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Tracking elite swimmers in real time with wearable low-power wireless sensor networks

Jeroen Lecoutere[a]*, Robert Puers[a]

[a]*KU Leuven ESAT-MICAS, Kasteelpark Arenberg 10, 3000 Leuven, Belgium*

Abstract

Monitoring elite athletes in real-time remains challenging. A lot of research has been conducted towards the application of inertial measurement systems for the quantification of performance in sports applications. The challenge however, remains in creating systems that meet high comfort standards in order to be able to apply them on a daily basis. The problem is mainly related to the requested volume of existing systems, which can be linked to the high power requirements and hence large batteries. This paper presents research towards the performance assessment of elite swimmers using wearable low-power sensor networks. This is the first work to focus on the reduction of power consumption by optimizing the power cost of signal processing and sensor use on a small and comfortable system. A built-in algorithm exploits the sensor data in order to predict which information is valuable to assess the motion of the athlete in real-time. Moreover, the algorithm is designed to run on a low-power microcontroller unit and uses lightweight computational techniques that further reduce the power requirements. By intelligently putting the sensor system into a low-power mode whenever possible, a reduction in sensor power consumption of 96% is estimated over minimally 80% of the swimming time, depending on the swimmer's lap times. Stroke types and turns were detected with high accuracy for each tested swimmer, despite different stroke techniques.

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Keywords: swimming; inertial sensors; sensor networks; wireless; tracking; motion; low-power

1. Introduction

Automating performance assessment enables coaching staff to focus more on crucial aspects in the training process, such as technical or mental skills. Compared to many other applications for on-body wearable electronics, monitoring elite athlete performances might be one of the most demanding ones. In contrast to recreational sports or daily life tracking, elite athletes value every possible small increase in performance. Hence, these athletes demand wearable trackers that should be as unobtrusive as possible. Swimmers basically only wear a swimsuit, goggles and a swim cap, so wearing any additional device already poses a significant obstruction. This environmental factor has been one of the major restrictions for wearable technology to be adapted into the sport of swimming, in contrast to e.g. cycling and running.

Nowadays, stopwatches are still the most commonly used tool to keep track of a swimmer's split times or stroke frequencies. The use of a stopwatch as a coaching tool inherently restricts the coach in being able to track many athletes synchronously and in giving every athlete his much-needed feedback. This research designed a system that automatically registers parameters such as lap time, stroke type, lap count, average distance per stroke and stroke frequency. Keeping track of these parameters enables the coach and swimmer to quantify the athlete's performance during a workout or entire season. This gathering of information can be used to adapt training periodization or prioritization, rendering an improved and personalized training program during the preparation towards an important goal or competition.

* Corresponding author. Tel.: +3216321108;
E-mail address: jeroen.lecoutere@kuleuven.be

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Previous work [1-2] has shown that an indication of training intensity can be acquired through the measurement of these swimming parameters. Therefore, these parameters can be used to steer the physiological load throughout a workout. The most common methods in swimming for evaluating stroke efficiency and technique involve video systems that capture images of the motion of the athlete [3]. The interpretation of videos and pictures is the easiest way of providing feedback towards athletes concerning movement control and technique execution. However, video systems often do not generate any automated and quantifiable parameters [4]. This makes it hard to use this method to keep track of long-term performance and progress. Furthermore, the application of video analysis tools in a training environment with many swimmers training at once is not feasible. A final disadvantage of imaging techniques is the restrictions many pools impose towards video in order to safeguard the privacy of other pool guests.

In the search for systems that can easily extract parameters Craig et al. [5] have attached swimmers to a pulley with a cable system. This system allowed the capturing of speed and position of the swimmer. They combined the measured signal with video registration in order to make the data easily interpretable. The use of cables in a daily training environment is however not feasible with multiple swimmers in one lane and because of the hindering effect a cable has on the biomechanical movements of a swimmer.

In the last decade, research has emerged using microelectromechanical systems (MEMS) to track biomechanics in several sports [6-7]. For swimming, MEMS sensor systems were placed on several locations on the body (i.e. head, back, wrist, sacrum) [8-11]. The combined research showed the ability to extract parameters such as time per stroke, stroke frequency, stroke type and lap times. Ohgi et al. [12] were able measure several phases within a freestyle arm pull and was also able to assess fatigue [13] offline. Online measurements and parameter extraction have been researched [14]. However, no system provided real-time data collection and parameter extraction whilst utilizing a small and comfortable system.

Achieving a small and comfortable system contains several challenges. The major size determinant in current wearable devices is the battery. Batteries store energy for the system to run on. The less energy the system requires, the smaller the battery and system will be. So, to achieve a comfortable, unobtrusive system size, system design must include low-power implementations of hard- and software, which is the main goal of this work.

2. Materials and Methods

2.1. Low-power electronic hardware design

In order to measure performance parameters on a daily basis, our system is directed towards comfort and miniaturization [15]. Our proposed system consists of a CC430 transceiver and microcontroller [Texas Instruments], an MPU-6000 inertial sensor system [Invensense] and a N25Q064A13EF640E 64Mb NOR flash memory [Spansion] whilst achieving a total size of 16 mm × 12 mm × 10 mm (Fig. 1a). The accelerometer and gyroscope are sampled on three orthogonal axes at 40 Hz within a respective range of ±2 g and ±250 °/s at a resolution of 16 bits in order to accurately register the motion of the athlete. In the MPU-6000 [Invensense], both sensors are integrated in a single package and share the digital interface, which reduces size. A NOR flash memory N25Q064A13EF640E [Micron] with a capacity of 64 Mb was selected. The system can therefore register the aforementioned raw motion data for 116 minutes, which is ample for registering data during our preliminary validation tests. Communication between digital blocks uses the Serial Peripheral Interface protocol (SPI). The design of our system is smaller than any of the existing systems [7], which makes it ideal for wearable application in swimming, as swimming athletes are very demanding with respect to comfort. Big bulky devices hinder the athlete and create a specific and different proprioceptive awareness in the water, which is unfavourable because a workout should always try to closely simulate the competition situation.

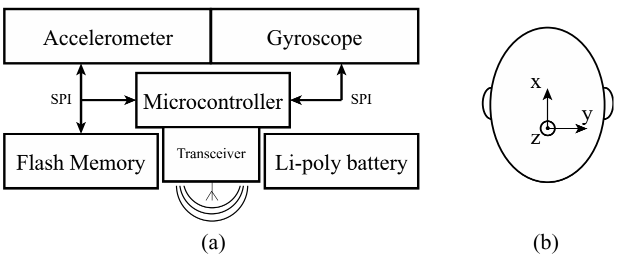

Figure 1: (a) A schematic representation of the system building blocks [15] and (b) the orientation of the inertial sensors on the back of the head

2.2. Low-power embedded software design

This work mainly aims to reduce power consumption through the intelligent use of sensor information. Previous work shows that this can be achieved by processing the recorded raw data down to essential parameters with lightweight algorithms [16]. The essential parameters and timestamps extracted from the raw data in our work are: stroke type (ST), time of turn (ToT), time of stroke (ToS) and time of breath (ToB). With these values, the most important, currently used stroke parameters in swimming can be deduced (Table 1). This paper will specifically discuss the extraction of ST in more detail. The parameter extraction algorithm is developed for a microcontroller and thus avoids complex calculations, overflow problems and huge memory buffers. Despite being an online algorithm, which calculates parameters in real-time, there are only 12 bytes worth of temporary variables needed to determine the four previously mentioned time stamps. This saves calculation time and complexity, and thus power.

Table 1. Acquired swimming parameters

Deduced swimming parameter	Basic swimming parameter deduction	Unit
Stroke Type	ST	/
Stroke Rate	1/(ToS(2)-ToS(2))*60	Strokes/min
Breathing Rate	1/(ToB(2)-ToB(2))*60	Breaths/min
Lap Time	ToT(2)-ToT(1)	Seconds/lap
Average distance per stroke	Lap length / Stroke count	Meters
Underwater time	ToS(1)-ToT	Seconds

By combining the information contained in the processed data with prior knowledge of swimming biomechanics, the efficiency of the system can be increase even more. To determine the current ST during swimming, the algorithm takes into account that the swimmer has a glide phase after each push-off from the wall (ToT). During this phase, it is simply not possible to detect ST, so the algorithm turns off all sensors until the probability of performing a swimming stroke is higher. This not only saves a significant amount of sensor power, but can also be used to turn off the radio communication, as the swimmer will at that point be in an underwater phase. Being underwater means a much lower probability for efficient radio communication. Turning off the transceiver in an intelligent way based on a smart integration of sensor information can save a lot of power, as transmission power is typically a large factor in the energy budget of wireless sensor devices. So in short, reducing wireless communication by reducing data, and reducing sensor overhead through smart algorithms, increases power efficiency.

2.3. Experimental setup

For this work, nine elite athletes (National Championships level, 7 male, 2 female) were asked to perform a 200 meters individual medley in a short course (25 meter) pool. A 200 meters individual medley consists of respectively two laps of butterfly, two laps of backstroke, two laps of breaststroke and two laps of front crawl. The swimmers were asked to swim at an easy pace with a sensor node placed on the back of their head (Fig. 1b). The swimmers were also filmed with a waterproof video camera [Sony] in order to validate the inertial data and parameter extraction algorithms visually. The nine elite athletes each have their own specialization stroke(s) (Table 2), which enables us to analyze stroke technique variability effects on the algorithm's accuracy. The swimmers were also inquired concerning the wearability of the device. Questions were asked about the size and location of the device on the body during swimming.

Table 2. The elite swimmers' stroke specialization(s)

Specialization	Swimmer ID#'s
Butterfly	3,4,5
Backstroke	6,7,9
Breaststroke	1,2
Freestyle	4,6,8

3. Results

Our stroke and turn detection algorithm reduces the raw data of six sensors at 16 bits per sample and a sample rate of 40 Hz, or 3.84 kbps, down to 16 bits per lap. These 16 bits contain lap time and stroke type information. Furthermore, our proposed method does not only reduce data through processing but also completely turns off specific sensors that contain no additional information depending on the detected activity (Fig. 2). The proposed online algorithm was able to reduce the amount of used sensors to maximum three. By intelligently putting the sensor system into a low-power mode with the gyroscopes turned off whenever possible, a reduction in sensor power consumption of 12 mW (96%) is estimated over minimally 80% of the swimming time, depending on the swimmer's lap times. This is because gyroscope power consumption is significantly higher than that of the accelerometer. Freestyle, backstroke and the occurrences all turns were detected with 100% accuracy for each tested swimmer, despite different stroke techniques. For breaststroke, the classification algorithm resulted in a classification error of 28% misclassified breaststroke laps. They were classified as being butterfly. All butterfly laps were correctly classified as butterfly.

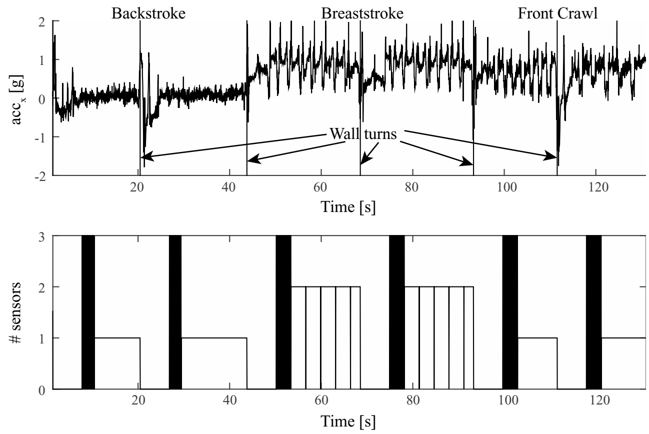

Figure 2: (top) Typical x-axis accelerometer with automatic stroke and turn classification and (bottom) the amount of sensors activated over time with gyroscope activation in solid black

It can be stated that the size of our device does not influence the training process or the biomechanical environment of the swimmer. Test subjects unanimously indicated no hindering effect of the measurement device on the back of their head and found the size of the system comfortable to wear on a daily basis. An important factor for acceptance is the motivation to wear the device due to its clear advantages for the swimmer, which are explained in the introduction.

4. Discussion

Our system can collect raw accelerometer and gyroscope data and compress it into relevant parameters. By reducing this raw data, wireless communication throughput, memory usage and power consumption are drastically reduced. ST can be detected together with turns, breaths and strokes. The breaststroke classification error is mainly due to subject-related stroke technique differences. Historically and skillwise, breaststroke and butterfly stroke are very related strokes, especially when looking at the biomechanics of the head movement. Further research is needed to determine whether it is possible to separate these two strokes in large datasets. Previous work often does not take one of these two strokes into account and/or is based on very small data sets.

Current work is investigating the effect of swimming biomechanics on the wireless communication link. Combining the extracted biomechanical parameters with wireless link quality information is expected to grant a deeper understanding of how to develop an efficient application specific wireless communication protocol. This could reduce power consumption even more.

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