A Comparison of Computational Methods to Determine Intra-stroke Velocity in Swimming using IMUs.

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Abstract—Sacrum located IMU sensors were used to monitor three axis acceleration and three axis rotation from elite swimmers in competition conditions. The intra-stroke velocity was determined for each swimmer using their preferred swim stroke (freestyle, backstroke and breaststroke) using three different calculation techniques - dual axis acceleration, dual axis acceleration eliminating the static gravity constant and AHRS. The mean intra-stroke velocity variation (averaged over one 50 m lap) in freestyle swimming was less than 0.6% in all cases. This resulted in a timing under-estimate of less than 0.60ms for freestyle, 4.0ms for breaststroke and a timing over-estimate of less than 6.2ms for backstroke. The difference was less than 5% over the complete stroke (one way ANOVA p > 0.05), indicating no significant difference in the velocity profiles. These simple, robust analysis techniques can be used to quantify variations in every stroke as the swimmer fatigues providing significant information to coaching staff and athletes.

Index Terms—IMUs, AHRS, swim velocity, intra-stroke variation, freestyle, breaststroke, backstroke, velocity algorithm.

I. INTRODUCTION

Monitoring and assessment of athlete movement during training and competition is a major goal of wearable technologies. One direct method of measuring movement is through the use of wearable inertial sensors (IMUs). Commonly, these devices are small enough to cause minimal interference with movement and, through the use of MEMs (micro-electro-mechanical) sensors, three axis acceleration and three-axis rotation can be detected and recorded at relatively high sampling speeds. The competing location technologies include image analysis from video records, multi-camera motion capture systems and tethered lines. These technologies are either highly expensive, difficult to install, or cumbersome and all have positional errors which result in velocity errors. In swimming, video images are highly distorted by the variations in the water surface causing major reflections and the presence of bubbles.

While IMUs are small, unobtrusive, convenient, low cost, and accurate, and have been effective in swimming performance assessment [1 - 3], they have significant errors associated with skin and muscle movement (movement artefacts). In the case of accelerometers, numerical integration and gravitational offsets cause errors in velocity calculations. In swimming the movements are highly repetitive, the orientation of the torso is relatively constant except during the start and the ends of the 50m laps, and the direction is linear. This provides some advantages to signal processing of the IMU data. In this paper these advantages are explored with the objective of minimising computational processing complexity while still providing accurate results.

It is well known that the swim velocity varies significantly during a race [4]. To date, the measurement of intra-stroke velocity has proved challenging [5]. In much of the swimming IMU literature [1-3, 5], as with the use of IMUs in other sports and human monitoring activities, the acceleration data is filtered to remove “sensor drift” and to remove the static gravitational acceleration component. In this paper we demonstrate that filtering is not required and probably is counter productive in the fine detailed analysis of the biomechanics of swimming highlighting stroke-by-stroke variations. The intra-stroke variation is of vital importance to swimmers and coaches seeking to improve their lap times and to assess the degradation of velocity as the swimmer fatigues and/or loses focus on their swimming technique.

II METHODS

A. Participants

Three elite able-bodied freestyle swimmers (FINA point score average 744.33 ± 78.01, aged 19 years) participated in the study. Ethical approval was obtained by the Human Research Ethics Committee at Griffith University (GU Ref No: 2016/314).
B. Experimental Design

The research protocol consisted of two parts: a familiarity session using and wearing the IMU, in the swimmer’s daily training environment and secondly, competition racing at a domestic competition organized by Swimming Australia in preparation for the 2016 Olympic Games.

Each participant was first informed of the procedure and IMU specifications during a short briefing at the beginning of a normal training session. After consent, the single IMU was powered on, secured with waterproof medical adhesive underneath the fabric of the racing non-textile suit in close proximity to L3 on the lower spine. Each participant swam with the IMU for the length of the session and was asked for feedback regarding comfort, disturbance and whether they would like to continue wearing the IMU during training and competitive meets.

After consent from the technical officials, Swimming Australia and the participants, the swimmer wore the IMU during their competitive event. In marshalling, prior to their race, participants were fitted with the single IMU as previously worn during familiarization. The participants wore the IMU for the entire race event and the IMU data were collected from the participant after their race was completed.

Fig 1: Location of the IMU and the associated coordinate system. Y is the horizontal direction of the swim, and z is the vertical. The body roll angle \( \theta \) was measured from the x axis in the xz plane.

C. IMU Sensor Technology

The IMU (IMeasureUTM, New Zealand) is housed in a silicon casing with external dimensions 38 x 37 x 20 mm including metal clip, which is visible on the posterior of the swimming suit. The unit contains a 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer, weighs less than 25 grams, logs data at a sampling rate of 100 Hz that is downloadable and chargeable via a waterproofed USB output. The unit is powered on and off by magnetic conduction and a light indicate data logging. All sensors were calibrated at time of manufacture.

D. Algorithm

Data from the IMU sensor were downloaded onto a PC and post processed using software created on MATLAB (MathWorks, Massachusetts, USA). The times of maximum acceleration at the mediolateral x axis used to identify the ‘start’ of the stroke. This corresponds to the “catch phase” in freestyle swimming [6]. Each stroke in one pool length (approximately 18 strokes) was used to calculate the mean instantaneous acceleration of the individual stroke cycles in each axis (x, y and z). The longest stroke cycle was used as a master sample and all individual strokes were time-normalised using linear interpolation. The sample lengths ranged from 79 to 126 samples for freestyle, 141 to 181 for breaststroke and 126 to 149 for backstroke. Standard error bars between the mean and individual stroke cycle values generated (see Figure 2) show a highly consistent profile and relative minor velocity and acceleration variations.

\[
\sum_{t=1}^{T} \left( v(t) \right) = \sum_{t=1}^{T} \left( v(t-1) + \Delta t \frac{a(t) + a(t-1)}{2} \right) \tag{1}\n\]

where \( v(0) \) is mean velocity of the swimmer (added as an offset), \( a(t) \) and \( a(t-1) \) are adjacent acceleration values and \( \Delta t \) is the sampling period.

Before integration, the grand mean value of acceleration in each axis was adjusted to zero to prevent the integrated velocity approaching infinity. A linear correction was used to force the start and stop velocity of the mean stroke cycle to be the same. These velocity profiles were subjected to three different computational methods to determine the mean intra-stroke velocity profiles of the swimmers.

Method 1: The magnitude of the y and z axis acceleration \( a_h(t) \) was computed using

\[
a_h(t) = \sqrt{a_y^2(t) + a_z^2(t)} \tag{2}\n\]

where \( a_y(t) \) is the y axis acceleration and \( a_z(t) \) is the z axis acceleration. This vector defines the horizontal acceleration experienced by the swimmer.
Method 2: The acceleration in the z axis (vertical plane) was taken as a gravitational constant (9.8 ms\(^{-2}\)) and was subtracted.

\[ a_h(t) = \sqrt{a_y^2(t) + (a_z - g)^2} \]  

(3)

where \(a_h(t)\) is the horizontal acceleration, \(a_y(t)\) is the y axis acceleration, \(a_z(t)\) is the z axis acceleration and the gravitational acceleration \(g = 9.8 \text{ ms}^{-2}\).

Method 3: The swimmer’s body roll was taken into consideration, as it is unlikely that the gravitational constant will remain at 1g due to the orientation of the swimmer’s body. Madgwick et al [6] generated a novel orientation filter using an Altitude and Heading Reference System (AHRS). When compared to retro-reflective motion capture, a dynamic RMS error less than 1.7 degrees was found [7]. This algorithm was used to find the corresponding body roll angle of the swimmer during a stroke cycle and the horizontal acceleration calculated using

\[ a_h(t) = a_{yz}(t) = \sqrt{a_{yz}^2(t) - (g \cos \theta)^2} \]  

(4)

where \(\theta\) is the angle of body roll calculated using the AHRS algorithm.

The three different computational methods were compared statistically using a one way ANOVA (\(\alpha = 0.05\)) for each swimmer to evaluate the gravitational offset experienced by the IMU sensors and its impact on the calculation of the intra-stroke velocity profile. The cumulative time error (CTE) between method 1 and 2 (CTE\(_{1,2}\)) and method 1 and 3 (CTE\(_{1,3}\)) over one stroke was calculated using the equations

\[ CTE_{1,2} = \frac{\Sigma(v_1(t) - v_2(t))}{\Sigma(abs(v_1(t) - v_2(t)))} \]  

(5)

\[ CTE_{1,3} = \frac{\Sigma(v_1(t) - v_3(t))}{\Sigma(abs(v_1(t) - v_3(t)))} \]  

(6)

where \(v_1(t)\) is the instantaneous velocity of method 1, \(v_2(t)\) is the instantaneous velocity of method 2, and \(v_3(t)\) is the instantaneous velocity of method 3. The CTEs were then multiplied by 100 to get a %CTE. The %CTE was multiplied by the time duration for a single stroke cycle to calculate the relative precision.

II. RESULTS

The three computational methods used to calculate the intra-stroke velocity were compared. Figure 3 shows the mean absolute intra-stroke velocity calculated by the three different methods for one participant during a 50 m freestyle heat. The largest difference between the velocity profiles is 0.02 ms\(^{-1}\) and occurs at the three velocity peaks. The cumulative time error over one stroke is less than 0.046% for freestyle, less than 0.18% for breaststroke and less than 0.42% for backstroke. This translates to a timing underestimate of less than 0.60 ms for freestyle (stroke time 1.26 s), an underestimate of less than 4.0 ms for breaststroke (stroke time 1.81 s) and an overestimate of 6.2 ms for backstroke (stroke time 1.49 s).

IV. DISCUSSION

The purpose of this research was to compare three different computational methods of determining intra-stroke velocity from the same IMU data and to quantify the effect of gravitational acceleration when calculating instantaneous, intra-stroke velocity. Method 1 ignored the gravitational offset, Method 2 considered the gravitational offset to be 1g and Method 3 computed the gravitational offset dependent on the instantaneous body roll of the swimmer.

Qualitatively, it is evident that there is a minor difference between the mean velocity calculated by all three methods. The results were similar for breaststroke and backstroke. For freestyle and backstroke, Methods 2 and 3 which incorporate the gravitational offset appear almost identical, whereas Method 1 results in a slight underestimate of the intra-stroke velocity, particularly at the times of velocity maximum. The variation in the mediolateral tilt angle is so small as to be insignificant in this case and equations (2) and (3) give very accurate velocity profiles without the use of the AHRS technique.
when including the gravitational offset, the mean intra-stroke velocity calculated for freestyle and breaststroke is slightly higher than when it is ignored.

V CONCLUSION

The use of a single IMU on the lower spine (sacrum) can be used to accurately and reproducibly derive the intra-stroke variations in swimming. The simplest method (method 1) is just as accurate as the other two methods and therefore is recommended.

![Fig 4. Intra-stroke velocity profile (Breaststroke) $a_0(t)$ calculated using three different computational methods blue = Method 1, red = Method 2 and yellow = Method 3. (The lines are almost coincident).](image)

The use of a single IMU on the lower spine (sacrum) can be used to accurately and reproducibly derive the intra-stroke variations in swimming. The simplest method (method 1) is just as accurate as the other two methods and therefore is recommended. The roll angle and $a_0$ data are not required and no data filters were used.

The variation in velocity within each stroke allows the swimmer and the coach to quantify stroke-by-stroke variations caused by the effects of fatigue, loss of concentration and perhaps water movements from adjacent swimmers. The consistent acceleration variations in each stroke (see Fig. 2) cannot be attributed to sensor “drift”, but rather indicate biomechanical processes.

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REFERENCES


