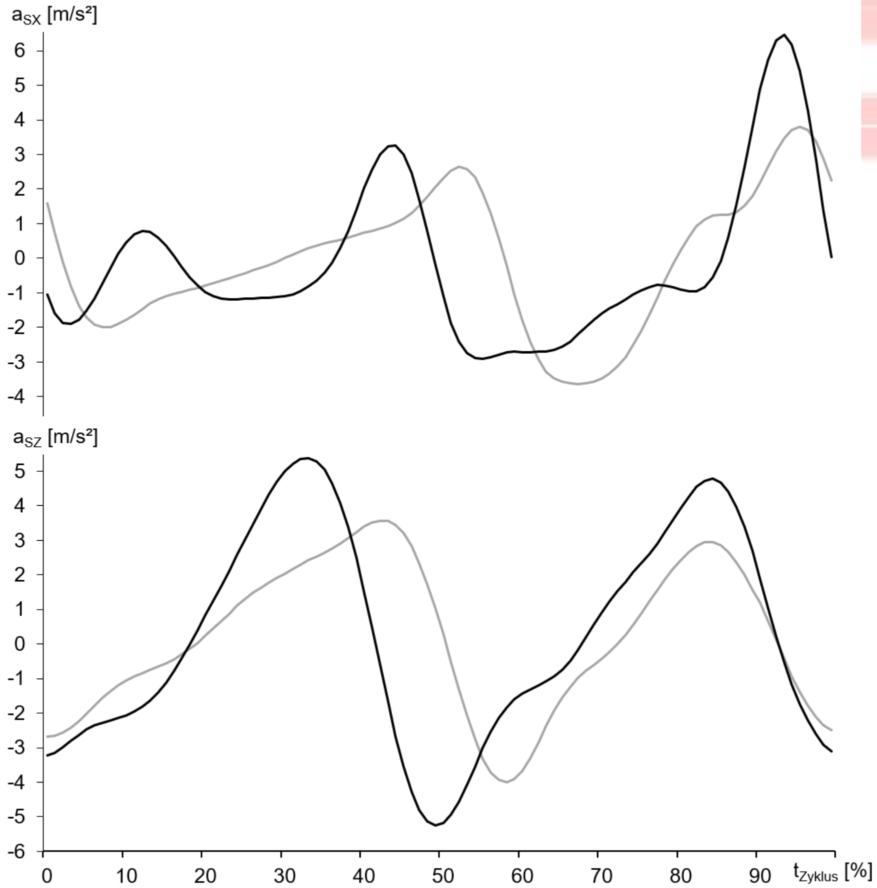

Figure 8: Comaprison of the time-normalized data of the horizontal (upper graph) and vertical acceleration (lower graph) of a non-elite swimmer (grey) and an elite swimmer (black).

Bringing all athletes together

Figure 9 summarizes all ten athletes and the data points at the beginning of each of the four phases of the arm stroke. Our focus is on the arm stroke, as the more complicated action, whereas the key positions and their corresponding data points of the kicking action are easier to understand. The upper graph in Figure 9 depicts the forward acceleration, whereas the lower graph depicts the vertical acceleration of the sensor. The swimming strokes of all athletes were time-normalized to 100%, and the bold black line represents the mean curve of all athletes, whereas the grey area represents the minimum / maximum acceleration value achieved by the different athletes at this certain point in the stroke cycle,

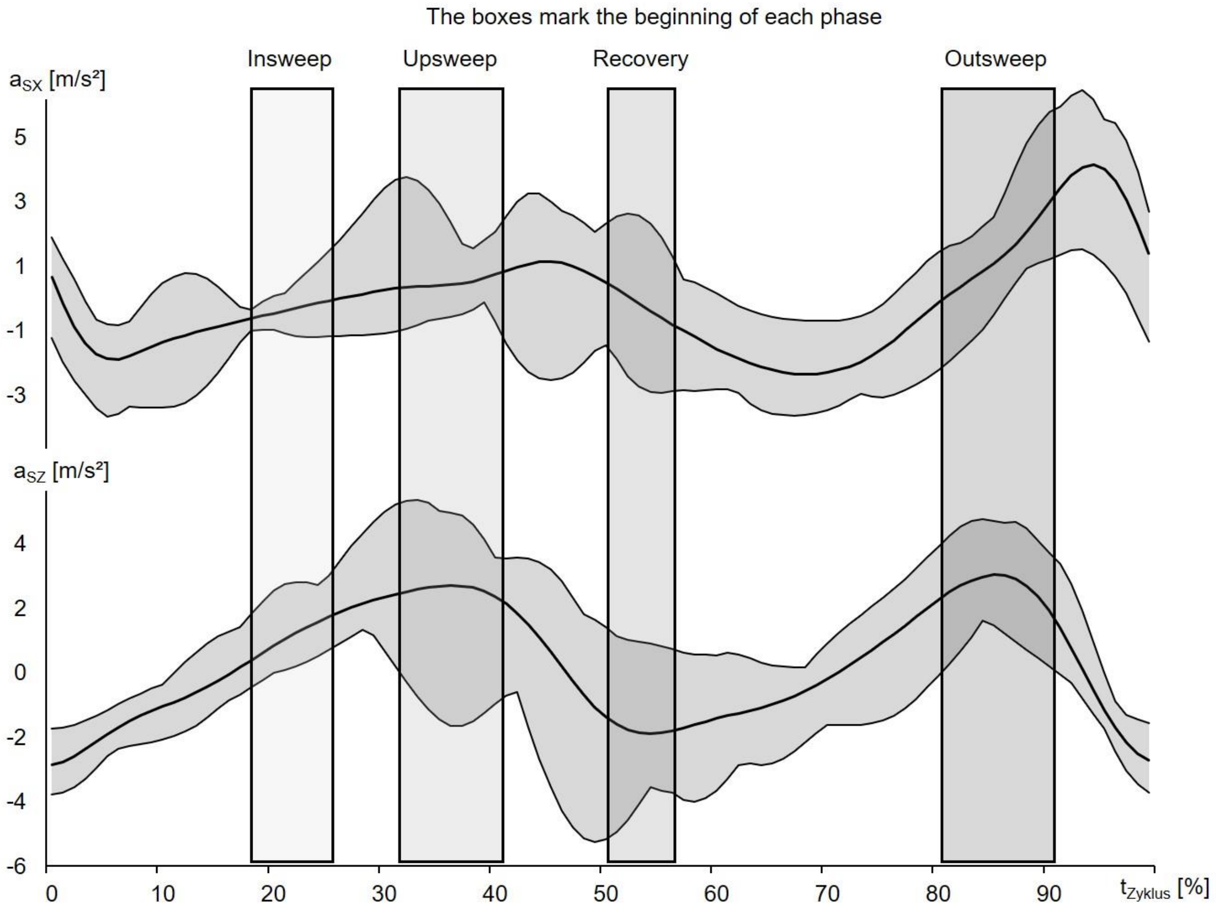

Figure 9: Each box marks the beginning of the corresponding phase of the arm stroke. The width is the variance from 10 athletes. The upper black line represents the forward acceleration (a_{sx}); the lower black line the vertical acceleration (a_{sz}). The grey area depicts the corresponding minimum respectively maximum value of all athletes at this point of the cycle.

Across all swimmers, there is only a small variance in the appearance of each key position. Put simply, the underwater stroke starts at the second maximum in vertical acceleration and ends at the second following minimum in vertical acceleration. Subsequently the recovery lasts from the minimum in vertical acceleration until the next maximum in vertical acceleration.

Regarding the dolphin kick, which could also be taken as an indicator for stroke count and stroke frequency, there is only a small variance in the key positions and correlating data points. Throughout the whole sample we observed the same characteristics as presented in Figure 6. Noteworthy, the key positions of the hip (top turnaround point and bottom turnaround point) do not always coincide with the reverse key position of the feet.

The data structure of the mean curve shown in Figure 9 is considered as a model for the development of an algorithm for the detection of certain parameters of the butterfly stroke. This algorithm should at least be able to distinguish between the underwater phase and recovery phase of the arm stroke. It should be oriented at the up and down movement of the hip as the graph for the vertical acceleration shows almost a sine waveform. We observed the same global characteristics for all athletes regardless of their skill level. Those are two maxima occurring in forward and vertical acceleration as well as two minima in these two parameters during one stroke cycle. Likewise, the maximum in forward acceleration appears shortly after the maximum in vertical acceleration. In many cases, the minimum values in vertical acceleration differed: sometimes it is the first (low value) or the second (higher value) upbeat. Unfortunately, this is not consistent for all athletes. The cause of this is not entirely known.

DISCUSSION

This paper presents an approach towards the automatic intra-cyclic analysis of the butterfly swimming stroke for the first time using an IMU by going further than previous studies, which extracted global parameters like stroke rate (10, 16, 22, 28, 30) numbers of strokes per length (10, 22, 28) and time (10, 15) without providing information about the intra-cyclical characteristics. The data of 10 athletes, who swam with the sensor positioned on the lower back, were measured and summarized. Commonalities between the movement and IMU data structure were found regardless of the athletes' skill level. It was possible to demonstrate that the key positions of the butterfly swimming stroke that were theoretically described from several authors (6, 17, 19, 25) correlate with certain characteristics of the measured IMU data in terms of forward and vertical acceleration. The overall data structure is similar to that obtained by Daukantas (7) and Silva (29).

The entry of the arms correlate with a minimum in forward acceleration in accordance with Seifert and colleagues (27), as the arms produce form drag when they enter the water and the major part of the recovery is non-propulsive. During the following outsweep movement, the legs kick downward and produce a great push forward which results in a large acceleration peak. The beginning of the insweep is related to a minimum in vertical acceleration, because the hips pass the bottom dead center. The athlete has a large front surface and therefore an increased form drag. That is, why the propulsive movement of the arms during the insweep (19, 27) produces only a small acceleration peak. During the in- and upsweep the hip moves upward and therefore the feet execute the second downbeat which ends at the same time as the upsweep ends. This overlap of propulsive arm and leg movement produces the second large acceleration peak occurring at the end of the underwater part of the arm stroke, when the hands pass the thigh (19, 27). The start of the recovery and release of the hands out of the water coincides with the maximum in propulsive (forward) acceleration and is followed by a decrease in forward acceleration. Taken together, the acceleration curves of all athletes show two large acceleration peaks per cycle that correspond to the downbeat of the legs. The maximum in vertical acceleration appeared shortly before the maximum in forward acceleration among all athletes. This originates because of the positioning of the sensor on the hip, as the hip reaches the top turnaround point shortly before the feet reach the bottom turnaround point, where the maximum in propulsion is generated.

Even though the qualitative data structure is congruent between different athletes and speeds, there are differences in the quantitative parameters that could be the reason for performance differences. The athletes differed in quantitative parameters such as the absolute values for the minima and maxima in vertical and horizontal acceleration, which leads to differences in amplitude between minima and maxima. Besides, differences in stroke duration (i.e. stroke frequency) between national and regional level athletes occurred, as proposed by Seifert and colleagues (27). Further, rhythmical features, such as timing of the dolphin kick were different for different athletes. Future investigations should focus on the differences to describe why elite athletes perform better than recreational athletes. Special focus should be on the kicking action as it should be symmetrical in both directions (1) and performed with a high frequency to be effective (11). Also, the timing of the leg kick and arm stroke should be taken into consideration. This has already been investigated by Seifert et al. (27) with qualitative video-analysis and a hip velocity-video system. They found differences in timing between elite, national and junior athletes.

A limitation of the current study is the synchronization process between data and video. The resulting footage produced an inaccuracy due to the low sample rate of the video, which lead to an error in detecting the key positions and corresponding data points by 0.06 seconds. Following investigations should try to minimize this error to obtain a higher accuracy in detecting the key positions. To distinguish between the four different competitive swimming strokes, Oghi and colleagues (22) already proposed a way by considering the amplitude of forward acceleration. This first decision, based on analyzing the rotational movement, leaves two pairs (freestyle and backstroke or butterfly and breaststroke), where the latter pair is further differentiated by analyzing the vertical acceleration. This is neglectable in the case of breaststroke and produces large amplitudes for the case of butterfly. To analyze the intra-cyclic characteristics for butterfly swimming, data of the vertical acceleration should be taken, as there are two clearly visible peaks in the vertical acceleration data, regardless of the athlete's skill level.

While it is known that all parameters have an impact on performance, it remains an open question in what way a skilled butterfly swimmer differs from a less skilled butterfly swimmer. The IMU data presented in this paper offer the advantage of automatic analysis of intra-cyclic parameters and promise to be a powerful tool for sports scientists and coaches. The time relationship between the first and second and from the second to the next first downbeat can be easily calculated. In addition, the ratio between the duration of the downbeat and the recovery phase of the arm stroke is given. However, it is not known whether the amplitude of the hip movement can serve as an indicator of effective kicking action (downbeat). The hip movement must be symmetrical, but it is unclear how far the hip should be stretched (i.e., the distance between the zero position and the maximum or minimum value).

Future work should focus on evaluating the algorithms in terms of reliability in order to develop an interface capable of providing the data information generated by the sensor to the coach. Consequently, the coach will have more time to work with individual athletes without having to permanently use the stopwatch for timing purposes. In addition, the coach will be able to observe all athletes, rather than just one or two at a time, to get an objective view of movement execution. In addition, it should be possible to adjust training load based on technical performance (e.g., vertical hip acceleration and amplitude) rather than time-based to improve the swimming technique performed.

CONCLUSIONS

Automatically analyzing a swimmer's technique and providing immediate access to important, performance enhancing parameters is essential for the progress in training and competition. In this study, we demonstrated that athletes of different skill levels show the same characteristics in their IMU data. This builds the basis for developing algorithms in order to analyze the butterfly swimming stroke by not only considering frequency and stroke count as in previous studies (7, 16, 30), but also to get access to intra-cyclic parameters, e.g. the pause between the two dolphin kicks, the timing of the two kicks with respect to the arm stroke, the time of the arms spent underwater and in the recovery as well as the amplitude of vertical hip movement as an indicator for an efficient kicking. It was demonstrated by Strzała et al. (33), that the timing of the first kick and the pause between the two dolphin kicks indicates the effectiveness of performing the butterfly swimming stroke. Hence, the pause between the two kicks might be different for skilled swimmers compared to less skilled swimmers. In addition, the propulsion generated during each swim cycle, as well as the stroke frequency and its respective evolution over the distance swum, could be an indicator of fatigue and used to assess when to stop the current exercise.

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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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