DEVELOPMENT OF A LOW-COST IMU FOR SWIMMERS' EVALUATION

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Swimmers improvement is built on rigorous and controlled training. This work aimed to develop a light-weight, practical and low-cost inertial measurement unit (IMU) for swimming monitoring. A 21g device was optimized for including the data acquisition hardware (based on an attitude and heading reference system – AHRS). Eleven male swimmers with different skill levels tested the system under the four different swimming strokes. Based on the AHRS data, three novel indicators were developed: trunk elevation, body balance and body rotation; and anayzed on an individual basis. The proposed unit has unique features to be further explored for training monitoring.

KEYWORDS: swimming; inertial data; monitoring.

INTRODUCTION: Competitive swimming is based on covering a previously known distance in the shortest possible time. Being one of the most popular sports in the world, there are multiple technologies available to support swimmers and coaches in their daily work, promising to help improve performance and prevent injuries. In competitive swimming, each swimmer takes their own lane without direct interference from the opponents. Therefore, the training process is highly individualized, seeking to perform in competition what has been trained. For instance, elite swimmers know a priori how many strokes they will perform in each course, trying to ensure maximum efficiency (Aspenes & Karlsen, 2012). Accordingly, the high training volume and intensity provide that necessary background, illustrating the crucial importance of control and evaluation. Kinematical evaluation requires time-consuming work that is very dependent on the observer's capabilities, restricting the direct feedback (Dadashi, et al. 2015). In addition, highly expensive cameras and the negative effects in signal accuracy induced by water are other drawbacks that limit its' functionality. Researchers usually adopt visual markers on the swimmer, but camera calibration is difficult. Some systems also consider multiple recording cameras, requiring a larger effort for synchronization. Data processing requires locating the markers in each video frame, to reconstruct the swimmer's movement and extract relevant parameters. Marker visibility is often impaired by water turbulence, refraction or reflections of light. To facilitate processing the use of optoelectronic markers may be used. Still, these seem to condition performance due to an additional drag force (Washino, et al. 2019).
Taking benefit of technological advances, other approaches have been tested. For the last three decades, inertial measurement units (IMUs) have proven to be extremely useful tools for human movement analysis. Both the portability and the low-cost have attracted researches to use them for sports biomechanics. For swimming, it is in its primary developments but already with some promising results (Dadashi et al., 2015). Actually, a systematic review demonstrated that the use of inertial sensors seems to allow swimming data acquisition without the previously identified constraints (Magalhaes, et al., 2015). IMUs can have a small size and weight, transmitting data wireless can perform short-time analysis, do not require complex calibrations and can be worn easily. Moreover, it is possible to examine and monitor the whole swimming trial continuously without specified spatial limitation, a typical feature of the video analysis (Cortesi et al., 2019). If so, much information may be obtained to help coaches building a tailored prescription and monitoring for their swimmers.

The aim of the present research was to develop a convenient, practical and low-cost system, applied to the practice of swimming, including the data acquisition hardware (based on an attitude and heading reference system – AHRS). It was hypothesized that this system would be able to rapidly extract key features for each swimming stroke.

METHODS: Eleven male swimmers volunteered to participate in the experiments (age: 20.3 ± 2.6 years old; stature: 175.1 ± 4.3 cm; body mass: 64.6 ± 6.3 kg). Participants had different levels of performance, providing heterogeneous performances for developing a representative database (3 international level, 5 national level and 3 retired). All participants provided written informed consent to participate in this study. The protocol was approved by the institutional ethics committee in the spirit of the Helsinki Declaration.
The preliminary development of the hardware was previously described (Félix et al., 2019). It includes an inertial measurement unit (IMU) with a 3-axis accelerometer, gyroscope, and magnetometer, allowing the calculation of the absolute orientation of the module in space. Even though the device streams the acquired data via Wi-Fi, due to the signal weakening in aquatic environment it was modified to store data in a memory card. Data logging is done at 100-Hz, recording the sampling time [ms], the nine channels of the accelerometer [g], gyroscope [º/s], and magnetometer [gauss], and the three Euler and heading angles [º], in comma-separated values (CSV) format. The developed firmware is publicly available as open source. In Figure 1 are presented the device (weighting 21g) and its dimensions (panel a), the fixation of the device on a swimmers back at level L2-L3 (panel b) and the axis orientation when swimming (panel c).

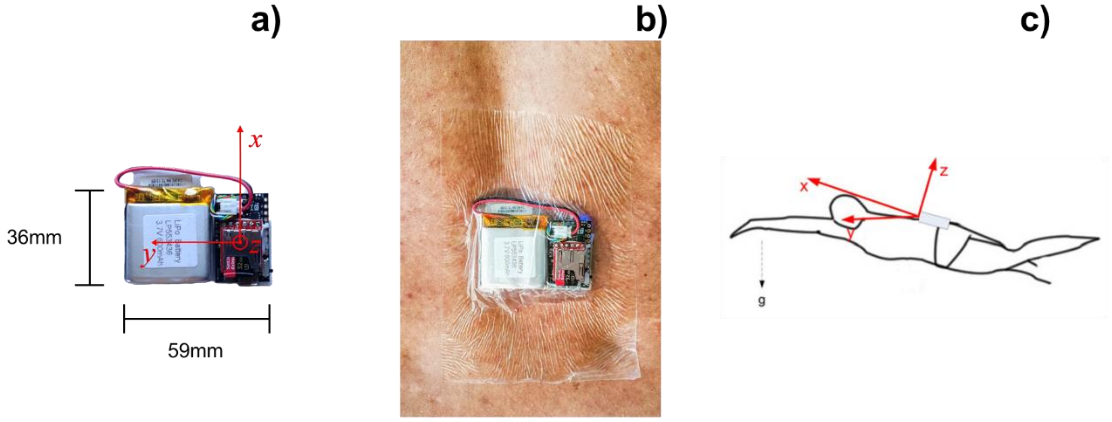

Figure 1: Developed unit dimensions (panel a), location (panel b) and orientation (panel c).

Data were collected in a 50 m swimming pool with a minimum depth of 1.8 m. After completing their typical activation and pool warm-up, each athlete was asked to swim 100 m in each swimming stroke. No information was given regarding: the order they should perform, the pace they should apply, or the interruptions they could make. Data processing algorithms were developed to analyse the swimmer performance, as previously described (Félix et al., 2019). The next step is to estimate the stroke technique the athlete is swimming, to proceed with the features' extraction related to his performance and technique. We developed a set of data processing algorithms to empower, both swimmer and coach with the ability to analyse not only the swimmer's technical movements, but also his performance throughout the training. A MATLAB® script was created with the aim of analysing and extracting information from the athlete's movement, always taking these considerations into account.
Trunk Elevation: The trunk elevation is a feature applicable to symmetrical strokes (breaststroke and butterfly). It consists of the difference between the maximum and the minimum pitch angle values within an arm stroke. Thus, a notion of the trunk elevation in each executed stroke can be taken. The average trunk elevation at each lap is also computed. While a poor trunk elevation of the torso leads to a hard stroke recovery, an

excessive trunk elevation represents not only an unnecessary expenditure of energy but also slows the forward displacement.

Body Balance: The body balance, or pitch angle, is a very important and indicative performance indicator of several structural problems in swimming technique. For instance, a weak leg kick during front crawl ends in a too low pitch angle. There are two ways to present this indicator, depending on the stroke. For non-symmetrical strokes (front crawl and backstroke), the goal is to keep a pitch constant and close to 0º; we averaged the lap pitch. For the symmetrical strokes (breaststroke and butterfly) the pitch varies greatly during each stroke execution. Thus, in these cases a vector of maxima and a vector of minima, whose size is equal to the number of strokes performed by the athlete in a given lap, is returned. Thus, for all given strokes in a lap, it is possible to analyse the minimum and the maximum pitch angles. In each lap, the maximum pitch was averaged and minimum was computed.

Body Rotation: The body rotation, or roll angle, is also used to correct swimmers technique. A low body rotation weakens the slide after the propulsive action, while an excessive rotation of unbalances and slows down the swimmers.

RESULTS: Data were visually inspected and further analysed. Differences were observed for body rotation (front crawl vs. backstroke, ~+8-12%, $p<0.01$) and for trunk elevation (butterfly vs. breaststroke, ~+12-15%, $p<0.01$). As expected, high variance was obtained among swimmers. Thus, individual analyses were performed for each stroke. It was possible to obtain a continuous assessment of the studied variables for each swimmer, as shown in figure 2. Furthermore, discrete measurements were computed for each stroke of each swimmer, as exposed in table 1.

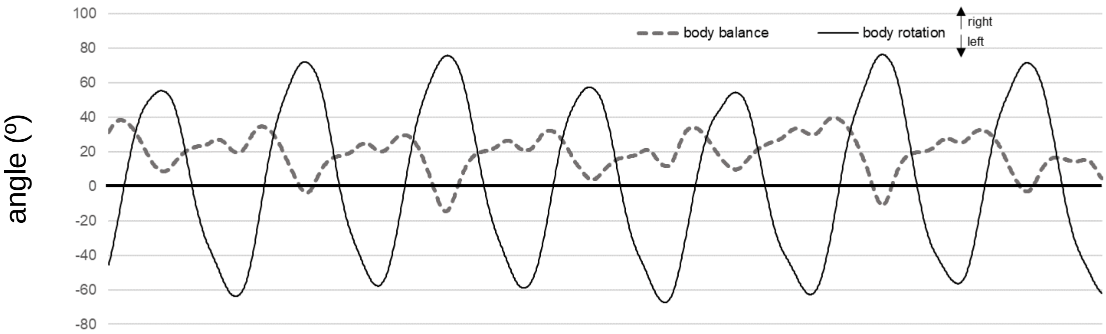

Figure 2. Illustrative representation of the body balance (dashed line) and body rotation (above 0º body is rotating to the right) in front crawl.

Table 1: Example of the obtained data for one swimmer; all measurements are in degrees.

	Mean±sd	C.Var	Max	Min
Breaststroke - trunk elevation	24.9±2.4	9.5%	29.8	19.5
Butterfly - trunk elevation	39.2±3.8	9.6%	48.9	33.3
Front crawl - body balance	17.9±4.5	24.9%	27.1	6.5
Front crawl - body rotation right	47.9±3.4	7.2%	55.5	41.4
Front crawl - body rotation left	55.1±2.7	5.0%	62.6	49.0
Backstroke - body balance	8.6±3.3	38.4%	12.1	5.5
Backstroke - body rotation right	33.6±4.3	12.8%	39.3	27.5
Backstroke - body rotation left	36.5±5.2	14.2%	42.2	31.0

DISCUSSION: The main goal of the present study was to develop a prototype device able to collect inertial signals from a swimmer, for providing relevant information. This was achieved by modifying an available low-cost hardware. We ended up with a low weight, low-cost and practical device able to assess 14 instantaneous variables. Further studies will cross validate the intracycle velocity variations (with a speedometer) and body angles (with kinematical analysis), to come up with a functional training tool for swimming coaches.

Video approaches are the most widely used techniques by athletes and coaches around the world, to correct technical errors and monitor some of the essential parameters for good swimming practice. If we consider a simple setup, it is possible to see why this is the most used technique today: in a comfortable and fast way, for instance with a mobile phone (out of water recordings) or an action cam (underwater recordings), it is possible to record any athlete in any environment for further analysis. However, it is mainly qualitative in nature rather than quantitative. When considering a more complex setup (e.g. SwimPro, SwimRight, Qualisys Oqus, or analogous systems), the potentials extend. Yet, the larger the number of cameras to record the swimmers from different angles, the more complex the setup becomes and, consequently, more time spent in the synchronization and data processing will be required. This can be facilitated by recent advances on IMUs. With the collected data, algorithms for the computation of performance indicators were developed. Not only was aimed to deliver a high number of variables, but mainly to adopt an efficient algorithm for providing immediate results. Accordingly, a set of algorithms have been developed using Matlab®, that compute relevant performance indicators (e.g. trunk elevation). Body streamline is a main feature for optimal performance, but difficult to evaluate by coaches. Monitoring this variable during a typical series would be valuable to examine the inference of fatigue and technical errors. And, to the best of our knowledge, this is the first system to use the Euler angles to perform processing and compute swimming performance indicators.
Once waterproofed, IMUs provide several advantages over the signals collected through video in the analysis of dynamic behaviour in athletes. Firstly, because digitization of the collected data is not necessary: part of the processing may be done directly in the IMU, and the remaining postprocessing is consequently performed on the computer (Magalhaes et al., 2015). Secondly, it is much more practical, as the discomfort caused by a small attached device is much less than the discomfort caused by a complete swimsuit with visual markers attached to it (Washino, et al. 2019). Thirdly, this type of device can, in some cases, store a huge amount of information (Dadashi, et al. 2015). Fourth, once the processing is done automatically on the computer, the results are ready in a very quick and simple way. Lastly, it is an affordable alternative and every athlete can easily acquire one.

CONCLUSION: In this work we described the design and development of a swimming system capable of assisting coach and swimmer in their daily training. On one hand, when applied to swimming, the video analysis used in other sports is unpractical, inefficient and too expensive. On the other hand, the analysis based on inertial signals are poorly developed, providing few performance indicators to athletes and coaches. Based on this premise, a system based on inertial signals was designed by using an AHRS and adapting it to the aquatic environment by making some changes to its hardware and firmware, a prototype of such a system has been developed, together with software modules for data analysis.

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