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# Swimming velocity analysis using wearable inertial sensors and speedometer: a comparative study

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KEY WORDS: BIOMECHANICS, SWIMMING, TRAINING, PERFORMANCE, BREASTSTROKE, SPEEDOMETER, INERTIAL SENSORS

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## Abstract

The speedometer is a device widely used to evaluate the speed of swimming. However, its use is dependent on some constraints, such as the possibility of evaluations only in one sense of swimming with limited distance, impossibility of analysing turns and only allowing to evaluate one athlete at a time. With the appearance and constant development of inertial units (IMUs), it is expected that these can be an alternative to the speedometer. In this sense, a study was carried out with the objective of comparing the IMU data with the data provided by a speedometer during the prone swim. Sixteen swimmers, nine males (20.3 ± 3.3 years old; 65.8 ± 11.2 kg of body mass; 1.75 ± 0.07 m of height) and seven females (18.7 ± 1.1 years old; 57.7 ± 9.1 kg of body mass; 1.61 ± 0.10 m of height) performed 4 x 25 m breaststroke at maximum speed. The participants were equipped with an IMU (GT9XActiGraph Link, Florida, USA) composed of a 3D accelerometer and a 3D gyroscope fixed to the swimmer in the sacrum and properly sealed. At the same time, an electromechanical speedometer was used, fixing the line at a central point in the swimmer's lumbar region.

From a qualitative curve-profile interpretation it there was an agreement in the shape of the curves, there were differences ($p<0.001$) regarding the magnitude of velocity with lower values measured by the IMU. Both IVV and CV were different ($p < 0.01$) when extracted from both methods. There was a consistent distribution of data points between the limits of agreement (~96-97% placed inside the confidence bounds) but with a large bias detected. It can be concluded that, although the velocity curves acquired from both devices have the same profile, there is an underestimation of velocity and the distance retrieved by the IMU. Both devices showed a higher degree of agreement, but it remains a larger bias that compromise comparison.



KEY-WORDS: BIOMECHANICS, SWIMMING, TRAINING, PERFORMANCE, BREASTSTROKE, SPEEDOMETER, INERTIAL SENSORS

# Resumo

O velocímetro é um aparelho muito utilizado para avaliar a velocidade de nado. No entanto, a sua utilização está dependente de alguns constrangimentos, como a possibilidade de avaliações apenas num sentido de nado com distância limitada, impossibilidade de analisar viragens e apenas permitir avaliar um atleta de cada vez. Com o aparecimento e constante desenvolvimento das unidades inerciais (IMUs), espera-se que estas possam ser uma alternativa ao velocímetro. Neste sentido, foi realizado um estudo com o objetivo de comparar os dados da IMU com os dados fornecidos por um velocímetro durante o nado de bruços. Dezasseis nadadores, nove do sexo masculino (20,3 ± 3,3 anos de idade; 65,8 ± 11,2 kg de massa corporal; 1,75 ± 0,07 m de altura) e sete do sexo feminino (18,7 ± 1,1 anos de idade; 57,7 ± 9,1 kg de massa corporal; 1,61 ± 0,10 m de altura) realizaram 4 x 25 m bruços à máxima velocidade. Os participantes foram equipados com uma IMU (GT9XActiGraph Link, Florida, EUA) composta por um acelerómetro 3D e um giroscópio 3D fixada ao nadador no sacro e devidamente selada. Ao mesmo tempo foi usado um velocímetro eletromecânico fixando a linha num ponto central da região lombar do nadador.
A partir de uma interpretação qualitativa do perfil da curva houve concordância na forma das curvas, houve diferenças ($p<0,001$) quanto à magnitude da velocidade com menores valores medidos pela IMU. Tanto a variação intra cíclica da velocidade quanto o coeficiente de variação foram diferentes ($p < 0,01$) quando extraídos de ambos os métodos. Houve uma distribuição consistente dos pontos de dados entre os limites de concordância (~96-97% colocados dentro dos limites de confiança), mas com um grande viés detetado. Pode-se concluir que, embora as curvas de velocidade adquiridas de ambos os dispositivos tenham o mesmo perfil, há uma subestimação da velocidade e da distância adquirida através da IMU. Ambos os dispositivos mostraram um elevado grau de concordância, mas apresentando um viés que compromete a comparação.
PALAVRAS-CHAVE: BIOMECÂNICA, NATAÇÃO, TREINO, RENDIMENTO, BRUÇOS, VELOCÍMETRO, UNIDADES INERCIAIS

# Abbreviations

**IMU –** Inertial Measurement Unity

**IVV –** Intracycle Velocity Variation

**CV –** Variation Coefficient

**AI** – Artificial Intelligence

# 1. Introduction

The competitive swimmer wants to travel a given distance as fast as possible. Swimming speed is characterised by the intermittent application of propulsive force to overcome the water resistance (Figueiredo, Barbosa, et al., 2012). The movement of the body in the water, it's not uniform and results from the propulsive forces achieved through the actions of the lower limbs, upper limbs, and trunk, which suggests an intracycle variation of speed (Barbosa et al., 2010; Vilas-Boas et al., 2010). This variation in the swimmer's velocity during each stroke cycle is commonly called intracycle velocity variation (IVV) (Figueiredo, Kjendlie, et al., 2012; Vilas-Boas et al., 2011). So, at some point, the evaluation of the IVV can be used as a tool for evaluating the swimmer's technique (Fernandes et al., 2012).

Over the years, several studies on IVV have been conducted (Barbosa, Costa, et al., 2013; Colman et al., 1998; Fernandes, Goethel, et al., 2022; Leblanc et al., 2007). It seems obvious that to be effective in swimming, all parts of the swimmers' body must work simultaneously and in coordination. But, it is difficult for swimmers to notice their mistakes, because they cannot observe themselves, what makes external feedback essential (Ödek & Özcan, 2023). Swimming coaches give feedback to their athletes based on what they observe and on what they can do through verbal descriptions or even demonstrations (Pérez et al., 2009; Williams & Ford, 2009). However, regardless of how it is given, this feedback may not be precise in terms of the biomechanical factors that facilitate or condition performance, since they are not always easily observable and easy to explain without images or data. In fact, elite coaches consider biomechanics as one of the most important domains to be assessed and can easily be improved through training (Mooney et al., 2016). In this sense, coaches are constantly tracking their swimmers, using the available methods to analyse their performance and define enhancement strategies.

In elite swimmers, a broad range of methods are used to access performance, monitor athletic performance, and inform coaches practices (Mooney et al., 2016). To access swimming velocity or to define and analyse the displacement patterns of swimmers, and the accelerations resulting from propulsive actions, and the decelerations caused by the aquatic environment and the shape and actions of the swimmer's body, various resources can be used: (i) video cameras, using two-dimensional (2D) and three-dimensional (3D) kinematics, with and without markers (Colman et al., 1998; Fernandes, Goethel, et al., 2022; Figueiredo, Barbosa, et al., 2012; Gonjo et al., 2018; Gourgoulis et al., 2013; Gourgoulis et al., 2008; Psycharakis et al., 2010); (ii) speedometer (Barbosa et al., 2017; Barbosa et al., 2014; Barbosa, Morouço, et al., 2013; Craig et al., 1988; Feitosa et al., 2013; Leblanc et al., 2007; Miyashita, 1971; Morais et al., 2013; Neiva et al., 2021), (iii) GPS (Beanland et al., 2014); (iv) radar (Kolmogorov et al., 2021); (v) marker tracking (Chainok et al., 2022); (vi) infrared (Domingues et al., 2021), and; (vii) accelerometers or inertial measurements units (IMUs) (Bachlin, 2012; Clément et al., 2021; Dadashi et al., 2016; Engel et al., 2021a; Ganzevles et al., 2017; Magalhães et al., 2015; Ohgi et al., 2002; Ohgi et al., 2000; Stamm, James, & Thiel, 2013).

All of these methods have advantages and disadvantages; some require more equipment, others less. And, some are more time consuming than other in processing the information. Video analyses requires a huge computational (off-line) effort, favouring a delay in providing quantitative information (Magalhães et al., 2015) and, on a regular basis, the coaches want a more friendly-user system, in order to provide valid and fast results. Another very popular device for assessing the velocity of swimmers is the speedometer. Speedometer is a device that was widely used by various researchers over the years (Barbosa, Morouço, et al., 2013; Craig & Pendergast, 1979; Feitosa et al., 2013; Morais et al., 2013; Neiva et al., 2021; Soares et al., 2014) and as passed successive validations over time. But, like the video systems, the speedometer also has its own constraints, because the cable measures up to 50 meters, not allows the swimmer to perform any turns, and measures just one swimmer at a time taking up a full swimming lane for testing. In addition to these limitations, there is also the problem of the measurement angle because of the cable position in relation to the swimmer's displacement. Gonjo et al. (2020) suggested an equation ($V_{adj}$=V.cos [$\sin^{-1}$(1.00/Lw)] to obtain the horizontal velocity component since the cord used for the velocity measurement is not aligned with the swimming direction, causing a little bias in data acquisition.

Within this background, the use of IMUs has become a relevant solution for quantitative human movement and performance analysis (Magalhães et al., 2015). IMUs are devices that incorporate accelerometers to measure accelerations, gyroscopes that measure angular velocity and magnetometers to measure the magnetic field or magnetic dipole moment. IMUs have been already used to study swimming and seem to provide a reliable solution for extracting kinetic and kinematic features. According to Félix et al. (2019), recent developments concerning the dimensions, reliability and price of IMUs have made this equipment a reliable option for the evaluation of swimmers, providing fast and easy to use information on detailed performance-related metrics. Still, there are few constraints related to the aquatic environment, that may impair the IMU's data transmission and further treatment. Although few studies used IMUs in swimming research, this is a recent topic that could be further explored (Davey et al., 2008; Magalhães et al., 2015). Nevertheless the use and application of accelerometers is becoming popular in the biomechanical quantification of health and sports activity (Davey et al., 2008).

With this work, our goal was to understand if inertial sensors can be useful tools to replace speedometers and overcome its limitations while assessing swimming velocity.

This study aims to compare inertial sensors data with data provided by a speedometer during breaststroke swimming. For this purpose, we compared the magnitude of the velocity values obtained by the swimmers provided by a speedometer and by an IMU and verify if the patterns of the successive cycles are identical, as well as the velocity variations in each cycle, the mean velocity and the distance covered. It was hypothesized that IMU measurements will show a high level of agreement with those extracted from the speedometer.

# 2. Literature review

## 2.1 Intracycle velocity variation

To Vilas-Boas (1993), the swimmer's velocity variation, per swimming cycle, happens according to the accelerations and decelerations resulting from propulsive and resistive actions. Changing the shape of the body must be taken into account once combinations of motion, shape and flow type are determinants of the amount of propulsion and drag (Ungerechts, 1988). The fact that the swimmer's movement, resulting from his propulsive actions and the drag forces he suffers from the environment, it is not uniform, suggests the intracycle variation of velocity as a relevant performance determining factor (Barbosa et al., 2010; Vilas-Boas et al., 2010). So, IVV refers to variation in the swimmer's body speed, resulting from the forces acting during each swim cycle (Figueiredo, Kjendlie, et al., 2012; Vilas-Boas et al., 2011).

When the swimmer's speed is not constant, this means that the swimmer will have to expend an extra amount of energy to counteract the inertial forces, which will impact energy expenditure and swimming performance (Vilas-Boas, 1996). As mentioned by Alves (1996), an economical swimmer will be the one who spends less energy for submaximal swimming speeds and is able to have a higher maximum swimming speed.

Considering the different swimming techniques, propulsive pattern of breaststroke is different from other swimming techniques (Nicol et al., 2021). The stroke cycle is divided into two phases, pull and kick, with each phase divided into propulsion, recovery, and glide (Takagi et al., 2004), even at high swimming speeds, the glide is practically imperceptible or even non-existent.

To Leblanc et al. (2007), the time-velocity profile of breaststroke swimming is associated with two maximums and two minimums. The first acceleration phase and the first maximum are associated with the arm propulsion phase, after which there is a deceleration phase and a first minimum of speed that occurs during the arm and leg recovery phases (Leblanc et al., 2007). When the leg propulsion phase begins, the velocity increases again reaching its second maximum, which is followed by a second deceleration phase and a minimum that is associated with the in-sweep and glide phases of the leg (Leblanc et al., 2007). From the analysis of the swimmer`s body segment using Newton`s second law of motion (Bao et al., 2022), or with the application of computational fluid dynamics models (Barbosa et al., 2010) we can better understand how to generate the greatest possible propulsion, avoid water resistance and increasing swimming efficiency. In this regard, it will be important that coaches work with sports science professionals to be able to apply scientific methods in their training to help them collect more detailed information (Callaway, 2015).

## 2.2 Methods to access intracycle velocity variation

### 2.2.1 Video analysis

Video analysis are traditionally used by coaches to acquire reliable biomechanical swimming performance data (Chainok et al., 2022; Daukantas et al., 2008; Fernandes, Mezêncio, et al., 2022; McCabe et al., 2011; McCabe & Sanders, 2012; Rudnik et al., 2022; Soncin et al., 2021; Vezos et al., 2007) and are the most commonly data collection tool (Mooney et al., 2016), being accepted as the gold-standard method for examining an athlete's technique (Pansiot et al., 2010). So, over the years, during swimming analysis, patterns of motion were observed, and coaches tried to figure out the best stroke techniques. Cameras played a key role in the analysis of swimmers' performances, involving either 2D or 3D approaches (Psycharakis et al., 2010). Over the years, several studies have been conducted using 2D and 3D kinematics (Psycharakis et al., 2010; Samson et al., 2015; Sanders, 2007; Smith et al., 2002). The most popular technique to transform 2D image coordinates in 3D space coordinates is the direct linear transformation (DLT) (Chen et al., 1994; Wood & Marshall, 1986). In the DLT, an appropriate number of points with known 3D coordinates is used, in a calibration structure, for calibration of the performance space. In 2013, Silvatti et al., conducted a study to investigate the applicability of underwater 3D motion capture based on submerged cameras in terms of 3D accuracy. In the study, the authors concluded that, 3D video-based motion analysis, based on submerged cameras, is to be considered appropriate to aquatic applications. The results of wand and 2D plate camera calibration approaches provided similar and highly accurate results, leading to the application of the two alternative calibration methods for high accurate 3D underwater motion analysis. 3D video-based is the most used technique for motion analysis of swimmer's hand (Ceseracciu et al., 2011; Samson et al., 2015) and for stroke phase detections (Psycharakis et al., 2010), but the complexity of the process of data acquisition (Ceccon et al., 2013), sometimes force the coach to prefer 2D video-analysis (Mooney et al., 2016).

In Synthesis, video-base motion analyse systems are used to capture the human movements, use computers to process and analyse data (Silvatti et al., 2013), and seems to be the preferred method for extracting quantitative information like temporal (lap time, start time, rotation time, wall contact time) and kinematic (stroke length, stroke rate, swim velocity, acceleration) categories in swimming (Smith et al., 2002). In the same line, Callaway and Cobb (2012) refers that video based analysis of swimming performance allows calculation of variables like stroke rate and stroke length and the assessment of swimmers general technical characteristics.

Although the importance of recording and evaluation of speed, among others, is recognized, the aquatic environment still presents many difficulties in data collection (Dadashi et al., 2012). In underwater conditions, there are a number of specific technical issues related to the camera, the camera calibration protocol and methodology, and the control of movement capture data (Silvatti et al., 2013). Data processing is very time-consuming (Magalhães et al., 2015) and the water environment negatively affects the signal accuracy (Cortesi et al., 2014; Gourgoulis et al., 2008). To overcome the constraints of the aquatic environment over the years, technical solutions have been proposed, such as periscope systems, underwater windows, and underwater cameras (Gourgoulis et al., 2013; Pease, 1999; Yanai et al., 1996). Many periscope systems use two parallel mirrors, one above the water level and one below, reflecting the images of their media, which are captured by a camera, in a single image (Yanai et al., 1996). The use of underwater windows requires special features in the construction of swimming pools and although useful, restrict the protocols, because they are a physical condition that cannot be changed. In addition to the constraints that the aquatic environment places on the investigation such as parallax errors, hidden or obscured body segments, and water turbulence (Callaway et al., 2009; R. Mooney et al., 2015), the digitization of markers and body segments, as well as data analysis is a process that takes long time, making this method difficult to match the needs of trainers to provide immediate feedback (Payton, 2008; Phillips et al., 2013), limiting its application in practice (Mooney et al., 2016).

### 2.2.2 Speedometer

The speedometer is a popular method with the first uses in the late 70s (Craig & Pendergast, 1979). In 1988, (Craig et al.) conducted a study using the same method described by Craig and Pendergast (1979) about patterns of velocity in competitive breaststroke swimming. In 2005 (Lima) conducted a study to develop, validate and evaluate a biofeedback system for training the breaststroke technique, with the aim of studying the intracycle variation of the velocity of a fixed point of the swimmer (hip). Other validations of this system continued to be carried out, as it is the case of Feitosa et al. (2013) that tried to validate a speedometer for the analysis of speed in backstroke and butterfly. Their results showed that the speedo-meter system met all the validation criteria tested. The same kind of results were shared by Capitão et al. (2006) with a speedometer used to accessed velocity in breaststroke and by Morouço et al. (2006), in butterfly. The speedometer continues to be used by several researchers (Barbosa et al., 2021; Barbosa et al., 2017; Barbosa, Morouço, et al., 2013; Soares et al., 2014). However, speedometer measurements are limited to the length of the device's wire and swimming in only one direction. And as it only allows one athlete to be assessed at a time and takes up one lane, it creates space constraints and a lot of time, which limits its use by coaches.

### 2.2.3 Inertial measurement Units (IMU)

The devices and sensors are becoming more readily available for athletes and provide increasingly valid results (Camomilla et al., 2018; Seshadri et al., 2017). This way, it has been proposed the use of inertial measurement units (IMUs), that are becoming a relevant solution for monitoring and performance analysis. IMUs are used not only in sports but even in other different areas, like clinical and ergonomics (Camomilla et al., 2018), automotive and aerospace industry. IMUs have been used to study swimming (James et al., 2004; Ohgi et al., 2002) and seem to provide a credible solution for extracting Kinetic and kinematic features.

According to Félix et al. (2019), recent developments concerning the dimensions, reliability and price of IMUs have made this equipment a credible option for the evaluation of swimmers, providing fast and easy to use information on detailed performance-related metrics. In this sense, IMUs worn by the athletes have been proposed as an alternative tool for in-field sports performance analysis to overcome the limitations of video-based methods. The application of IMUs in sport is a new trend of sport biomechanics (Ayrulu-Erdem & Barshan, 2011; Marsland et al., 2012). Lecoutere and Puers (2014) have created an inertial sensor system consisting of a gyroscope and accelerometer, with the aim of measuring basic parameters such as split time, stroke frequency, breathing patterns and stroke distance and these devices can be placed on various parts of the body to access data. Inertial sensors are an easy-to-use system with short set up time that can be used openly by coaches in swimming pool and can be placed on different sites on swimmers body (Dadashi et al., 2011). IMUs, in addition to being small, perform short-term analyses, do not require complex calibrations, can be used easily and can analyse and monitor all swimming test continuously without specified spatial limitation, a typical feature of video analysis (Cortesi et al., 2019). IMUs allow continuous data acquisition throughout swimming, require only a simple measurement configuration, and have the potential to provide trainers with performance parameters at the end of each test during training sessions (Fantozzi et al., 2016). According to Davey et al. (2008) sensors with accelerometers and gyroscopes tend to offer greater flexibility in data processing methods, in comparison to video based methods, require less personnel and technical resources. In sports, and particularly in swimming IMUs can provide valuable information about swimming phases, as well as during underwater and turn phases (Guignard et al., 2017; Magalhães et al., 2015; Robert Mooney et al., 2015). Rad et al. (2021) showed that a single sacrum inertial sensor can provide a wide range of performance-related swimming kinematic variables. Through the tri-axial accelerometer of the IMUs is possible to provide, in real time, stroke rate (SR), stroke count (SC) and lap times (LT) (Davey et al., 2008; Ganzevles et al., 2017; Magalhães et al., 2015). But while there may seem to be advantages to using inertial sensors, not everything is an advantage and water still poses a challenge to data collection. Although waterproof inertials begin to appear, many of the inertials used in swimming studies must be placed in watertight boxes or must be insulated. The number of IMUs placed on the swimmer may have effects on drag level and the swimmer's swimming speed may have an effect on IMU accuracy, as verified by Pla et al. (2021). To Pla et al. (2021) the inertial seems to be a good tool to support the trainer in the analysis of kinematic variables, but in their study they revealed problems in short and high intensity intervals of swimming. Swimming speed was relevant to acquisition of information.

Also, the instantaneous velocity profile can be obtained, but not easily, due to orientation problem of the sensors (Dadashi et al., 2012; Stamm & Thiel, 2015; Stamm et al., 2011). In the study of Stamm et al. (2011), the researchers noted that speed information can be derived from acceleration data, but there is still a difference compared to the SP5000 speed. In the opinion of the researchers, it will be necessary to find better approaches in removing the orientation of the sensor. Many other studies used IMUs to extract kinematic variables showed that these devices are a powerful tool for swimming analysis (F. Dadashi et al., 2013; Stamm, James, Burkett, et al., 2013).

Although Holmer (1979) has already used accelerometry in swimming, with a uniaxial accelerometer, the first study with the use of IMUs in swimming was conducted by Ohgi et al. (2000), and, in this, authors proposed a new methodology to analyse and evaluate swimmer's stroke technique using micro accelerometer. With the micro accelerometer, they had measured tri-axes wrist accelerations in freestyle swimming on Japanese top level college swimmers. Authors concluded that wrist accelerations have some useful information about underwater stroke phase and swimmer's skill level. Since then, some validation studies have been carried out (Dadashi et al., 2012; Davey et al., 2008; Stamm, James, & Thiel, 2013). Lee et al. (2010) carried out a study with the aim of determining the level of agreement between an inertial sensor and infrared camera-based estimates of stride, step and stance durations. Protocol crossed a range of running speeds and authors concluded that inertial sensors are suitable to measure stride, step, and stance duration, and provide the opportunity to measure running gait outside of the traditional laboratory. IMUs are considered swimmer-centric and do not require a complex measurement set-up in the swimming pool (Pansiot et al., 2010). Over time, the devices have become smaller with lower energy consumption and can be placed in different body positions on the swimmer (Magalhães et al., 2015). According to Lee et al. (2012), the use of data from inertial sensors has proven to be a valuable addition to video for the analysis of the swimming technique. Sensors and devices capable of monitoring performance are becoming more available and allow to quantify performance more accurately (Camomilla et al., 2018; Seshadri et al., 2017). In the same line, Magalhães et al. (2015) referred that the use of IMUs has been shown to be an overall effective tool for monitoring human movement patterns and an increasing range of inertial sensors, and protocols have been proposed for swimming performance assessment. Also using IMUs, supported by video, Cortesi et al. (2019) proposed and validated an algorithm for automatic complete stroke phase detection based on the 3D wrist trajectory using IMUs. According to that, many electrical devices have been developed to support the training of an athlete (Bachlin, 2012).

With a research focused on development of easy to use sensor capable to provide useful information for swimmer, directly in the pool at the time of routine training, Daukantas et al. (2008) showed that accelerometer without fusion with other sensors could be used successfully in swimming sport for timing application and measurement of time durations of intervals, periods and phases. To use sensors in the water, is important to provide that they are hermetic sealed, and to be present that their size and positioning can potentially affect the drag of the swimmer (Magalhães et al., 2015). It is very important that IMUs position does not increase the drag force (Bächlin et al., 2009; Davey, 2004), does not bother or influence the action of the swimmer (Davey, 2004), and does not limit the swimmer`s free motion (Bachlin, 2012). The results obtained by a study of Davey et al. (2008), showed that the measurements obtained through the use of accelerometer are identical or more accurate when compared to the records obtained manually by the coach. This can reduce the need for the coach to use timing, to know the lap times, freeing him up for tasks of observation and correction of the technique. Delhaye et al. (2022) tried to develop a deep learning AI (artificial intelligence) model devoted to analysis of swimming using a single IMU attached to the sacrum. With this single IMU they tried to classified swimming activities at several swimming velocities and to assess the performance of the model in automatically calculating lap times during the exercise. The authors (Delhaye et al., 2022) considered that the use of this model may be of great value for elite swimmers and coaches because the model can be promising for a wide range of applications and many key performance variables in swimming can be derived from the swimmers activity. For example, although time spent underwater and turning time are little investigated by coaches, represent up one third of the final performance (Morais et al., 2019). Still according to the study by Delhaye et al. (2022), using a single IMU, lap time results highlight minimal loss compared to stopwatch measurement, which may be relevant to coaches who can automatically monitor multiple swimmers at the same time. Callaway (2015) held a study with the aim to demonstrate the validity and reliability of accelerometers in their ability to identify the swimmers lap time, velocity, stroke duration, stroke rate and identifying the phases of the stroke. In this study, with multiple sensor system, the authors reported that it was demonstrated the capabilities of multiple sensor systems in processing multiple variables simultaneously on a swimmer. In their opinion, although multiple sensor systems may become the future of monitoring in sport, it is necessary to require further development in terms of usability, output data visualization and ease of synchronization. Using inertial sensors Le Sage et al. (2011) aimed to characterise the swimming strokes in real time. The results proved to be a system that allows a faster processing of the acquired data and proved to be valid for the acquisition of information in the aquatic environment. Also Dadashi et al. (2011) tried to describe arm coordination using 3D accelerometer and 3D gyroscope data to discriminate the propulsive and non-propulsive phases of the arm, and confirmed their hypothesis that inertial sensors can be used for automatic temporal phase detection during swimming.

IMUs were usually used to estimate temporal and kinematic variables, as well as for estimating stroke phases and stroke type and frequency (Hamidi Rad et al., 2021; Magalhães et al., 2015). Results of the studies aiming to identify temporal variables are consistent with the results of video-analysis studies (Callaway et al., 2009; Davey et al., 2008; Slawson et al., 2011). In a study of Lecoutere and Puers (2014), the four separate strokes, wall turns and breathing patterns were clearly distinguishable. However, although this previous evidence of the usefulness of IMUs in defining swimming patterns and to estimate temporal variables, there are few studies (Dadashi et al., 2016; Engel et al., 2021b) evaluating the variation of intracycle velocity using IMUs.

# 3. Material and Methods

## 3.1 Sample

Sixteen swimmers, nine males (20.3 ± 3.3 years old; 65.8 ± 11.2 kg of body mass; 1.75 ± 0.07 m of height) and seven females (18.7 ± 1.1 years old; 57.7 ± 9.1 kg of body mass; 1.61 ± 0.10 m of height) participated in this study. Inclusion criteria were defined as follows: (i) have a minimum competitive experience of three years; (ii) minimum classification of level two according to suggestions McKay et al. (2022); (iii) specialization in the breaststroke technique; (iv) have no injury in the six months prior to the time of data collection. Those were swimmers participating in 6.4 ± 2.6 training session per week, with a volume of 4100 ± 1300 m per session. The performance level of the swimmers was 386 ± 86 points in the 100m breaststroke event according with the World Aquatics Point Scoring. The study was conducted according to the Helsinki Declaration, and swimmers (or legal guardians) signed a written informed consent.

### 3.2 Study Design

The experimental setup was set on a short course indoor swimming pool with water at 25°C, 23°C air temperature and 60% humidity. The participants were initially tested for anthropometric measures using only their textile swimming suit and a cap. They were tested for body weight and body height for further body mass index computation. Then, they were asked to perform a standard warm-up composed by 100 m freestyle and 100 m in the breaststroke technique at light intensity, four repetitions of 50 m in the prone technique with increased intensity.

For the in-water testing, the swimmers randomly assigned to performed 4 x 25m breaststroke at maximal intensity with at least 2 min of rest interval between trials. The test began with the swimmers in the water pushing off the wall after an auditory signal.

The participants were instrumented with one IMU (GT9XActiGraph Link, Florida, USA) composed of a 3D accelerometer and 3D gyroscope. Accelerometer and gyroscope data were sampled at the same frequency (100 Hz) using a full scale set at ± 8 g and ± 2000 deg.$s^{-1}$, respectively.

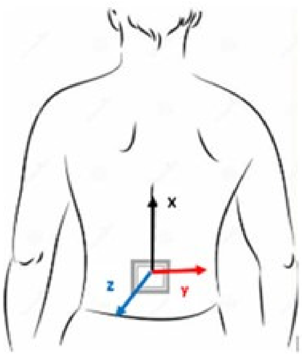


*Figure 1. Inertial sensor position and axis orientation.*

The IMU was attached to the swimmer at the Sacrum (Figure. 1) and waterproof by being inserted and sealed in a condom. The IMU was carefully positioned that the X axis measured the forward acceleration, the Y axis the side-to-side acceleration and the Z axis the vertical acceleration of the swimmer. Swimmers were also connected to an electromechanical speedometer (Figure 2), measuring the rotational velocity of a pulley over which a fine nylon line passes. The line was attached to the swimmer at a central point of the lumbar region, and the pulley was coupled to an incremental rotation sensor generating 500 impulses per full rotation (registered using in house developed acquisition software).

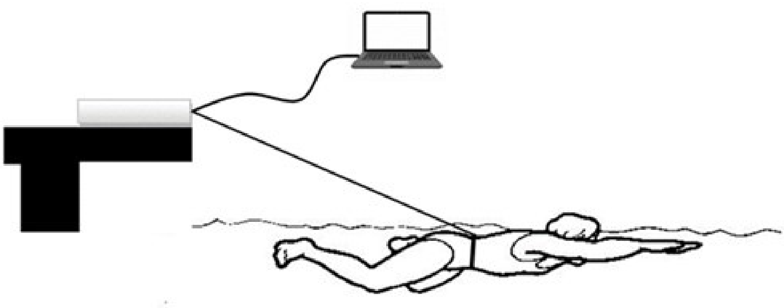

*Figure 2. Swimmer connected to the speedometer and computer that receives the data.*

Two moving video cameras (GoPro Hero 6, San Mateo, CA, USA) were placed on a sagittal plane 7 m far away from the swimmer, one above the water surface (50 m) and other underwater (26 m).

A speedometer was also used for instantaneous velocity measurement. The device has an acquisition frequency of 50 Hz and was created and validated by Lima et al. (2006). The device was placed on the starting block, attached to a strap placed around the swimmer's waist. In this case, the fixed point chosen is a point near the centre of mass. Some authors, such as Maglischo (1987) and Costill D. (1987), consider that this point on the trunk may be satisfactory for the representation of the centre of mass position. Recent studies have used this same position of fixing the speedometer cable (Barbosa et al., 2021; Barbosa et al., 2017).

### 3.3 Data collection

To extract data from IMUs, several frequencies were tested for data filtering, namely 0.50 Hz; 0.75; 1Hz and 2 Hz. At the lowest frequency there were events that did not appear and at the highest, the curve was mischaracterized. By analysing the speed curves, we assumed the cutoff frequency 1Hz as the one that best represented the swimmer's actions.  The speedometer output data was exported to two Microsoft Excel columns, and a speed-time line graph was subsequently constructed for each repetition.

Although the intracycle velocity variation of the centre of mass has been analysed through the coefficient of variation (CV) or through the differences between maximum and minimum speeds in swimming, both methods show limitations. While CV method can provide overall information about IVV, it cannot show maximum and minimum amplitudes, meaning that IVV might be underestimated when the mean speed is high (Gonjo et al., 2019). The difference between max-min values shows the maximum amplitude, but cannot present the overall IVV during a stroke cycle (Gonjo et al., 2019). For this study, the analysis of the velocity variations during the swimming cycle in breaststroke was made using the CV by his formula (SD/mean) and IVV by the equation (1):

$$IVV = \frac{vmax,LL - vmin,LL + vmax,UL - vmax,T}{vmean} \quad (1)$$

where the vmax,LL (in m/s) is the maximum centre of mass's velocity (achieved at the end of lower limb propulsion); vmin,LL (in m/s) is the first minimum peak of the centre of mass's velocity following upper and lower limbs recovery (the beginning of lower limb propulsion); vmax,UL (in m/s) as the maximum centre of mass's velocity at the end of the upper limb propulsion; and vmin,T (in m/s) as the minimum centre of mass's velocity during the transition between upper and lower limb propulsion. v is the mean swimming velocity of the center of mass during a cycle (m/s).

It was also considered the transformed Strukhal number used as an index of speed variation by Vilas-Boas (1993) but although it is built in reverse $(Sh=DC*[(V2-V1+V4-V3)*T]^{-1}$, the logic of calculation is the same!

### 3.4 Statistical Analysis

The Statistical Parametric Mapping (SPM) based on t-test independent analyses were done using the SPM1D package (version 0.4.3, https://spm1d.org/) on the bespoken MATLAB with α = 0.05, to compare the velocity curves profile obtained by the speedometer and the IMU. Descriptive Statistics were analysed using IBM SPSS (version 28.0). The Bland–Altman plot (Bland & Altman, 2010) was applied using BA Plotter (Goedhart & Rishniw, 2021) according to the guidelines (Giavarina, 2015) to quantify the agreement between 2 quantitative measurements by determining the bias (or mean difference) as a measure of accuracy and limits of agreement as a measure of precision. The mean of the 2 measurements was plotted against the difference between them with 95% of the differences expected to lie within the limits of agreement (mean [1.96 SD]) and respective 95% confidence interval (CI). The CI of the bias illustrates the magnitude of the systematic error, while the CIs of the limits of agreements provide an estimation of the extent of the possible sampling error (Bland & Altman, 2010; Giavarina, 2015). Used Prisma

GraphPad Prism 10 for analysis of the slope of the regression line using between the two analysis systems (to check for proportional error).

## 4. Results

Next, we will present the average velocity results of one swim cycle (Figures 3 and 4) and the first eight breaststroke cycles after the swimmer's head breaks the water surface (Figures 5 and 6), obtained both for males and females, with speedometer and IMU. The beginning of each cycle was considered at the lowest point of velocity, that is, immediately before the propulsive action of the lower limbs. From a qualitative curve-profile interpretation it seems to exist an agreement in the shape of the curves, in the average of a single swim cycle or the set of cycles. However, there were differences regarding the magnitude of the velocity values measured by the two instruments. The speedometer values showed to be higher than the values measured with the IMU for either the lower limbs action and upper limbs action.

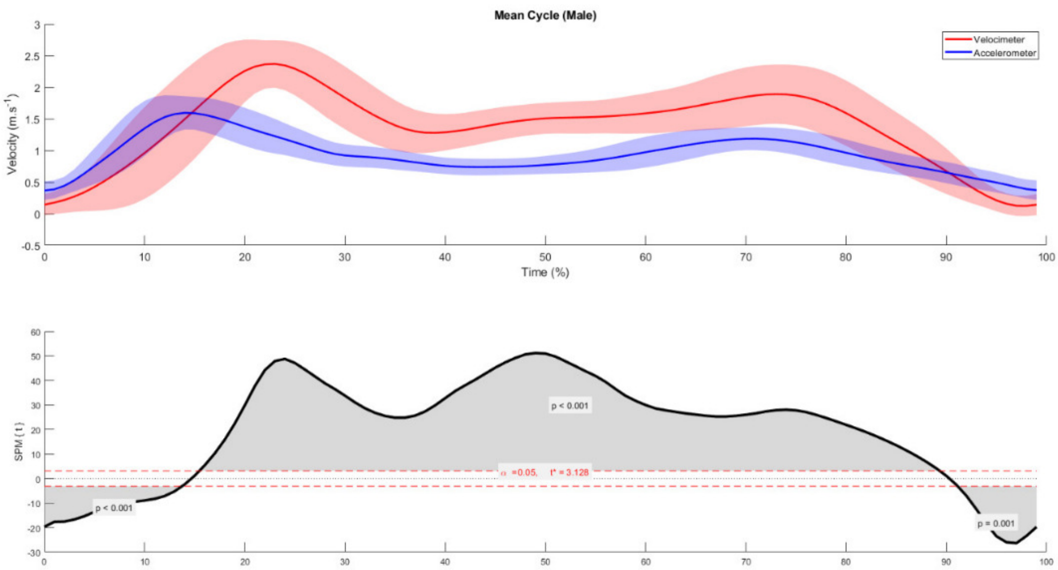


*Figure 3. Average male breaststroke cycle and respective SPM for comparison of measurements.*

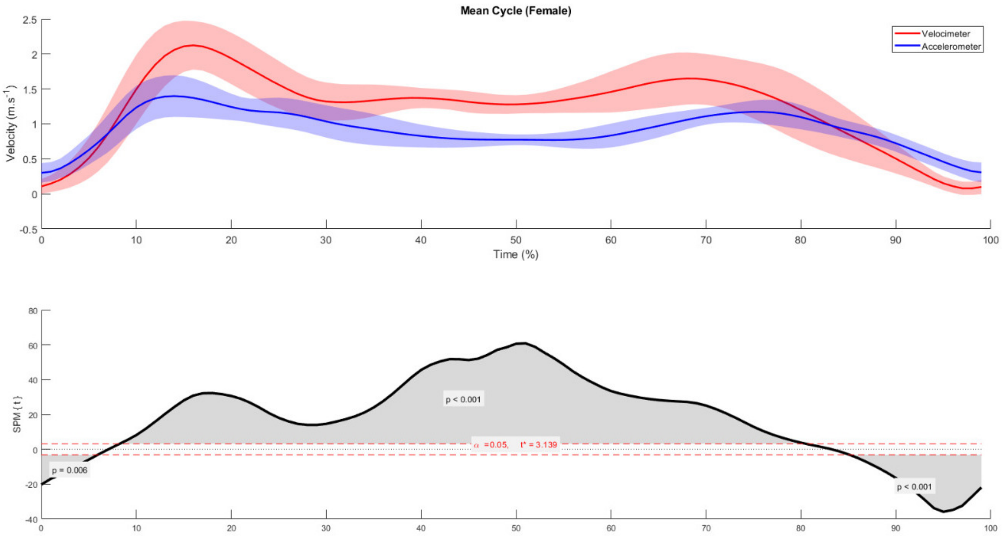


*Figure 4. Average female breaststroke cycle and respective SPM for comparison of measurements.*

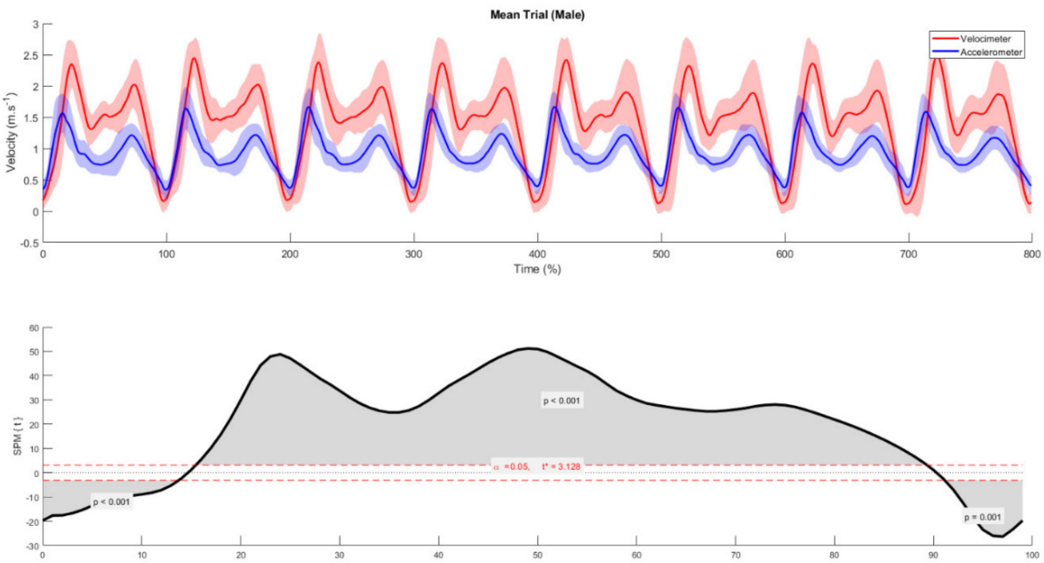


*Figure 5. Set of eight average breaststroke swimming cycles (male) and respective SPM to compare measurements.*

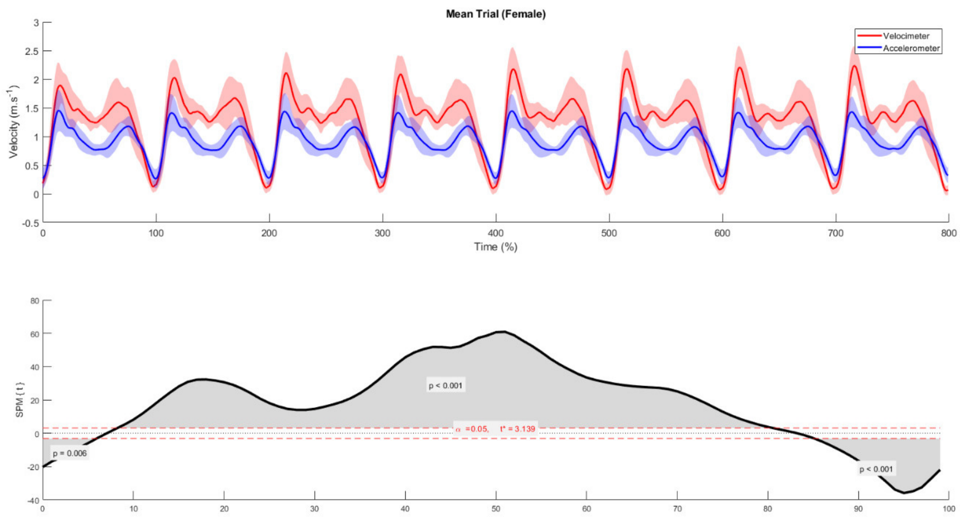


*Figure 6. Set of eight average breaststroke swimming cycles (male) and respective SPM to compare measurements.*

The distance covered by the swimmers with each of the devices was also estimated (Table 1). In both cases there was a different distance regarding the pool length, as the speedometer tended to overestimate and the IMU underestimate the real value (i.e. 25m).

*Table 1. Mean and standard deviation of distance (m) covered by swimmers.*

| | N | Mean | SD |
|---|---|---|---|
| **Speedometer** | 64 | 26,14 | 3,12 |
| **IMU** | 64 | 20,76 | 2,73 |

After verifying the differences in the magnitude of velocity values obtained by the IMU and the Speedometer, there was an attempt to compare the velocity variations within swimming cycles (Table 2). The data distributions were analysed and found to be normal in the IVV obtained from the data collected by the speedometer and accelerometer and in the CV obtained from values recorded on the accelerometer. Thus, Table 3 shows the values of mean and standard deviation and significance for parametric data treatment and median, interquartile range and P for non-parametric data treatment.

*Table 2. Comparison of IVV and CV: values are mean and standard deviation and P for parametric data treatment and median, interquartile range and P for non-parametric data.*

| | females | | | males | | |
|---|---|---|---|---|---|---|
| | **speedometer** | **IMU** | **p** | **speedometer** | **IMU** | **p** |
| **IVV** | 2.26 (0.51) | 1.96 (0.55) | < 0.01 | 2.60 ± 0.28 | 2.12 ± 0.39 | < 0.01 |
| **CV** | 0.47 (0.10) | 0.35 (0.08) | < 0.01 | 0.52 (0.10) | 0.37 (0.10) | < 0.01 |

Bland Altman Plots (Figure 7) were computed to verify the agreement between IVV and CV using the velocity values collected by IMU and speedometer. In the BA above, the mean of the differences is represented by the dotted line and the limits of agreement by the dashed lines. The confidence intervals are represented by the shading. To female IVV we have: bias - 0.33 and, despite some outliers, and some data points out of the limits of agreement, we observed a consistent distribution between the limits of agreement (-1.26 to 0.59) and respective 95% CI (96.24 % of all data points laid inside the confidence bounds). No proportional error ($p>0.05$) was noted. To female CV the bias was -0.14 and, likewise female IVV also observed a consistent distribution between the limits of agreement (-0.31 to 0.02) and respective 95% CI (96.42 % of all data points laid inside the confidence bounds). To male CV the bias was -0.15 and, despite some outliers, a consistent distribution was observed between the limits of agreement (-0.33 to 0.03) and respective 95% CI (97.33 % of all data points lay inside the confidence bounds). Comparing the male IVV obtained by the two methods we found a bias of -0,46 and, despite some outliers, a consistent distribution was observed between the limits of agreement (-1.36 to 0.45) and respective 95% CI. There is proportional error ($p<0.001$). A slight trend in the distribution was observed, although very slight, for a lower bias as IVV increases.

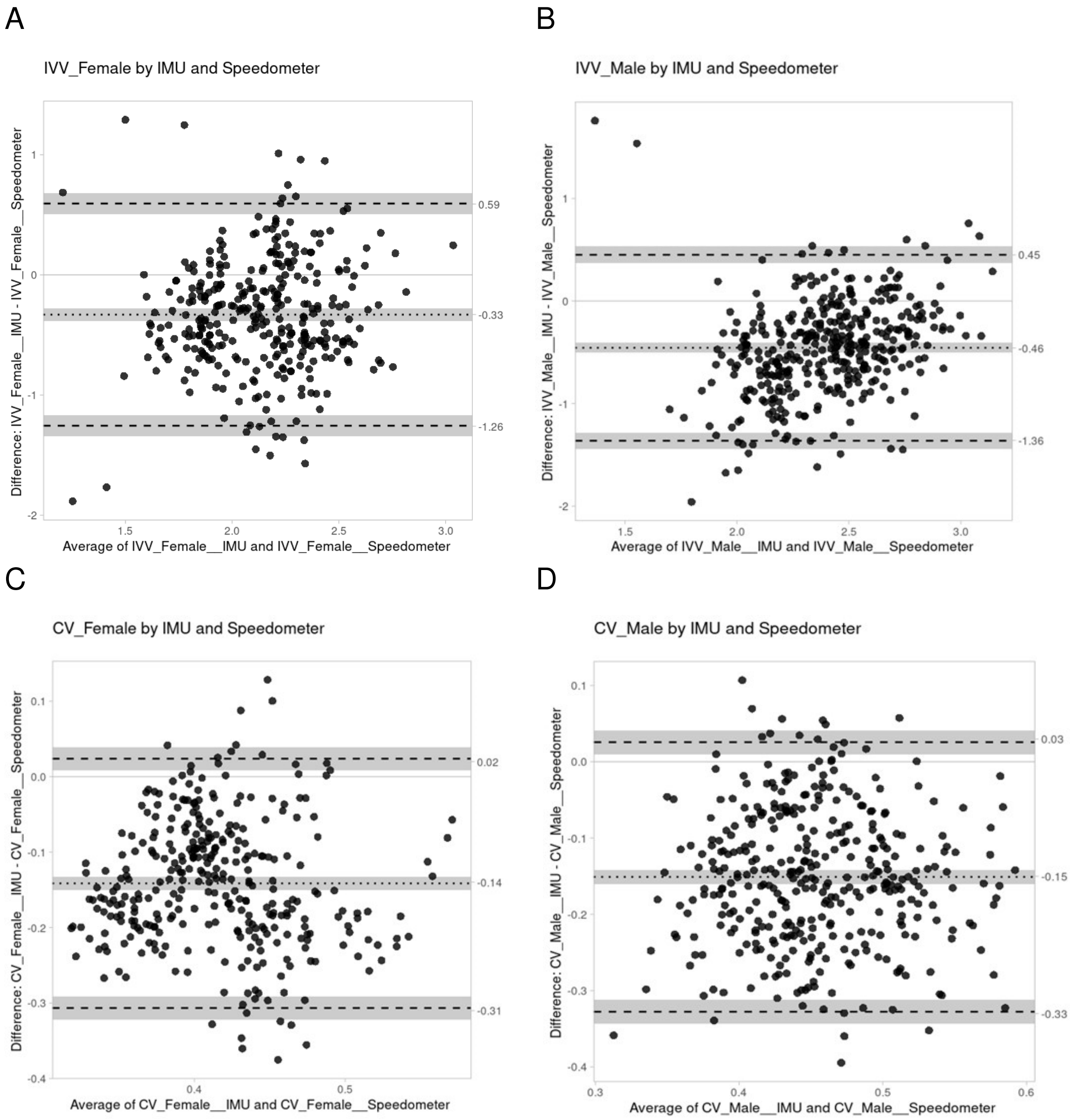


*Figure 7. A - Agreement between the female IVV obtained through the data collected by inertial and Speedometer; B - Agreement between the male IVV obtained through the data collected by inertial and Speedometer; C - Agreement between the female CV obtained through the data collected by inertial and Speedometer; D - Agreement between the female CV obtained through the data collected by inertial and Speedometer.*

## 5. Discussion

Considering the comparison of the two velocimetric methods, speedometer and inertial, we verified the existence of differences in the magnitude of their measurements such as swimming distances and speed values and a correspondence relating to the identification of events and swimming patterns.

Many inertial studies attempt to estimate lap time (Callaway, 2015; Hagem et al., 2013; Sage et al., 2010), turning time, stroke time and count (Davey & James, 2008; Lecoutere & Puers, 2014; Slawson et al., 2008; Stamm et al., 2011), but most studies do not present results on the estimated swimming distance by either device. The distance travelled by the swimmer is not the same as that covered by the inertial or hip of the swimmer (body area to which the speedometer wire was attached). When the swimmer is in the starting position, both the inertial and the attachment point of the speedometer wire are away from the wall. The same happens when the swimmer reaches the wall, when the hands touch the wall, depending on the height of the swimmer, the inertial and the fixed point of the speedometer wire, can be more than one meter from the wall. Having these points recorded on video, we can more correctly estimate the distance travelled not by the swimmer but by the inertial and the cable attachment point. According to the distance from the inertial to the wall at the start and the distance from the wall at the finish, the distance does not coincide with the length of the pool. This could be an aid in the interpretation of the values in table 1.

Considering that the position of the speedometer was not in the swimmer's line, we calculated the maximum error caused by the inclination of the speedometer wire and it will be 0.019m. This value doesn't seem significant in explaining the difference between the speedometer and inertial measurement values. So we may suspect that the difference in values may lie in the calibration method that is linked with the accelerometer position. Thong et al. (2004) refer to the possibility of bias in the data because of changing the cut-off frequency in the anti-aliasing resulting. Similarly, in the study of Stamm et al. (2011), the investigators passed the acceleration data through a 0.5 Hz low pass filter to gain the sensor orientation, which was then removed for further processing.

They calculated the velocity profile using the acceleration in swimming direction and the total acceleration and concluded that velocity information can be derived from acceleration. However, they found differences between the velocity values obtained through the inertial and the speedometer (SP5000), so the authors emphasize the need for further studies to improve the method of removing the orientation of the sensor. Future work needs to find a better approach in removing the sensor orientation.

Safeguarding the hypothesis that the speedometer is also not accurate in its measurements, it would also be interesting to carry out more studies comparing the data collected by inertial with more accurate and rigorous evaluation systems than speedometers.

Analysing the average swim cycle and the sequence of eight swim cycles of our study, we found differences in the data presented by the two evaluation systems (speedometer and inertial). When we look at our velocity curves (Figures 3, 4, 5 and 6), we found that there is a temporal pattern that is shared by the speedometer and the IMU. This is in line with the study of Cortesi et al. (2019) were results suggested that the 3D wrist trajectory can be used for an accurate and complete identification of stroke phases in crawl using IMUs. Fantozzi et al. (2022) developed and validated a protocol for integrated analysis of stroking, kicking, and breathing and found agreement between the inertial and the gold standard (video analysis) for all accuracy parameters investigated.

However, if we look at the magnitude of the velocity values and the intracycle velocity variation, we find that there are significant differences during almost the entire cycle. Looking at the SPM graphs (Figures 3 and 4), we can see that there is a tendency for the measured values to be closer at the beginning and end of the cycle considered, i.e., at the start of the lower limbs action and the end of the upper limb recovery. At the instants of greatest speed (lower limb propulsive action and upper limb propulsive action) the measurements obtained by the two methods are significantly different, as we can see from the results of the t-test. The same happens for the instant between the end of the lower limb action and the start of the upper limb action.

Analysing the comparison of the velocity curves extracted from the two tools, with profile similarities between the curves but with different magnitude of the values during most of the cycle, we tried to understand if these differences between the tools were observed for derived values of velocity, IVV and CV two measures commonly used for the analysis of speed in swimmers.

Trying to verify if there was agreement in the values of IVV and VC obtained from the two instruments, we used Bland Altman Plots BA plots. Reflecting on the Bland Altman plots data, most of the points are below zero and all bias are negative, which means that there is a tendency for the IVV and CV values obtained through the velocity measures accessed from the inertial to be lower than the values of speed variation obtained from the speedometer records, exactly what was verified through the analysis of the instantaneous values of velocity in the SPM. This raises the question of which values are correct, or even if both present deviations, which we explained above. Still in the analysis of the Bland Altman plots, it was found that, although the percentage of values outside the confidence intervals is not high, the bias is very large (14% and 15% for the CV of women and men, respectively). In addition, the values for the IVV showed to be different between methods about 0.33 and 0.46 for women and men, respectively. In this sense, the use of IMU to estimate CV or IVV is not comparable to the use of the speedometer.

For our study, although we have assumed the speedometer as the gold standard, due to being commonly used by the scientific community (Barbosa et al., 2017; Barbosa et al., 2014; Barbosa, Morouço, et al., 2013; Leblanc et al., 2007; Neiva et al., 2021), and with some validation studies (Capitão et al., 2006; Lima, 2005; Morouço et al., 2006). Dadashi et al. (2012) proposed a new wearable and algorithm to measure front crawl velocity, using a speedometer as reference, like we did. In their study they found a significant correlation between the two systems: wearable and cable speedometer. In author`s opinion, results demonstrate that their system is capable of measure velocity with accuracy and precision. This apparent controversy highlights the need for further studies with different speedometers and different inertial sensors and algorithms. And studies comparing accelerometers with video may present important information too. Stamm, James and Thiel (2013) in their study report that the differences between the values obtained by video and by accelerometer are not statistically different for temporal variables of stroke cycles in lower limb action. Fantozzi et al. (2022) found high agreement between inertial and video for parameters like timing of stroke, kicking and breathing, leading the authors to consider their protocol accurate and reliable, easy to use and unobtrusive for swimmers use during the training sessions. Cortesi et al. (2019) found a strong correlation in the wrist trajectories patterns between video and IMU, which highlights the value of inertial sensors in swimming arm-stroke phases complete assessment.

In our study, the video cameras did not cover the entire swimming space, which made it difficult to have comparison of kinematic values between video, IMU and speedometer. There was a slight bias regarding the space calibration that not allowed to retrieve values with accuracy. In this sense, the speedometer raised as the gold standard device, indicating that IMU is underestimating the values compared to it. At the end, we were trying to understand if one tool can replace the other, without stating that the data acquisition by one of the devices is better than the other.

Contrary to what was found in our results, several authors have, in recent years, conducted studies in which they verify the validity of IMUs for the study of velocity, considering them valid and accurate. As examples, the study of Worsey et al. (2018) carried out a study using a single IMU, placed in the region of the sacrum, in order to acquire swimming speed profiles and trying to obtain the average speed of each cycle by applying 3 computational methods to these profiles. They concluded that one single IMU placed in the region of the sacrum allows to derive intracycle velocity values with reproducibility and accuracy. In the same vein, Davey and James (2008) showed that inertial sensors are capable to measuring velocities characteristics, where butterfly and breaststroke have a greater range of velocity change on a stroke-to-stroke basis, in opposition to freestyle and backstroke, that showed a relatively constant velocity. Although they highlight the need of more research in this area. Stamm, James, Burkett, et al. (2013) also worked in the same direction, concluding that the use of a lower back mounted inertial sensor is a valid method to measuring a swimmer’s push-off velocity. By comparing the values of speed and swimming cycles obtained through their device (consisting of an accelerometer and a gyroscope) with the values reported in the literature, Staniak et al. (2016) state that this accelerometer-based assessment method can be an important tool for evaluating the swimmer's technique. These cases reported success of inertial sensors in the determination of parameters related to the evaluation of velocity or biomechanical parameters, which can be an aid to coaches and athletes. This growing interest in easy-to-use equipment and fast information processing, coupled with the successes obtained with inertial sensors, seem to make IMUs an important aid for trainers. As the study of Hamidi Rad et al. (2022b) demonstrates, a group of athletes who received feedback, during the ten weeks of training, with the support of IMU data, performed better than the control group in terms of lap times, have more consistent results, better progress, lower average lap times, and more consistent records. In the perspective of the coach, the IMUs provide very useful information, helping to make diagnoses and monitor performance during training sessions. The highest accuracy, precision, sensibility and specificity to predict swimmers progress were related to lap average velocity and swim average velocity, but also other metrics such as push, glide and stroke preparation, revealed high specificity and precision (Hamidi Rad et al., 2022a). Ohgi et al. (2003) examined the characteristics of the wrist acceleration in breaststroke and suggested that the three phases of the breaststroke (the recovery, the insweep and the outsweep), could be distinguished using a triaxial acceleration device. This can give to the coach very important information about which stroke phase would be changed in skill training, having the acceleration sensor device the potential to become a precise stroke monitoring tool in the near future. Slawson et al. (2008), comparing the results obtained by the accelerometer with video analysis, demonstrated that the accelerometer can be a useful tool in determining the basic characteristics of the stroke, such as frequency and duration. Callaway et al. (2009) highlight the importance of the information that can be gleaned from the swimmer's acceleration and deceleration profile, and the role played by the IMUs in collecting this information, as well as the improvements that have been verified in the development of the accuracy of inertials.

Tolza et al. (2017) in their study to validate the use of an IMU placed on the head to study the characteristics of the breathing movement and the possibility of immediate feedback for correction and, although highlighting some inaccuracy, considered that for progression of head rotation, the IMU can be constituted as an instrument of easy use and with immediate feedback.

Following on from what was reported, in recent years we have seen an increase in the number of studies validating inertial sensors (Cortesi et al., 2019; Dadashi et al., 2012; Davey & James, 2008; Fantozzi et al., 2022; Stamm, James, & Thiel, 2013), and with many uses of IMUs, like to identify stroke phases (Ohgi et al., 2000), swimming styles (Pansiot et al., 2010; Slawson et al., 2008), swim turns, underwater gliding and stroke (Vannozzi et al., 2010), even to quantification of energy expenditure, according to the good results of the study of Dadashi et al. (2013). However, there is still some controversy both regarding the comparison with other commonly used methods, the ease of use, and about the number of IMUs used in each evaluation. For example, Worsey et al. (2018) considers that an IMU placed on the sacrum can be used to measure the velocity, but for Callaway (2015), one single IMU is not sufficient to determine or infer the phases of the stroke with accuracy. According to Adesida et al. (2019) wireless data transfer is a necessity, but signal loss needs to be minimized. From their systematic review, they highlighted that there have been discrepancies in the amount of detail given in the studies carried out with the sensors but it has also been shown that they can provide information relating to biomechanics, which can be explored in sport. Félix et al. (2019) also consider the importance of more investigation using IMU in different body locations, using more units and improvements of the classification accuracy, considered as a limitation of their study. Camomilla et al. (2018) refer to the need for a compromise between the potential of technology and practicality in the field. For these authors, it is necessary to solve the issues related to the lack of adequate standardization of data acquisition and tools for subsequent analysis, so that their use by coaches is increased. We also consider as small the number of studies that compare instantaneous velocity values between methods as well as measurements derived from velocity such as CV and IVV (Dadashi et al., 2012). We recognize the advantages of using a tool that has been evolving in the sense of having increasingly reduced dimensions and appearing on the market at increasingly accessible values. For the other side, does not obstruct swimming, can collect a lot of information at the same time and allows to evaluate more than one swimmer simultaneously. In this sense, we realize the impact that a system like this could have in the future on evaluation of temporal and biomechanical parameters of swimming. In our opinion, further studies should be carried out in this area, which will enable the development of algorithms and other procedures that will lead to the collection of increasingly accurate and easy-to-use information. Our results did not show agreement between the values recorded for the instantaneous velocity or for the IVV and CV between the IMU and the speedometer, although we were able to identify the pattern of swimming through the information collected from the IMU, which is in agreement with some of the literature mentioned above (Cortesi et al., 2019; Fantozzi et al., 2022; Hamidi Rad et al., 2022a). For Ödek and Özcan (2023), although inertial sensors can be used for time variables in swimming techniques, their use by coaches is not yet at the desired level, particularly due to the complexity of processing the data. In the same line, Ceseracciu et al. (2011) states that accelerometers are a type of technology that is already relatively inexpensive and provides higher sampling rates, but the processing of the information extracted and its interpretation is not yet straight-forward. According to (Callaway, 2015) multiple sensor systems could be the future of monitoring in sport, and it will be necessary more investigation in terms of usability, visualization of output data and ease of synchronization. Coaches, swimmers and sports scientists must recognize that for monitoring or evaluation protocols to be effective, they must be incorporated into the training and competition program in an integrated and seamless manner (Smith et al., 2002).

## 6. Conclusion

Based on the results of the present study, there are some main conclusions that can be drawn:

- The velocity curves acquired through the speedometer and the IMU have the same profile. It means that they record the same events in a restricted time interval.
- There is an underestimation of velocity and the estimated distance values by the IMU when compared to the values of the speedometer.
- Although both devices show a higher degree of agreement, there is a larger bias that compromise comparison.

It is undeniable the existence of advantages when using inertial devices for swimming evaluation. From our results we can say that those advantages were not found, at least at high velocities in breaststroke. This IMU cannot replace the use of the speedometer, either for the evaluation of the instantaneous velocity, or in the calculation of IVV and CV.

Although there are satisfactory results when using IMUs in the field of swimming, we believe that more research is needed to check its accuracy in order to get easy and fast extraction of the information.

## 7. Limitations and further studies

This work opens a path for further studies according to the limitations that were found. Some ideas for further studies are listed below:

- Synchronize the IMUs with order systems with greater accuracy than the speedometer (i.e. capture or automatic motion detection systems);
- Conduct a more detailed analysis about velocity during different swimming phases as well as events within a single cycle;
- Expand the quantitative analysis around variables like IVV and CV;
- Implement teste and retest procedures in or to optimize the signal acquisition related to the sensor orientation.

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