A case study of elite breaststrokers using inertial measurement units

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ABSTRACT
This paper reports on a case study conducted in 2018 of national and world class breaststroke swimmers. These athletes were tested in conditions which replicate competition using inertial measurement units (IMUs). Analysis of the IMU data reveals certain features which are common to male and female breaststrokers, as well as some individual characteristics which vary widely. A detailed study of the underwater pullout phase is a focal point of this study. Finally, this study illustrates how IMUs can be used as a tool for enhancing the training of elite swimmers.

KEYWORDS
IMU analysis; performance analysis; competitive swimming

1. Introduction

For many years, researchers and athletic coaches have used technology in an attempt to assess and identify techniques which aid athletic performance. Since the 1980s, this technology has largely been in the form of digital video, where 24-60 frames per second characterize standard formats. About ten years ago, engineering companies began to introduce low-cost and lightweight sensors called inertial measurement units (IMUs), which have been used in various sports to detect athletes' acceleration to high precision. In fact, 512 Hz sensors are now common in the industry, offering the ability to collect far more data than digital video.

Recent studies, and a comprehensive study published in 2014, discuss the role of IMUs in competitive swimming (Callaway, Cobb, & Jones (2009); Mooney et al. (2015); Oghi, Ichikawa, Homma, & Miyaji (2003)). These works highlight the need for further research concerning the implementation of IMUs in the training of elite swimming athletes. Here we give the results of our 2018 case study of fourteen (six female and eight male) elite breaststrokers. All of the participants are recent US National Championship or National Collegiate Athletic Association (NCAA) Championship qualifiers in breaststroke. In fact, we note that half of the participants are world class, as 2016 Olympians, or current members of the US National Swim Team, or 2018 NCAA Division I All-Americans.

1.1. The Definition of Breaststroke

Breaststroke is quite interesting in that there have been many rule changes over the years regarding its legal definition and execution. The point of this study is to examine elite breaststrokers, to determine some common features exhibited by all of them, and to determine some roles in which inertial sensors (accelerometer/gyroscope) can be used to enhance training methods at the highest level of the sport.

The international governing body of competitive swimming, Fédération Internationale de Natation (FINA), defines breaststroke by six rules:[1]

SW 7.1: After the start and after each turn, the swimmer may take one arm stroke completely back to the legs during which the swimmer may be submerged. At any time prior to the first breaststroke kick after the start and after each turn a single butterfly kick is permitted.

SW 7.2: From the beginning of the first arm stroke after the start and after each turn, the body shall be on the breast. It is not permitted to roll onto the back at any time. From the start and throughout the race the stroke cycle must be one arm stroke and one leg kick in that order. All movements of the arms shall be simultaneous and on the same horizontal plane without alternating movement.

SW 7.3: The hands shall be pushed forward together from the breast on, under, or over the water. The elbows shall be under water except for the final stroke before the turn, during the turn and for the final stroke at the finish. The hands shall be brought back on or under the surface of the water. The hands shall not be brought back beyond the hip line, except during the first stroke after the start and each turn.

SW 7.4: During each complete cycle, some part of the swimmer's head must break the surface of the water. The head must break the surface of the water before the hands turn inward at the widest part of the second stroke. All movements of the legs shall be simultaneous and on the same horizontal plane without alternating movement.

SW 7.5: The feet must be turned outwards during the propulsive part of the kick. A scissors, flutter or downward butterfly kick is not permitted except as in (1). Breaking the surface of the water with the feet is allowed unless followed by a downward butterfly kick.

SW 7.6: At each turn and at the finish of the race, the touch shall be made with both hands simultaneously at, above, or below the water level. The head may be submerged after the last arm pull prior to the touch, provided it breaks the surface of the water at some point during the last complete or incomplete cycle preceding the touch.

The first rule **SW 7.1** addresses the underwater pullout, which is one primary focus of this study. The pullout is the underwater phase of a breaststroke event which occurs immediately after the dive-in and immediately after each turn. Although this rule seems innocent at first glance, its formulation and evolution over the years has played a central role in the downward progression of breaststroke world records. In particular, the second sentence which states that a single butterfly kick is permitted at any point before the first breaststroke kick led to much faster breaststroke times. The second rule **SW 7.2** is relatively straightforward and provides the basis for the breaststroke arm movements shown in Figures 1 and 2 below. The third rule **SW 7.3** is quite important, because, along with the first rule, it prevents swimmers from completing an entire lap underwater using breaststroke pullouts, which will be discussed further in the section below on the history of breaststroke. The final three rules **SW 7.4-7.6** are similar to the second in that they outline the basics of breaststroke.

[1]FINA website: https://www.fina.org/content/fina-rules, Swimming Rules

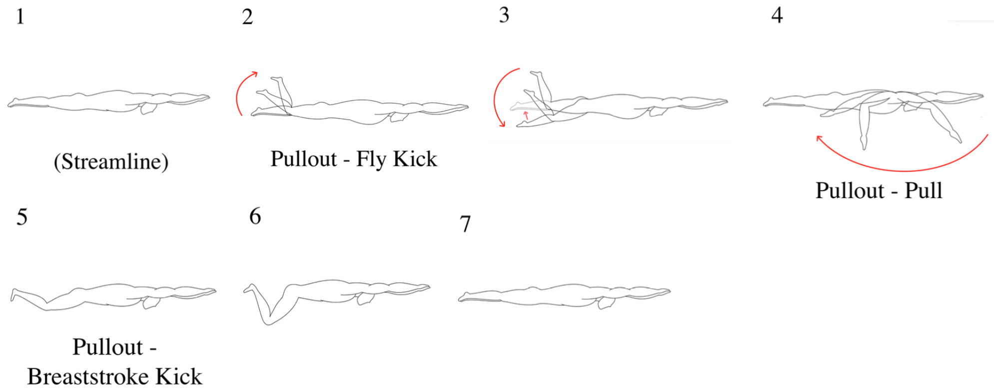

Figure 1: Breaststroke underwater pullout

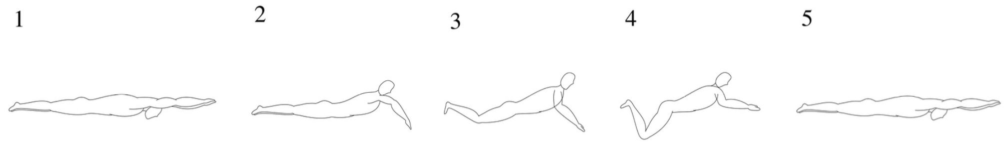

Figure 2: Breaststroke stroke

1.2. The History of Breaststroke

Breaststroke-style swimming events were introduced to the Olympics in the 1904 games in St. Louis. However, the modern breaststroke would not be introduced until after the 1956 Olympic games in Melbourne. In 1956, the Japanese swimmer Masaru Furukawa virtually swam the entire 200 long course meter (LCM) breaststroke (four lengths of a 50 meter pool) underwater, and he won the Olympic gold medal by almost two seconds. After his success, other swimmers began to compete breaststroke in this way, nearly eliminating the need for the stroke in an event that bears its name. Furukawa swam by basically stringing together consecutive underwater pullouts.

Out of concern for safety, FINA was forced to change the rules (Maglischo (2003)), allowing only one underwater pullout off of each wall and requiring some part of an athlete's head to remain above water otherwise. Some swimmers had lost consciousness due to oxygen deprivation while attempting to perform breaststroke. Breaststroke rules remained largely unchanged from the late 1950s until 1987, when FINA passed a rule (Maglischo (2003)) allowing swimmers to submerge their heads after each stroke. These rules define what is now commonly referred to as modern breaststroke, where swimmers are allowed to lunge forward into a full streamline position after each stroke.

The latter change resulted in a dramatic drop in the world record for the 200 LCM breaststroke. In 1984, three years before the rule change, the world record was broken by Victor Davis of Canada in 2:13.34; in 1990, three years after the rule change, the record was broken by Mike Barrowman of the United States in 2:11.53, which was nearly two seconds faster than Davis' record.

The next important FINA rule change came in 2004 (Maglischo (2003)), following controversy at the 2004 Olympics. Japanese breaststroker Kosuke Kitajima appeared to perform a butterfly kick during the pull phase of each pullout. However, it was difficult for officials to tell whether this was a distinct butterfly kick or simply body undulations. FINA responded by updating the pullout rule to allow for a single butterfly kick during the pull phase of each pullout. From 2005 until December 2014, athletes pushed the limits of this rule in order to maximize the gain from the butterfly kick. Technically, the butterfly kick had to occur "during" the pull, so athletes would barely separate their hands from streamline, perform the full butterfly kick, and then complete the pull phase of the pullout. In December 2014, FINA updated (Maglischo (2003)) the rule to its current state, allowing one butterfly kick at any point before the first breaststroke kick, thus allowing athletes to stay fully streamlined for their single butterfly kick.

The effectiveness of performing a butterfly kick in streamline is reflected by the all-time top performers[2] in the men's 100 and 200 short course yard (SCY) breaststroke events. Nine of the top ten performers of all time in both the 100 and 200 SCY breaststroke, fifteen of the top twenty performances of all time in the 100 SCY breaststroke, and seventeen of the top twenty performances of all time in the 200 SCY breaststroke occurred after December 2014. Obviously, the butterfly kick during breaststroke pullouts has dramatically impacted the execution of competitive breaststroke. The sport continues to evolve rapidly. In fact, there are many athletes who purposefully do multiple butterfly kicks during their pullouts. Cameron Van der Burgh famously admitted to cheating (Maglischo (2003)) by using multiple butterfly kicks after winning the Olympic gold medal in London in 2012. FINA has even discussed, although not passed, a rule that would allow unlimited butterfly kicking up to 15 meters, similar to the other strokes. Naturally, given the importance of pullouts in modern breaststroke, using IMUs will give insight into how athletes can maximize benefits from pullouts under the current rule constraints.

1.3. Goals of the Study

In this study, we aim to address the following questions:

Q1. What are the common quantitative characteristics of breaststroke execution among world class competitors?

Q2. What are the mean, variance, and standard deviation of measurements used to quantify and evaluate breaststroke performance?

Q3. Are there clear roles in which IMUs can be used to enhance the training of elite breaststroke swimmers?

2. Materials and Methods

This study was approved by the Emory International Review Board (EIRB); the protocol number is IRB00104919. Each participant was informed of the procedures and potential risks and provided written consent prior to participating in the study.

2.1. Materials

The IMUs used in the study were GaitUp Physilog 5 Sensors (see Figure 3). Each sensor contains a tri-axial accelerometer and a tri-axial gyroscope which both record data at 512 Hz. The sensors also include a barometric pressure sensor which was turned off during data collection. An air hole on one side of the sensors helped with consistent orientation during data collection. The sensors weigh approximately eleven grams and have an IP64 water resistance rating (dust resistant and splash proof).

[2] from the November 2018 all-time top performers list

Figure 3: GaitUp Physilog 5 Sensor

While the IP64 rating is suitable for land-based studies, this level of water resistance is insufficient for underwater use. Therefore, steps were required to waterproof each sensor. The method described below requires 5 cm × 9 cm resealable plastic bags, Cramer flexi-wrap (typically used by athletic trainers), Scotch 3M 142 2-inch acrylic tape, 1-inch Nexcare waterpoof adhesive tape, multi-fold paper towels, and SensiCare nitrile gloves.

2.2. Methods

Each sensor was wrapped in a paper towel and flexi-wrap, and then placed in a resealable bag, which was further reinforced with tape. With this dressing, the waterproofed sensors are approximately 12-13 grams.

Each swimmer was outfitted with three sensors. One sensor, the "lumbar sensor," was placed over the L4 and L5 vertebrae and oriented so that the sensor's air hole pointed downward (see Figure 4). The sensor was attached using 1-inch Nexcare waterproof tape. Cramer flexi-wrap was then used to further anchor the sensor in place (seven to ten tight wraps around the athlete). One sensor was placed onto each of the swimmer's hands between the third and fourth metacarpals with the air hole pointing towards the wrist (see Figure 5). Both hand sensors were attached with 1-inch Nexcare waterproof tape. Finally, the swimmer's hands were placed into SensiCare nitrile gloves, which were then taped at the wrist with standard 1/2-inch waterproof adhesive tape to achieve a snug fit. Although the gloves initially changed the "feel" of the water for the athletes, the tests revealed that all of the participants quickly adapted (within a few minutes) and were able to perform their customary stroke at both low and high speeds.

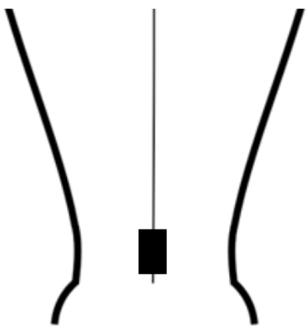

Figure 4: Lumbar sensor

Figure 5: Hand sensor

Each participant in the study warmed up for fifteen to thirty minutes before testing began. Among the data collected, this paper concerns fast 100 yard/meter breaststroke swims.

3. Results

IMU data was collected from fourteen participants at 512 Hz, resulting in a large data set. The next subsection explains how one can understand and interpret this data.

3.1. The Participants

This study involved fourteen elite breaststrokers. Table 1 below gives the best 100 SCY breaststroke times as of November 2018 for the eight men, along with the number of strokes[3] taken during each of the four 25 yard laps in a competition swim. Table 2 offers this information for the six female participants. A cursory glance reveals that there is some variation among the number of strokes taken by these athletes. However, it is important and not surprising that the women tend to take more strokes than the men. Furthermore, it is interesting to note that two of the athletes that took the fewest strokes stand at 6'8" and 6'9", and the third is primarily a 200 SCY breaststroker (see rows 3, 5, and 6 in Table 1).

Table 1: Male Participants

100 SCY Breaststroke Best Time	# Strokes Lap 1	# Strokes Lap 2	# Strokes Lap 3	# Strokes Lap 4
50.80	5	7	8	8
50.94	5	7	7	7
51.16	4	5	5	6
51.16	4	6	7	8
51.78	4	5	5	6
52.58	4	5	5	6
52.68	4	6	6	6
53.60	5	6	6	6

Table 2: Female Participants

100 SCY Breaststroke Best Time	# Strokes Lap 1	# Strokes Lap 2	# Strokes Lap 3	# Strokes Lap 4
58.09	6	8	8	8
58.44	6	8	8	9
59.52	7	8	8	9
59.69	5	7	7	8
1:00.65	7	7	8	8
1:00.70	7	9	9	9

The data in Tables 1 and 2 is easily found (e.g. https://www.collegeswimming.com for best times) by watching the athletes' races and counting their strokes in each lap. Obviously, breaststroke is too complicated to be reduced to times and simple stroke counts. The purpose of this study is to make use of the more precise data collected by IMUs. The 512 Hz sensors used here capture microscopic acceleration changes in each of the x, y, and z directions (see Figure 6), eclipsing information which is only available from digital video.

[3] The number of strokes in lap 1 is generally smaller due to the high speed generated by the dive off of the blocks.

3.2. The Data

The fourteen participants were asked to execute a competition-speed 100 SCY or LCM (depending on the set-up of their training facility) breaststroke swim outfitted with the waterproofed sensors described above.

3.2.1. Interpreting IMU Data

The IMUs used in this study contain accelerometers which simultaneously measure acceleration in the x, y, and z directions relative to the sensor, as well as gyroscopes which measure rotational velocity in the same three directions (see Figure 6). Data was collected at 512 Hz throughout the testing.

Interpreting the data requires a well-defined global orientation (relative to the swimmer), which is represented here by the X, Y, and Z directions. As illustrated in Figure 7, the Y axis represents the center of a lane in the swimming pool. With respect to this convention, positive X represents the right direction, which is perpendicular to the Y axis as shown below. The positive Z axis points upward in the direction of the sky.

Figure 6: Sensor orientation

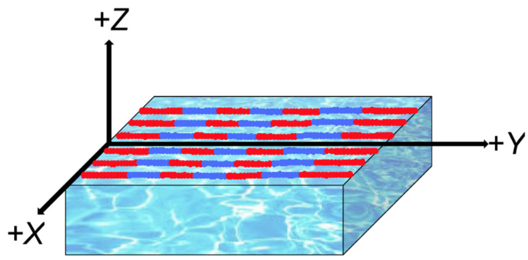

Figure 7: Global orientation of pool

Since the sensors are generally in motion, there is no simple correspondence between the x, y, and z directions of the sensors and the fixed global X, Y, and Z directions. When the swimmer is swimming prone, however, the relative y direction of the lumbar sensor will be closely aligned with the global Y direction. Therefore, the acceleration data collected by the lumbar sensor in the y direction essentially gives the forward acceleration of the swimmer throughout the swim. The x and z directions relative to the sensors depend on which component of the stroke the swimmer is currently performing, and comparing the tri-axial acceleration data of the hand sensors and the lumbar sensor reveals which components of the acceleration data correspond to each component of the stroke.

After acceleration data points were collected by the sensors, programs written in the software package Matlab were used to analyze the collected data. In particular, the graphs presented here represent the "best fit curves" for the collected data. The horizontal axis of these graphs represents time t (measured in 1/512 seconds to reflect the 512 Hz frequency of the sensors), while the vertical axis represents acceleration in g's (9.8 m/s^2). Since the accelerometers are tri-axial, data was collected in the x, y, and z directions. Throughout, acceleration in the x direction is rendered in red, y in black, and z in blue.

To illustrate these graphs, consider the following two cartoons. Figure 8 is a cartoon of the acceleration graph produced for a sensor at rest. Notice the horizontal blue line at 1 g. The z data points rest at positive 1 g when there is no movement in the z direction. This is due to the fact that gravity pulls the sensor downward (in the negative z direction) at a constant acceleration of 9.8 m/s^2, so the force of an object preventing the sensor from falling at 9.8 m/s^2 results in an acceleration of positive 9.8 m/s^2. It is this preventative force which is detected by the sensor.

Figure 9 is a cartoon of the acceleration graph produced when the sensor moves precisely forward (in the y direction) in a straight line, and then comes to a complete stop. The forward acceleration produces the upward spike in the black curve, while the downward spike represents the deceleration until the sensor stops. That the red line is horizontal reflects the fact that the sensor moved forward in a straight line without any left/right motion.

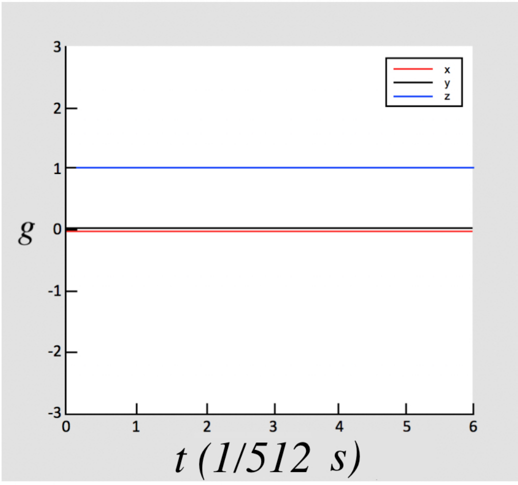

Figure 8: Sensor at rest

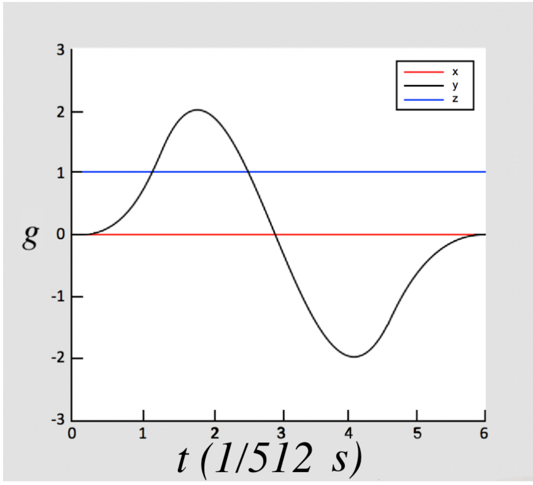

Figure 9: Sensor moving in y direction

3.2.2. Results

The underwater pullout data is quite revealing. The pullout is defined as the portion of the breaststroke swim which occurs immediately after the dive and after each turn, but it does not include the dive or push-off. The dive and the push-offs are considered separate components. Therefore, the pullout (see Figure 1) consists of a glide in streamline position to carry the momentum from the dive/push-off, one butterfly kick, one pull in which the arms move from the streamline position all the way down towards the swimmer's feet, a short period of time in which the swimmer glides through the water and returns the hands to streamline position, and one breaststroke kick before the start of the breaststroke strokes.

How does one use accelerometer data to determine the *duration* (length of time in seconds) of the pullout? Naturally, one makes use of the lumbar sensor, as it collects information concerning the overall motion of one's center of mass. In view of the discussion above, one makes use of the acceleration of this sensor in the y direction, which mirrors the swimmer's acceleration in the global Y direction. Therefore, the first pullout begins the instant that the dive-in ends, which for the purposes of this study is defined as the moment the swimmer makes contact with the water. This instant is easily identifiable as the minimum value of the steep downward y acceleration spike which is caused by the higher density of water as compared to air. The remaining pullouts (those executed after turns) begin the instant that the swimmer's feet leave the wall. This instant is identified by the maximum y acceleration point after the push-off, since the conclusion of the push-off results in immediate deceleration due to resistance. The end of the pullout is measured by the minimum y acceleration point immediately after the breaststroke kick, which represents the instant before the initiation of the first stroke. Hence, the duration of the pullout is the length of time in seconds from the beginning of the pullout to the end of the pullout as defined above. The duration of the pullout at the 50 yard/meter mark of each swim is given in Table 3.

Obviously, the goal is to execute breaststroke as quickly as possible in the global Y direction. One can use the lumbar sensor to evaluate the forward acceleration of the swimmer within the separate components of the pullout. We define the *maximum acceleration* during the fly kick as the maximum y acceleration point between the dive/push-off and the pull. The maximum acceleration during the pull and the breaststroke kick are defined analogously for those components. This information is easily identified from the acceleration data (which is given in g's).

This data perhaps represents the first accurate quantifiable measurements of underwater pullouts. Tables 3 and 4 contain the data for the underwater pullout performed at the 50 yard/meter mark. To maintain confidentiality, a random letter from A to H (resp. I to N) was assigned to each of the male (resp. female) participants. These letters do not correspond to the order of the swimmers in Tables 1 and 2.

Table 3: Underwater Pullout at 50 yards/meters for Male Participants

Swimmer	Pullout Duration (in s)	Max y-Accel. Fly Kick (in g's)	Max y-Accel. Pull (in g's)	Max y-Accel. Br. Kick (in g's)
A	5.116	1.1050	-0.0751[a]	1.5146
B	5.965	1.3628	0.0246	1.8296
C	5.537	0.9629	0.3169	1.5845
D	5.947	1.4453	0.3655	1.4478
E	5.012	0.7581	0.1807	1.2251
F	5.451	1.0691	0.2405	1.3921
G	4.855	2.0498	0.4495	2.8970
H	5.994	0.9104	0.1057	2.1597

[a]This negative value is correct. Physical movements result in acceleration in three different directions. This swimmer consistently experienced large up/down bobbles and left/right swerving during his pulls.

Table 4: Underwater Pullout at 50 yards/meters for Female Participants

Swimmer	Pullout Duration (in s)	Max y-Accel. Fly Kick (in g's)	Max y-Accel. Pull (in g's)	Max y-Accel. Br. Kick (in g's)
I	3.888	0.8994	0.4866	1.6692
J	4.280	0.7783	0.1006	1.0981
K	5.039	1.1831	0.5339	1.3704
L	5.590	1.0327	0.1655	0.9976
M	5.129	1.0583	0.7556	1.0840
N	4.098	1.1204	0.0496	1.1394

To determine the commonalities of the data in Tables 3 and 4, we now compute standard statistical information. This information is given in Tables 5 and 6. A detailed discussion of the significance of this data will be offered in Section 4.1.

Table 5: Statistics of Underwater Pullout for Male Participants

Statistic	Pullout Duration	Max y-Accel. Fly Kick	Max y-Accel. Pull	Max y-Accel. Br. Kick
Mean	5.485	1.2079	0.2010	1.7563
Standard Deviation	0.457	0.4088	0.1775	0.5434
Variance	0.209	0.1671	0.0315	0.2953

Table 6: Statistics of Underwater Pullout for Female Participants

Statistic	Pullout Duration	Max y-Accel. Fly Kick	Max y-Accel. Pull	Max y-Accel. Br. Kick
Mean	4.671	1.0120	0.3486	1.2265
Standard Deviation	0.676	0.1489	0.2841	0.2504
Variance	0.457	0.0222	0.0807	0.0627

4. Discussion

This section consists of three main parts. The first subsection offers clear evidence that there is wide variation in the execution of underwater pullouts by elite breaststrokers. This knowledge suggests that IMUs can be used as a coaching tool to identify targets for potential performance improvement. The second subsection offers sample analyses which illustrate how IMU data can be used to enhance the coaching of individual elite athletes. The final subsection describes an anecdotal test concerning Swimmer A, who exhibited pronounced left/right veering in his first test. Steps were taken to reduce this tendency, and this is described in detail along with evidence of improvement.

4.1. Interpretation of the Data Set

Tables 3–6 constitute the data collected in the study as it pertains to underwater pullouts. Here we summarize the conclusions which are easily drawn from this information. It is important to note that conclusions related to max acceleration can only be obtained from IMU data, as this information is impossible to capture from video.

(1) Men generally have longer pullouts than women (4.855 s - 5.994 s compared to 3.888 s - 5.590 s).

(2) Men generally have larger max acceleration than women for both butterfly kick and breaststroke kick.

(3) The max acceleration of the butterfly kick and the breaststroke kick both **dwarf** the max acceleration for the pull. The genuine role of the pull might come as a surprise. The data reveals that the pull is better thought of as a component of the pullout which attempts to restore speed lost due to deceleration after the butterfly kick.

(4) The max acceleration for the breaststroke kick is generally larger than the max acceleration for the butterfly kick. However, both kicks generate significant acceleration.

(5) There is wide variation in the max acceleration of the butterfly kick (0.76 g - 2.05 g for men and 0.78 g - 1.18 g for women). This variation might suggest deficiencies in execution, thereby offering coaches targets of opportunity to enhance performance.

(6) There is wide variation in the max acceleration of the pull (-0.07 g - 0.45 g for men and 0.05 g - 0.76 g for women). This variation might suggest deficiencies in execution, thereby offering coaches targets of opportunity to enhance performance.

(7) There is wide variation in the max acceleration of the breaststroke kick (1.23 g - 2.90 g for men and 1.00 g - 1.67 g for women). This variation might suggest deficiencies in execution, thereby offering coaches targets of opportunity to enhance performance.

(8) The quality of butterfly kick and breaststroke kick are not necessarily correlated. For example, Swimmer H has the second best breaststroke kick but the second worst butterfly kick among the eight men studied.

Remark 1. Although the mean max acceleration of the pull is larger for women than for men (compare Tables 5 and 6), we do not conclude that women generally have stronger pulls due to the presence of several potential outliers (e.g. Swimmer A and Swimmer M).

Remark 2. Overall, Swimmer G for the men (resp. Swimmer K for the women) exhibited the strongest pullout. However, it is interesting to note the unusually strong pull performed by Swimmer M and the unusually strong breaststroke kick by Swimmer I.

4.2. Sample Analyses

The data collected for each athlete consists of x, y, and z acceleration from each of three sensors. Throughout the remainder of this paper, the color key legend for the subsequent graphs is given in Figure 10. In particular, the red line represents x acceleration (left/right acceleration), black represents y acceleration (forwards/backwards acceleration), and blue represents z acceleration (up/down acceleration) relative to the sensors.

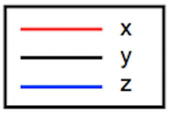

Figure 10: Legend

4.2.1. Hand Sensors

Although data was collected from the hand sensors, this study primarily analyzes lumbar sensor data, as this information offers the best reflection of the movement of a swimmer's center of mass. Nevertheless, here is a brief discussion of a specific example of data collected from the hand sensors. A full analysis of the graphs from the hand sensors would be interesting, but is not included in this paper.

Figures 11 and 12 are sample graphs produced by the right and left hand sensors of Swimmer G during three consecutive breaststroke strokes. The horizontal axis is time in 1/512 seconds (more specifically, the number of data points, measured at 512 Hz, during these strokes), and the vertical axis is acceleration in g's.

Since the orientation of the hand sensors is constantly changing throughout breaststroke strokes, these directions do not correspond to the global X, Y, and Z directions. The pull during a breaststroke stroke consists of the outsweep of the hands, the insweep of the hands, and the lunge forward into streamline position, in that order (see Figure 2). This full cycle occurs three times in Figures 11 and 12.

The large upward z acceleration spikes (the blue line) represent the first part of the lunge forward. Since the back of the hand faces forward at the end of the insweep, the sensors move in the positive z direction during the first part of the lunge forward. Throughout the lunge forward, the hands gradually change orientation so that the fingers point forward, which accounts for the large upward y acceleration spikes (the black line) immediately following the z spikes. The smaller upward y acceleration spikes between the lunges forward are largely caused by the breaststroke kick, which contributes to the forward acceleration of the hands while in streamline position.

It is important to note that the upward x acceleration spikes (the red line) in Figure 11 correspond to the downward x acceleration spikes in Figure 12, and vice versa. This is due to the fact that the outsweep causes the right hand sensor to move to the right (the positive x direction) while the left hand sensor moves to the left (the negative x direction). Therefore, the x acceleration of the left hand sensor is the negative of the x acceleration of the right hand sensor during breaststroke.

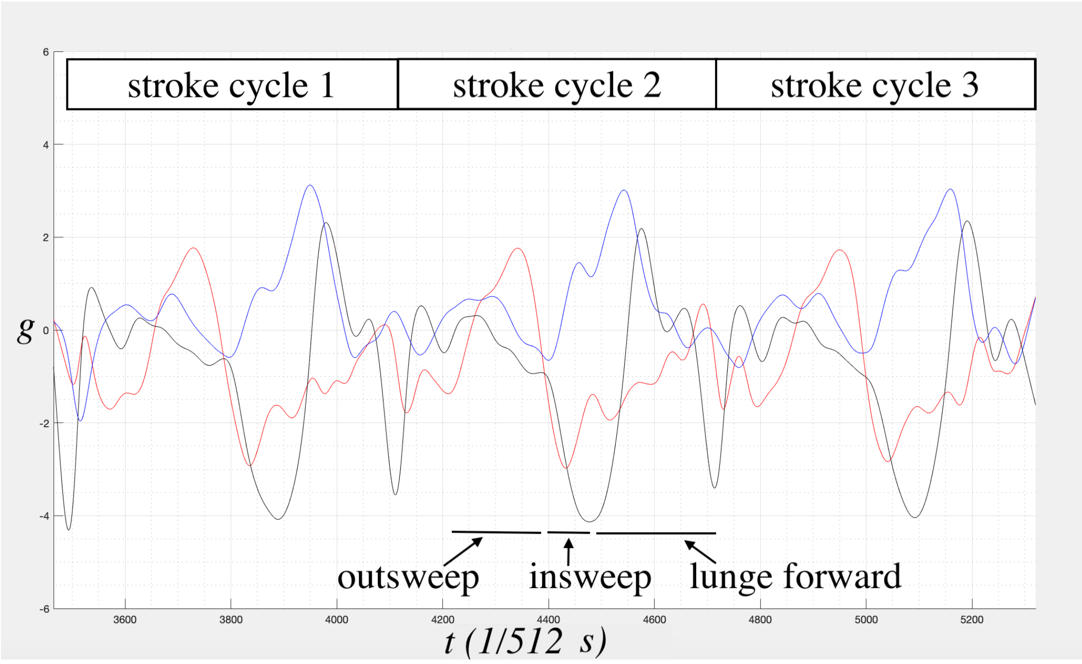

Figure 11: Sample right hand acceleration graph

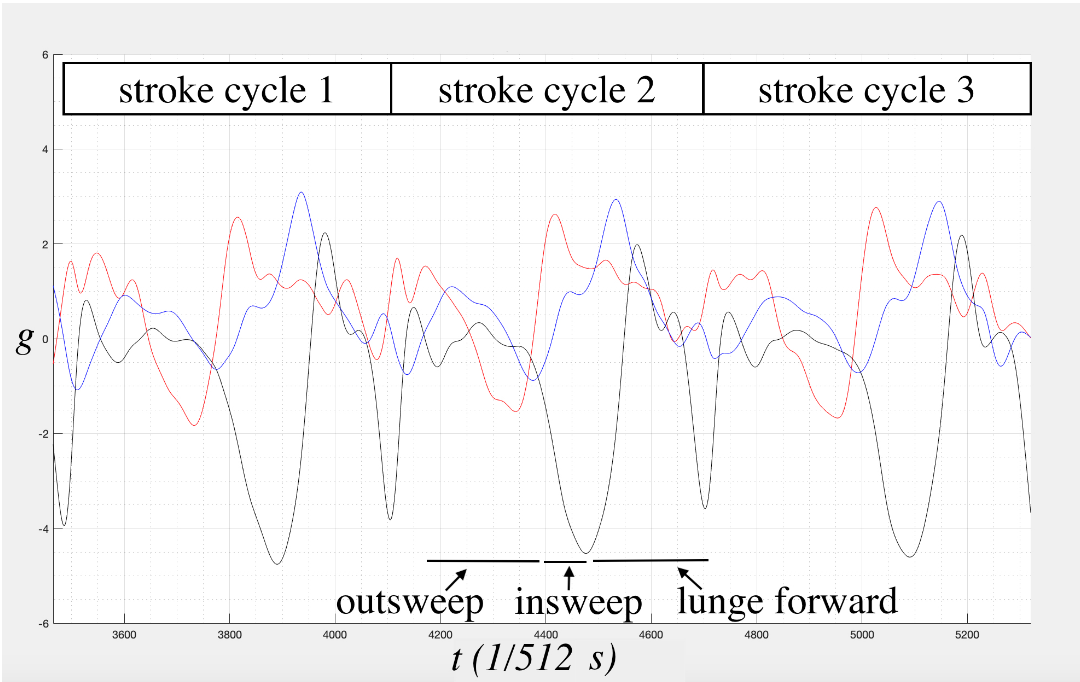

Figure 12: Sample left hand acceleration graph

4.2.2. Swimmer H

The graphs in Figures 13-16 give samples of the data collected by the lumbar sensor. As above, the horizontal axis is time in $1/512$ seconds, and the vertical axis is acceleration in g's. The y acceleration of the lumbar sensor (the black line in Figures 13-16) corresponds to acceleration in the global Y direction as discussed above, so the main goal of a swimmer in the context of this paper is to maximize this forward acceleration (and, of course, to minimize forward *de*celeration).

Figure 13 is a sample acceleration graph from the lumbar sensor during Swimmer H's fast 100 SCY breaststroke swim. This swimmer has a "textbook" breaststroke. In other words, the upward y acceleration spikes are relatively large (large forward acceleration), the downward y acceleration spikes are relatively small (small forward deceleration), and there is very little movement in the x and z directions during the breaststroke strokes (see the circled portion of Figure 13). The only major x acceleration spikes are the result of the expected right (or left) movement during the turns, and the only major z acceleration spikes are during the butterfly kicks in the underwater pullout phase. In general, minimizing acceleration spikes in the x and z directions for the remainder of the swim is important for maximizing y acceleration, since any amount of left/right swerving or up/down bobbles will reduce forward acceleration correspondingly. One weakness to note about the pullout phases of Figure 13 is that although the breaststroke kick is strong compared to the other swimmers, the pull is slightly below average, and the butterfly kick is quite weak (see Table 5).

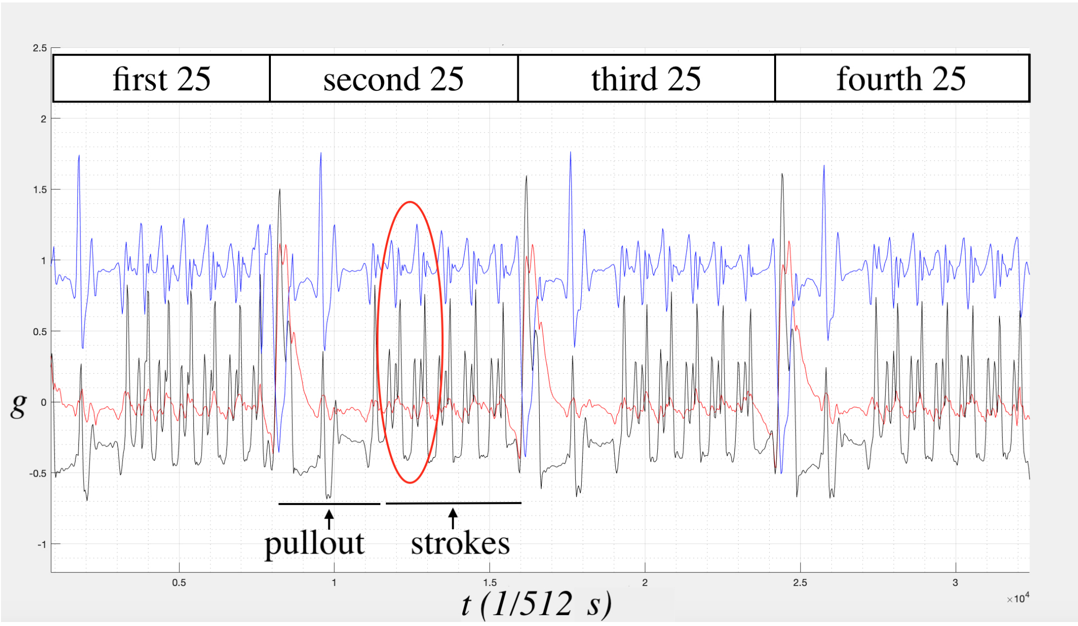

Figure 13: Sample 100 SCY breaststroke swim, Swimmer H

4.2.3. Swimmer D

The acceleration graph of Swimmer D is given in Figure 14. This swimmer has approximately average pullouts (see Table 5), but several weaknesses were detected by the sensors in his fast 100 SCY breaststroke swim (see the circled portion of Figure 14 as compared to the circled portion of Figure 13). First, there is significant left/right swerving during the breaststroke strokes. Each x spike diminishes y acceleration. Second, there are large downward z spikes with every breaststroke stroke. Although alternating upward and downward z spikes with similar magnitudes suggest undulation, dominant downward z spikes suggest sinking hips between breaststroke kicks. Therefore, this z movement undeniably reduces forward acceleration. Third, the upward y spikes during the strokes are relatively small when compared to the downward y spikes. One possible explanation for this is that Swimmer D does not have an optimal body position during breaststroke, causing less acceleration and more deceleration than some of the other swimmers. It is obvious from this graph that Swimmer D has several possible targets of opportunity to improve his breaststroke.

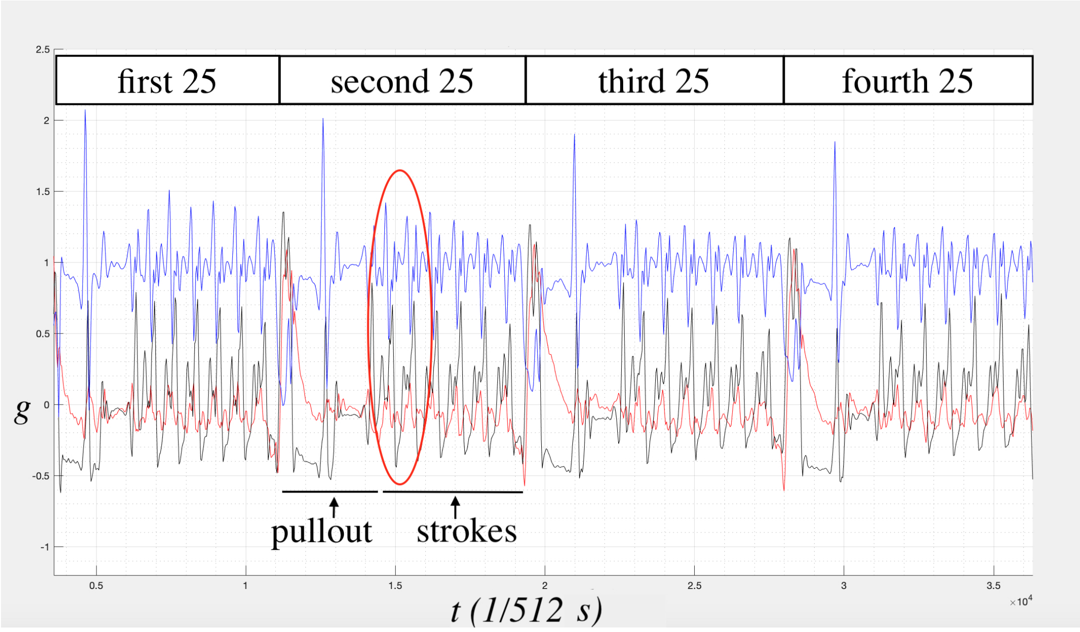

Figure 14: Sample 100 SCY breaststroke swim, Swimmer D

4.2.4. Swimmer K

Figure 15 is a sample acceleration graph from the lumbar sensor during a breaststroke pullout within Swimmer K's fast 100 SCY breaststroke swim. This swimmer has a "textbook" breaststroke pullout. Relatively, Swimmer K had the strongest butterfly kick and the second strongest pull and breaststroke kick (see Table 6). There are minimal x and z wiggles throughout the pullout except for slight left/right swerving during the breaststroke kick and slight up/down bobbles during the butterfly and breaststroke kicks. Any amount of left/right swerving detracts from forward acceleration, which suggests that Swimmer K could possibly improve her already excellent underwater pullout by decreasing left/right muscular imbalance during the breaststroke kick. The z acceleration spike during the butterfly kick is expected, and the spikes during the breaststroke kick are very common.

It is important to note, however, that some styles of breaststroke may result in larger z spikes without visibly detracting from forward acceleration. For example, breaststroke with larger than average undulations during the breaststroke kicks could possibly result in more deceleration from increased drag but more acceleration from increased force generated. More testing is required to compare z and y acceleration from the different styles of breaststroke before any conclusions can be drawn regarding these z spikes.

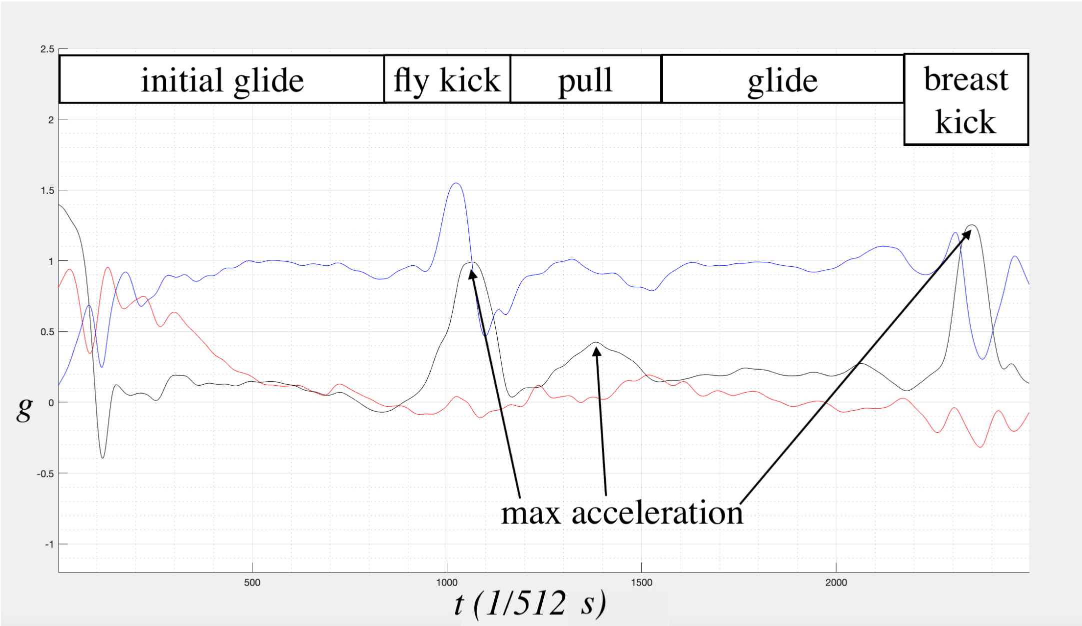

Figure 15: Sample breaststroke pullout, Swimmer K

4.2.5. Swimmer A

Figure 16 is the acceleration graph produced during one of Swimmer A's pullouts in a fast 100 SCY breaststroke. The data in Table 4 indicates that Swimmer A has a relatively weak pullout, as the y acceleration during his butterfly kick, pull, and breaststroke kick are all below average. In fact, this swimmer was the only one to experience a negative maximum y acceleration during the pull phase of the pullout. Although there are only small up/down bobbles and slight left/right swerving during the majority of the pullout, the maximum y acceleration during each component is quite low.

There are several important observations to be made here. Most importantly, negative maximum acceleration during the pull does not mean that the swimmer is swimming backwards; it only means that the swimmer was unable to fully counteract natural deceleration after the butterfly kick. In other words, Swimmer A's pull reduced forward deceleration but did not manage to provide forward acceleration. Slight x and z spikes also reduced forward acceleration during the pull phase. Strengthening the pull would undeniably strengthen the pullout in this case. Nonetheless, this phenomenon, along with the rest of the data, suggests that the main purpose of the pull is not necessarily to produce a large amount of acceleration but instead to attempt to offset deceleration.

One may notice that Swimmer A experiences moderate left/right swerving during the breaststroke kick in the pullout. In fact, this swerving continues throughout the swim, every time the swimmer performs a breaststroke kick. As discussed above, x acceleration spikes reduce forward acceleration, so this swimmer could potentially improve his breaststroke by working to fix his left/right imbalance (see Section 4.3 for further discussion).

Finally, it is important to recognize that Swimmer A is a world class breaststroker, even though his pullout is relatively weak. Since underwater pullouts only make up approximately half of a 100 SCY breaststroke swim, swimmers have the opportunity to counterbalance weak pullouts with strong breaststroke strokes. This swimmer could still improve his best 100 SCY breaststroke time by improving his pullout, but he already has one of the fastest times in the world due to his exceptionally powerful and efficient breaststroke strokes.

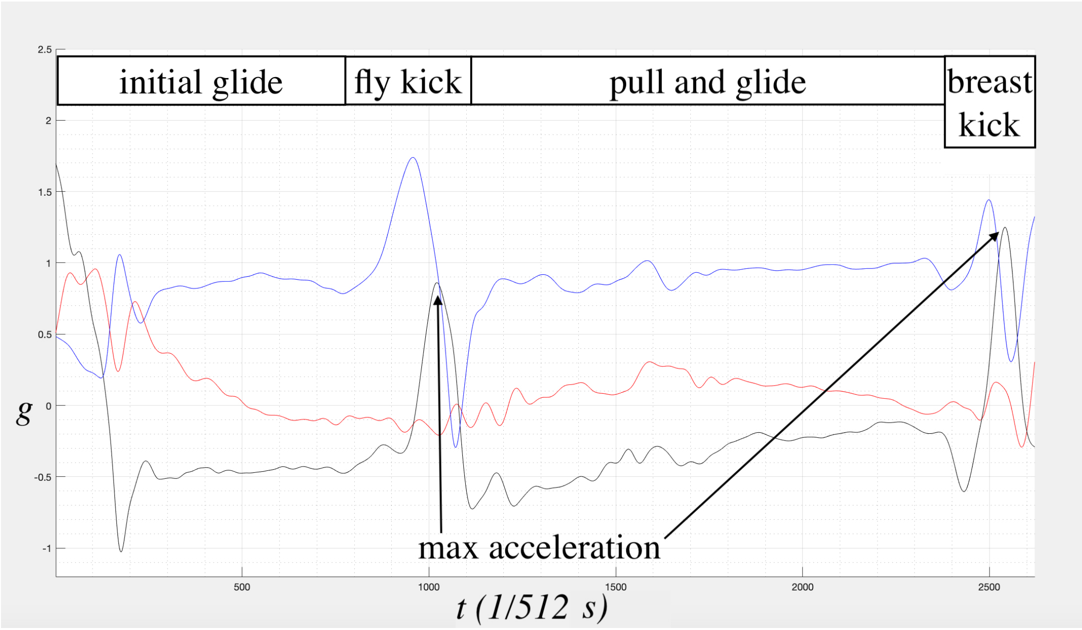

Figure 16: Sample breaststroke pullout, Swimmer A

4.3. An Anecdotal Test

The left/right swerving of Swimmer A is discussed further here. Below are two graphs that show Swimmer A's acceleration during 25 yard laps of two fast 100 SCY breaststroke swims. The test shown in Figure 18 was conducted in a narrow lane (69 inches wide) about two months after the test shown in Figure 17, which was conducted in a full-size lane (85 inches wide).

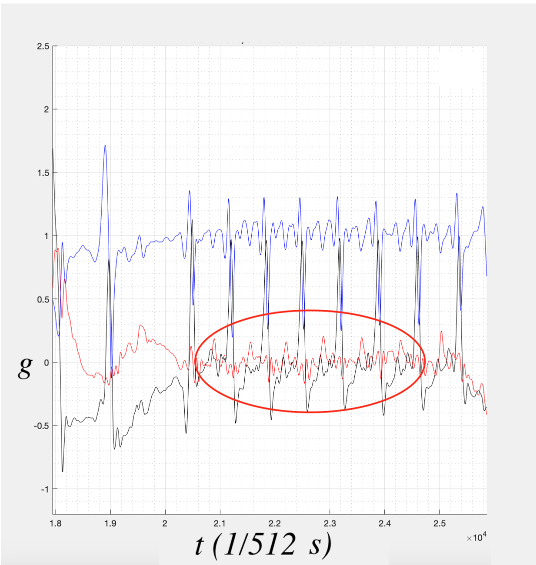

Figure 17: Full lane

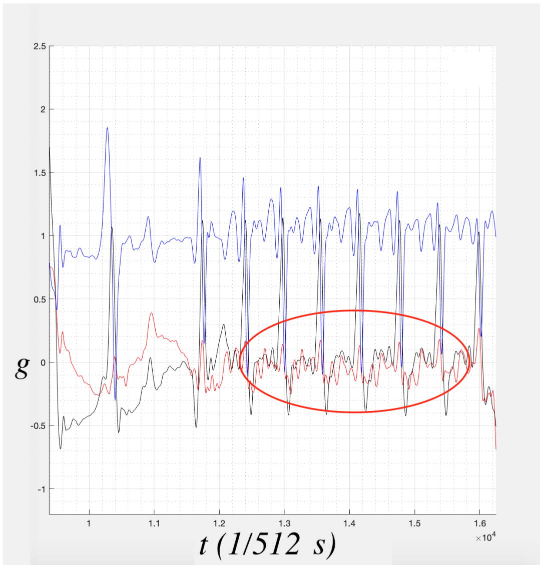

Figure 18: Narrow lane

The x acceleration spikes during the swimmer's breaststroke strokes are circled in red. After the first test in a full-size lane (Figure 17), it was explained to Swimmer A that unintentional left/right swerving during breaststroke kicks may have diminished forward acceleration, and accidental circle-swimming (swimming down the right side of the lane) caused him to swim more than 100 yards (approximately 1.5 - 2 yards longer than some others tested) in the y direction. In an attempt to improve his breaststroke, Swimmer A trained in a narrow lane for three weeks. He then participated in a second test in a narrow lane (Figure 18). It is clear from the circled portions of the graphs above that the x acceleration spikes produced while swimming in a narrow lane were smaller than the x acceleration spikes produced while swimming in a full-size lane. In other words, he swam in a straighter line in the second test.

For several reasons, this test does not provide conclusive evidence to support training in a narrow lane in order to improve breaststroke performance. Although Swimmer A experienced less x wiggle in the second test after training in a narrow lane for three weeks, there were additional factors that may have contributed to the difference between the two graphs. The swimmer's awareness of his left/right swerving may have been enough to reduce his x acceleration spikes. Between tests, the swimmer began to taper for upcoming championship swim meets, so he swam much faster in the second test than in the first test. The swimmer wore a technical swim suit for his second test, but he wore a training swim suit for the first test.

Therefore, one can conclude that some combination of these factors resulted in a straighter swim. To determine the contribution of each factor, it would be necessary to conduct further tests in which the factors are more strictly controlled. For example, requiring the swimmer to wear the same swim suit for both tests and to complete swim practices of similar difficulty before both tests would give a more accurate indication of the benefit of training in a narrow lane. Nevertheless, the IMU sensors were crucial for identifying this flaw in Swimmer A's execution. This flaw cannot be seen on video. In this way, the IMUs clearly have enhanced the training of a world class swimmer.

5. Conclusion

From the data collected in this study, it is clear that there is wide variation in the execution of breaststroke, even among world class breaststrokers, but there are also features of breaststroke which seem to be common to swimmers of this caliber. Because of this, the idea of introducing IMUs into coaching methods seems quite promising. IMU data can be collected following the protocol here. The data can then be used by coaches to identify targets of opportunity for improving the forward acceleration of swimmers, which is mirrored by the y acceleration values measured by the lumbar sensor. Furthermore, this data is far superior to video footage, since the 512 Hz frequency of the sensors allows for detailed and precise analyses of microscopic acceleration changes which are invisible from video footage. This study offers some sample analyses which indicate how IMUs can be used to enhance the coaching and training methods of individual athletes. Finally, an anecdotal experiment assessed whether a training method involving narrower lanes could reduce left/right swerving during races. The results of this experiment suggest a correlation between the narrow lane training method and reduced x acceleration spikes, and this test should be expanded to a wider group of athletes in order to determine its usefulness.

Disclosure statement

No potential conflict of interest was reported by the authors.

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