Wearable Monitoring Unit for Swimming Performance Analysis

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Abstract. BIOSWIM (Body Interface System based on Wearable Integration Monitoring) is a joint multidisciplinary effort involving a number of Portuguese R&D teams. It seeks a pervasive monitoring solution for physiological and biomechanical signals from a swimmer under normal training conditions, both in and out of the water. A wearable inertial monitoring unit (WIMU) was developed in order to serve as the biomechanical data processing unit of the system. The preliminary version of the WIMU has a commercially available microcontroller and transceiver set, as well as a tri-axial accelerometer and a bi-axial gyroscope serving as sensors. Testing in and out of the water has provided promising data and contributed to design modifications. These also took into account input from athletes, trainers, and physicians. Future work includes the integration of the WIMU within the complete BIOSWIM swimsuit system, complemented by truly integrated EMG and ECG textile sensors and a chemical monitoring unit.

Keywords: Wearable, Monitoring, Biomechanical parameters, MEMS, Swimming analysis.

1 Introduction

Visual markers and inferred biomechanical data used to be the reference of choice for coaches and trainers when evaluating an athlete's performance. Nowadays, miniaturized low-powered accelerometers and gyroscopes, embedded within wearable monitoring systems, have closed the gap between an athlete's perception and that of trainers. Micro-electromechanical systems (MEMS) represent a viable alternative which, unlike many of its counterparts; can be integrated within wearable-water friendly solutions that can aid on swimming analysis, without burdening the athlete with cumbersome garments and/or equipment. Electronic textiles, interactive clothing, smart garments and wearable are becoming commonplace terms within the rehabilitation and sports community, revealing recent research trends within biomedical engineering and textile technology. During the past decade, researchers and engineers from a number of universities and companies, have proposed several monitoring solutions and mechanism for a wide variety of objectives, from technical applications to leisure. Although it seemed at first that the development momentum favored multimedia applications, the research

A. Fred, J. Filipe, and H. Gamboa (Eds.): BIOSTEC 2011, CCIS 273, pp. 80–93, 2012.

community promptly foresaw such technologies potential for healthcare and sports applications. Currently there exist literature for a large number of projects intended to measure physiological parameters remotely, such as MyHeart and Wealthy projects [1], VTAMN [2] and more recently BIOTEX [3] and Vital Jacket [4].

Although the wearable inertial monitoring unit (WIMU) is still at a prototype stage, preliminary data reveals the promise of such a device.

2 BIOSWIM Project

The BIOSWIM project gained inspiration from emerging wearable monitoring technology solutions and intends to develop a full body smart garment for bio-signals and movement related parameters monitoring, while considering both health and sports performance. Until recently, healthcare, rehabilitation and sports gathered physiological and mechanical data through cumbersome apparatus that affected the behavior of the target individual and sometimes even constrained the range of movement. These solutions were in their majority limited to a controlled laboratory environment, utilizing unpleasant methods for fixing sensors to their intended location. Although the medical and sports community benefitted from such data gathering approaches for decades, more pervasive approaches are nowadays possible. In addition, the need for a controlled environment and especial laboratory setups generally increased the associated research cost and limited the amount of time with the patient or athlete, seldom achieving to collect data that truly reflected the average behavior or performance of the individual in natural conditions. Taking into consideration the before mentioned, past experiences, known obstacles and limitations reported in related literature; a wearable solution was agreed upon which combined ease of use and seamless electronic integration for a more ubiquitous signal monitoring experience. The main goal of the BIOSWIM project is the development of wearable prototypes for measuring several biological parameters, critical for sport performance and health purposes, oriented for in-pool (or underwater depending of the sports) activity, although usable for regular sports and a number of additional applications. Moreover, the wearable system was designed with user comfort as a guiding factor, comprehending the best combination of textile material with embedded microelectronics for signal acquisition and data transmission.

Electromyography, cardiac rhythm, respiratory effort, oxygen consuming taxes, motion capture, wrist and arm accelerations and rotations, speed, hydrodynamics' pressure; constitute some of the parameters of interest that are to be collected using the wearable system. The before mentioned parameters can be utilized for a number of diverse calculations, models, and applications of varying nature. Fig. 1 provides a graphical reference of possible locations for the parameter monitoring sensors.

Although a wide array of ready to use commercially available sensors can be obtained at a relatively low cost; the specificity of some target parameters and the particular measurements conditions, i.e., in-pool environment, forced the design and development of new sensors adapted for this project. A worth mentioning related research, resulting from the BIOSWIM project, concerns new textile sensors for ECG acquisition and respiratory frequency measurement. A comparison between electrodes based on different materials and structures was performed with promising results when performing vital signs acquisition under dry and wet conditions [5,6].

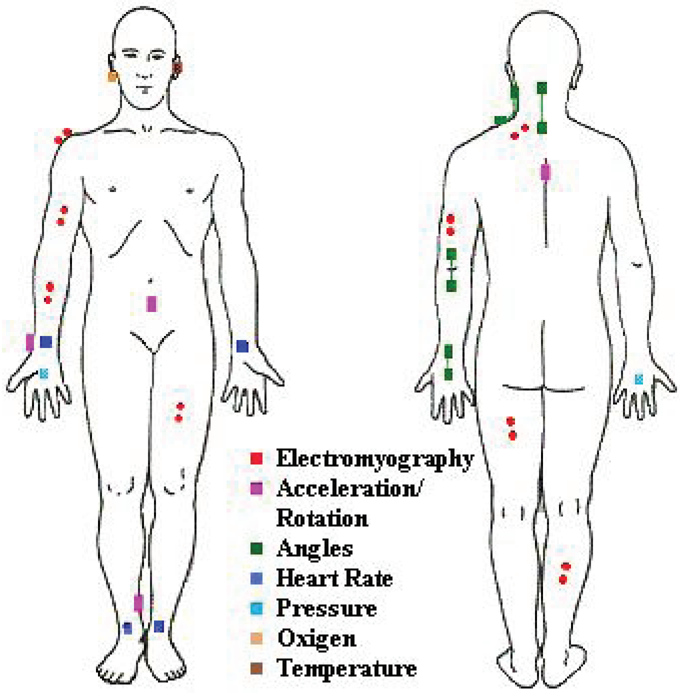


Fig. 1. BIOSWIM's monitoring objectives

This project represents a multidisciplinary effort of three research and development groups located within three well-known Portuguese institutions: the Centre of Textile Science and Technology of the University of Minho, the Institute for Systems and Computers Engineering of Porto (INESC Porto) and the Faculty of Sports of the University of Porto. The project proposal was submitted and approved by the Foundation of Science and Technology of Portugal and has been responsible for a number of academic projects and thesis at the undergraduate and graduate level, in areas such as electrical, biomedical and textile engineering. This multi-disciplinary and inter-institutional project is evidence of a growing trend in current research, which requires the collaboration of a number of specialties for achieving a common objective.

Although an immediate application of this wearable system is within sports, from competition athletes, to sport amateurs and body maintenance; the system itself can be adapted to a number of other applications. It is true that some current commercially available systems provide useful information for a number of activities, however when evaluating and improving an athlete's performance the number and variety of parameters to be monitored tends to require specialized (and therefore costly) equipment, especially at competitive levels. The overall goal for such scenarios can be at times simple, i.e. a faster free style 50 meter lap; however the movements, considerations and adjustments an athlete must include in their actions, in order to improve their performance even a fraction of a second, can become a puzzling task. To this complex process one must add the present paradigms shift taking place within data gathering solutions. Not only the expensive laboratories and awkward equipments are being replaced by more sensible sized devices; even the biomechanical models are being updated to consider measurements (and measurement locations) that were not available (or reachable) some years ago. Beyond vital signs, other physiological and/or biomechanical signals can prove crucial for optimizing an athlete's effort and reducing fatigue when subjected to intensive training or competition challenges.

The development of wearable monitoring devices for sports practitioners can present several noticeable repercussions in the sport community, both in reference to the optimization of the training process of elite athletes, as well as to the promotion of safety regulations within rehabilitation and leisure activities. The idea behind the BIOSWIM project was to produce an wearable elite training evaluation station, allowing the most innovative monitoring, ambulatory registration, real-time visualization and post-exercise display of both physiological and biomechanical relevant data for training (heart-rate, respiratory frequency, oesophageal temperature, sweat, arm tri-axial acceleration, etc.). Important repercussions are expected both for practitioners, coaches and scientists, allowing increased safety in physical activity, an augmented objectivity - and efficiency - of the elite training process, and stress-free data collection for scientific research in neuro-physiology and biomechanics of sport.

3 Archictecture Overview

Three main sections are to be considered when referring to monitoring systems:

- Sensing section.
- Processing section.
- Transmitting section.

The mentioned sections can be found separate, intermixed or integrated depending on the design, but the objectives of their functions can be readily separated if needs be.

Sensing Section. Advances in micro-fluidics, material science, nano-structures, micro-electromechanical devices, bioelectrical interfaces, and others; have contributed to a new generation of wearable and implantable sensors and monitoring devices. Healthcare has greatly benefitted from the development of biosensors (also referred to as chemical sensors) [7] and physiological sensors. Such achievements have paved the way for truly pervasive monitoring strategies, which will benefit patients and reduce the load to healthcare facilities. From a sport monitoring perspective, non-invasive, minimally intrusive sensors are the preferred choice, and consideration of their positioning, calibration, noise, offset, deviation, etc., are concerns [8]. There exist a wide array of commercially available sensors and even more experimental devices and concepts waiting their turn.

Processing Section. In today's market, the competition to claim to be the lowest powered microcontroller is fierce. Depending of the complexity required by the application and the feature extraction methods to be applied, an array of Reduced Instruction Set Computer (RISC) or Advanced RISC Machine (ARM) architecture based microcontrollers offer different features which accommodate varying solutions. Based on the popular "motes" designs and further research in the area (internal reports [9]), there seems to be a preference for Texas Instrument MSP430 ultra-low power, Atmel's ATMEGA ultra-low power, and the Microchip's extreme-low-power (XLP) PIC microcontrollers. Using the power specifications, indicated on the datasheet of each microcontroller, as a base for comparison, can sometimes lead to problems and confusion; careful attention must be paid to the conditions in which each manufacturer measures their devices power consumption.

Transmitting Section. When referring to wearable monitoring systems, it is unavoidable to consider a wireless component for interfacing with the system; either be it for real-time or sporadic updating to a remote processing node, or for downloading the collected stored data, or even for transmitting the data from a sensor node to the on-body or remote processing unit. The presence of cables or the need for physical removal of the device for data download represents an alternative that while permissible at prototyping and troubleshooting stages, is impractical at more advance stages of design and implementation.

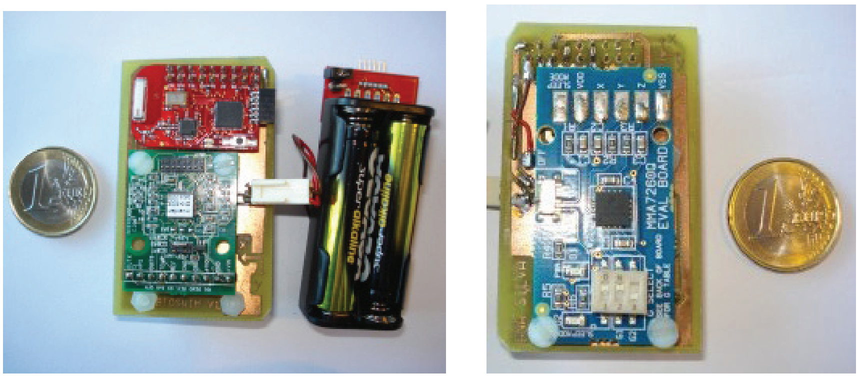
A number of alternatives exist for mid-range wireless communication including common protocols (GSM, WiMAX, UMTS, WLAN, etc.) and upcoming 4G mobile communication solutions. From a more local point of view the IEEE 802.15 Workgroup has introduced an array of solutions. Among the favorite standards one counts with the IEEE 802.15.1, known as Bluetooth, and the IEEE 802.15.4, also referred to as Zigbee. The number of low-power short-range transceivers in the market today is enough to overwhelm even experienced researchers. It seems every brand offers their particular RF solution, claiming low-power transmission; companies such as Texas Instrument, Atmel, Semtech, Maxim and Microchip (to mention a few), offer interesting and varying solutions.

4 WIMU

For years, numerous devices and setups have been implemented in order to assist on swimming performance analysis. Many of these devices were based on video analysis, while others made direct measurement and signal capturing through awkward setups, generally uncomfortable for the swimmers and thus affecting their performance. Advances in a number of fields have allowed for compact wearable monitoring devices, greatly improving the data gathering process and closing the gap for a truly seamless biomechanical signal monitoring solution. Although there is a relatively reduced number of biomechanical signal monitoring systems being used for swimming performance analysis today (particularly when compared to the number of wearable monitoring devices for healthcare or even for land based sports), a shift on the approaches for swimming analysis is being noted. Different strategies have been applied by the mentioned systems, however a common element seem to be their dependence on accelerometers. Some systems worth mentioning are the ETH Zurich Wearable Computing Laboratory's SwimMaster [10] and Imperial College BSN device [11].

4.1 Design Overview

The WIMU - Wearable Inertial Measurement Unit - was designed in the scope of the BIOSWIM project. The goal was to develop a MEMS-based wearable device for assessing biomechanical parameters of a swimming athlete. The inertial unit comprises a tri-axial accelerometer for linear acceleration and a bi-axial gyroscope for angular velocity measurements (however only one axes of the gyroscope was used in the current implementation stage); managed by a microcontroller for signal acquisition, packaging and wireless transmission. A photograph of the system can be observed in Fig 2. Both inertial sensors used are MEMS devices; micro-machined inertial sensors have a huge potential for applications in the biomedical field due to their small volume, portability, low power consumption and relative low cost.



(a) (b)

Fig. 2. Top 2(a) and bottom 2(b) view of the system

Commercially available evaluations boards were used to integrate the MEMS sensors into the WIMU. The accelerometer evaluation board consists of a small setup intended for evaluating the MMA7260QT Freescale Semiconductor accelerometer, adequate for fast prototype developing without the need of custom PCB designs. It also provides means for understanding the best mounting position and location of this accelerometer. Similarly, the IDG-300 Invensense gyroscope can be found integrated in an evaluation board along with the components necessary for application-ready functionality.

In order to integrate both the accelerometer and the gyroscope into the inertial unit, the Texas Instrument microcontroller based board, eZ430-RF2500, was selected from the many commercially available devices. The eZ430-RF2500 uses the MSP430F2274 microcontroller which combines a 16-MIPS performance with a 200 Ksps 10-bit analog-to-digital converter (ADC); paired with the CC2500 multi-channel radio-frequency (RF) transceiver, designed for low-power wireless applications. This board offers a combination of hardware and software appropriate for fast prototyping of wireless projects, while offering low-power consumption. The eZ430-RF2500 can readily use the SimpliciTI wireless communication protocol, a low-power RF (2.4 GHz) protocol aimed for simple and small RF networks (proprietary of Texas Instruments). The SimpliciTI protocol claims to use a minimal set of microcontroller requirements, which in theory lowers the associated system cost. In this case, the network topology was configured so that the WIMU behaved as an end device (ED), transmitting data packets to a remote or base station. There is room for future expansion, since the protocol permits multiple end devices; therefore multiple WIMUs could be allocated at different body segments, in a truly body sensor network scheme.

4.2 WIMU Architecture

As mentioned above, the WIMU consists of a tri-axial accelerometer, a bi-axial gyroscope, a microcontroller based board and a power supply unit. However only one of the gyroscope axes was utilized during this initial stage of implementation. The architecture of the WIMU is presented in Fig. 3.

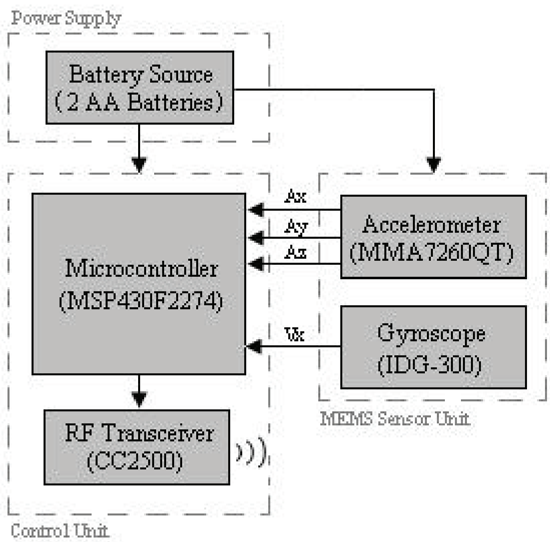
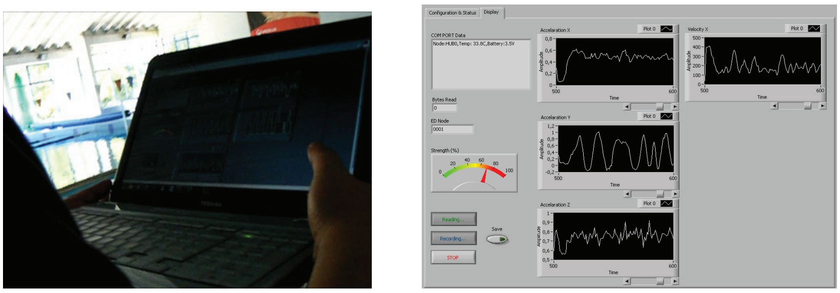


Fig. 3. WIMU's architecture

On the WIMU side, minimal pre-processing of the gathered data occurs, just enough to prepare the data for adequate packaging for transmission; however it should be pointed out that there is a potential for future signal conditioning at this stage. The acceleration and angular velocity signals are acquired and converted sequentially by the 10-bit ADC integrated in the MSP430F2274 micro-controller at a sampling rate of approximately 50 Ksps. The ADC was kept in a continuous loop, converting sequentially all sensor inputs. During the initial stage of implementation and testing, a simple broadcasting (from the WIMU point of view) time-window listening (from the receiver point of view) scheme was used for the data gathering. Although this strategy introduces reduced timing errors and is not applicable for faster data packects transmission rates or for multi-location sensors synchronization, it proved to be effective for this stage of implementation providing a modest maximum rate of approximately 20 rpps (received packets per second). A more robust strategy which relies on time-stamping and buffer optimization packaging has since then been implemented showing stable data flow at around 100 rpps; however further testing on more realistic scenarios is still pending. Additional data processing operations at the WIMU level were left for post-processing analysis, in order to alleviate microcontroller resources and speed up the communication process. Careful attention should be paid to the receiving protocol data handling, since bottlenecks can occurr due inefficient procedures, such as time consuming conversions that could be performed in software instead of hardware). These types of issues do not become readily evident until attempting higher data packets transmission rates with more complex data packets.

The receiver or base station is composed by a laptop (see Fig. 4(a)), eZ430-RF2500 setup counterpart, and a custom software application for the acquisition, processing and visualization of the sensor packets coming from the WIMU. National Instruments' LabVIEW platform was used for the computer interface implementation as shown on Fig. 4(b). The application allows for COM port parameters configuration, swimmer's personal information and note taking recording, database storing for data, and visualization of incoming data and signal strength from the WIMU.



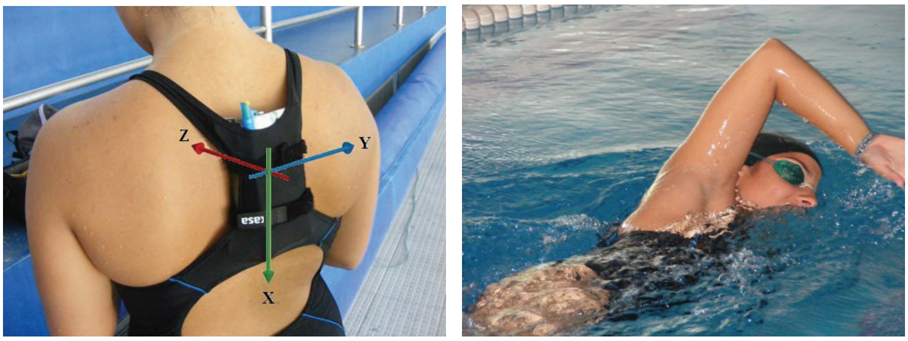
(a) (b)

Fig. 4. Data collection on the laptop through LabVIEWs user interface

The WIMU weights approximately 65.6 grams and measures 57x90.5x24 mm. The data collection was achieved at distances of up to 20 meters; however optimal signal strength was noticed after exceeding a distance of 10 meters depending of water conditions (agitation of the surface and existing obstacles). Two standard alkaline AA batteries insured the system could operate continuously during a couple of consecutive training sessions each of about two hours without any noticeable degrade in performance or signal intensity loss.

5 Experimental Results

The WIMU was located at the dorsal zone of the frontal plane, within the vertebral region at the inferior scapular section. This location was chosen in order to measure, in addition to the accelerations on the three axes, the longitudinal rotation of the trunk, as can be seen on Fig. 5.



(a) (b)

Fig. 5. (a) WIMU positioned at the upper back of the athlete. (b) The athlete swimming with the WIMU.

The longitudinal rotation is considered by some [12] as a useful factor when evaluating swimming performance, due to its correlation to the displacement velocity. Another important consideration was the comfort of the swimmer and avoiding restricting or modifying their average sequence of movements.

A number of preliminary tests were perform in laboratory settings, in order to optimize transmission protocols, verify waterproofness of the package and streamline data gathering protocols, both at the hardware and software level. A female athlete in her late teens served as the main tester at the initial stages. Before entering the pool, the swimmer was required to perform a number of flexibility related routines, in order to determine movement constraints. Once in the pool, she was asked to swim, submerge and perform various movements in order to determine if the WIMU's presence represented an obstruction to her movements. In both cases (outside and inside the pool) the swimmer reported that the unit did not affect her movements. Finally, the swimmer was told to complete several sets of laps using free-style (i.e. crawl) technique, then a number of laps with breaststroke, and finally butterfly. For all styles indicated the end of pool, the turn was perform through a vertical turnaround (i.e., stop-touch wall-turnaround), reversing direction without flipping under water. A second female swimmer with similar age, height and swimming experience collaborated in a comparison trial, however only free-style data was capture in such occasion.

Although data gathering for the crawl techniques laps did not required signal compensation strategies; the butterfly and breaststroke techniques did present some data gaps. The recorded data was later processed in Matlab applying compensation through cubic interpolation when required, followed by a simple moving average smoother

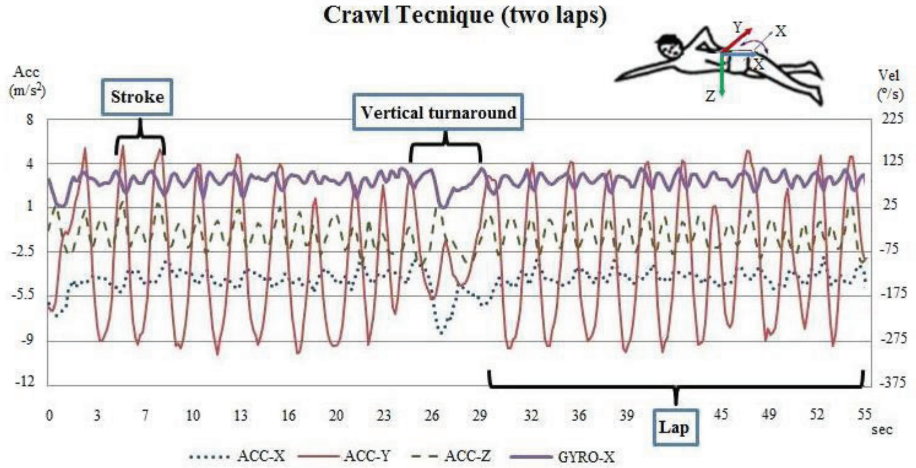


Fig. 6. Two laps using crawl technique signals. Gyroscope X-axis is located within the 25 and 125 °/s Vel lines.

based on window convolution; some results taken at a rate of approximately 7 rpps can be observed on Fig.(s) 6, 7 and 8.

It should be mentioned that the Fig.(s) 6 and 7 have a vertical scale in m/s^2 and °/s (for linear acceleration and angular velocity, respectively) which were obtained through calculations based on manufactures specifications. On Fig. 8, the different signals were computationally DC filtered and scaled for ease of comparison. All the mentioned figures have a horizontal scale in seconds.

Observing the graphs concerning each swimming technique, it was possible to differentiate between styles, each stroke, and start/end of lap. For example, free style can be readily distinguish from breaststroke and butterfly by the signal provided by the accelerometer in Y-axis or transverse axis. The referred signal presents large variations for the crawl technique, while for the other presented styles these variations are comparatively small. Alternatively, the butterfly and breaststroke technique can be differentiated from each other from the data produced by the accelerometers in the X and Z axes, or the longitudinal and anteroposterior axis respectively. At this point in time these observations are made from a qualitative point of view, since precise adjustments for reference compensation are still under study.

Fig. 8 shows the strokes of two female swimmers with similar age, weight, height, and swimming experience, offering a comparative view of an equivalent frame of time during a non-competitive (or relaxed) lap. Although both swimmers had similar lap times (close to 30 seconds for both) differing behavior can be observe. The visual perception of the swimmers during the measurements concurs with them presenting different styles. While swimmer one (1) had a calm, long and steady stroke, swimmer two (2) had a more intense and quick stroke.

It is still early in this project to produce conclusive results regarding feature extraction for performance analysis, and there is a clear need for accumulating data of diverse swimmers of different genders and competitive level; however these first steps

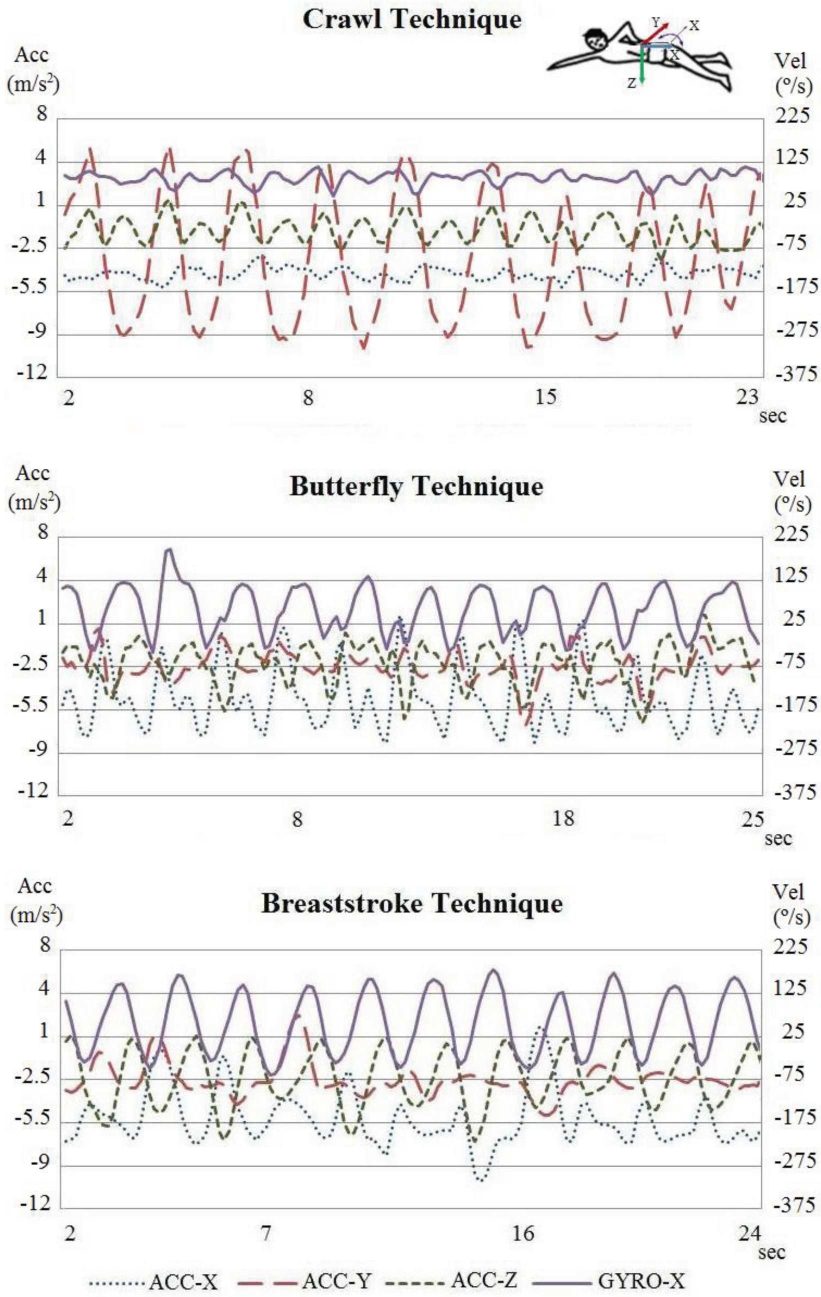


Fig. 7. Equivalent lap section captured signals for each performed technique

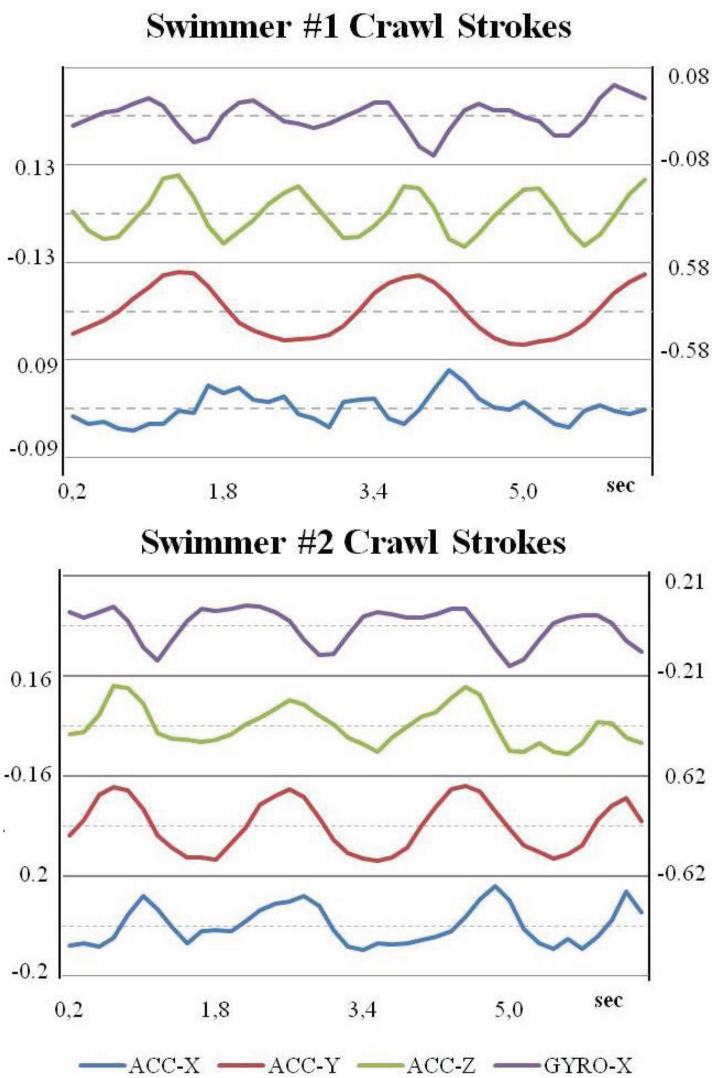


Fig. 8. Two swimmer strokes comparison. Signals from both swimmers correspond from top to bottom to: Gyro-X, Acc-Z, Acc-Y, Acc-X.

seem quite promising. Several challenges present themselves when considering the data acquired and the references of the setup; in particular when considering the mobile nature of the individual, the curvature of the back, the inherit offset present in some sensors and possible error introduced by the acquisition chain. A more comprehensive analysis of the data gathered up to now and future collections, as well as feature extraction strategies for performance analysis will be presented in future works. In a parallel effort, biomechanical models are being developed that utilize the data in order to take advantage of their specificities. Although not its original objective, the WIMU has been used to capture signals from lower and upper limbs in a number of varying activities, mostly for testing purposes. A particular case study of interest was the use of the WIMU during rehabilitation sessions for cases of cerebral stroke. The patients in such a case were undergoing rehabilitation terapy for upper limb movement restauration. The objective is the development and implementation of a home rehabilitation exercise assistant, utilizing the WIMU's signals for real-time audio-visual feedback.

6 Conclusions

In this paper, we present a prototype for swimming performance analysis monitoring based on accelerometers and gyroscopes, referred to as WIMU. The WIMU is one of the objectives of a much more ambitious multi-disciplinary effort of a group of Portuguese research and development teams, known as the BIOSWIM project. Such project seeks to characterize swimming through physiological and biomechanical signal capturing at points distributed throughout the athlete's body. Although the device presented is still at the prototype stage of development, it was capable of providing promising data under in-pool normal conditions. The current version of the WIMU serves as a basis for future implementations that will focus on wearability, energy harvesting, and integration within the BIOSWIM's project swimsuits.

Acknowledgements. The authors would like to acknowledge the Foundation for Science and Technology of Portugal for their support of the BIOSWIM project (PTDC/EEA-ELC/70803/2006) and some of the PhD students involved in this article (SFRH/BD/61396/2009 and SFRH/BD/60929 /2009). Additionally the authors would like to acknowledge the contribution of Barbara Mota and Catarina Araujo, main testing swimmers.

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