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Validation of an inertial measurement unit for the determination of the longitudinal speed of a swimmer

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Introduction

In swimming, the athlete's performance is reflected by swimming speed. Unfortunately, this measurement remains difficult due to the specific constraints of testing in an aquatic environment. Either the method constrains the task that can be analysed (only one length can be swum when using speedometers; Craig, Termin, Pendergast, 2006; Schnitzler et al., 2010) or the method, that offers greater flexibility, is complex, time-consuming and/or can not guarantee acquisition of all desirable data (such as bubbles around the swimmer's body and line-of-sight difficulties in the case of video based systems; Callaway, Cobb, Jones, 2009; Puel et al., 2012).

Technological advances however, that overcome these concerns are beginning to change the way we measure (and in turn perceive) athletic performance. The past twenty years has seen the increasing use of inertial measurement units in the study of human movements (Cuesta-Vargas, Galán-Mercant and Williams, 2010) and sports biomechanics, including swimming (Ohgi, 2002; Dadashi et al., 2011; Stamm et al., 2011), especially as these systems becoming more financially feasible (Mayagoitia, Nene, Veltink, 2002).

The aim of this study was to validate an inertial measurement unit prototype specifically designed for swimmer movement analysis (CIREN, Actris, Brest, France; Figure 1), against current gold standards for estimating rotational speeds, translational accelerations and longitudinal speed of the swimmer relative to a global reference frame.



Figure 1: Draft of CIREN, the inertial measurement unit prototype

Methods

The CIREN prototype is based on a NANO MEMSense inertial measurement unit that consists of a combined three-axis accelerometer sensor (\pm 5 g), magnetometer (\pm 1.9 Gauss) and gyroscope (\pm

600 °/s) and an embedded data logger, which records at 150 Hz. The sensor is assembled within a sealed housing (IP68, outer dimensions are 117 x 80 x 33 mm).

This study involved three different experiments.

The first one was conducted in a mechanical lab where CIREN was mounted on a MIKRON HSM 600U, a 5-axis machining centre that can reproduce and control chosen trajectories (Figure 2). Different sets of movements where tested (50 repetitions of one-axis rotation or one-axis translation).



Figure 2: Prototype's initial positions when mounted on the mobile plate of the machining tool

The following two experiments were then conducted in a pool and involved a sample of experienced swimmers. Participants wore CIREN, placed on the lower back, secured by a belt and belt loops specifically designed in the unit to mount it firmly (Figure 3).



Figure 3: Prototype's position when worn by a swimmer

The longitudinal speed of the swimmer was determined by three methods: the use of CIREN v6.0 software (Figure 4), which integrates all embedded sensors and predefined initial constraints (initial position of the swimmer and pool length); a speedometer, and; via a multi camera video system.

In Experiment 2, CIREN was compared with a tethered speedometer, used as the velocity measurement reference (Leblanc et al., 2007; Schnitzler et al., 2010; Dadashi et al., 2012). One regional swimmer swam a 25-m in her stroke speciality (breaststroke) and at her training pace.

In Experiment 3, one international swimmer swam an all-out 25 m in front crawl and comparisons were made between CIREN and 3D video based kinematics (5 aerial cameras, videos deinterlaced at 50 Hz, data extrapolated at 150 Hz to match sensor's data, calibration frame with 49 calibration points, 3.67 x 1.63 x 1.42 m).



Figure 4: CIREN's software interface for the determination of the longitudinal speed

Statistics.

For analysis of both the first and the third experiment Spearman's correlations (*r*), normalized pairwise variability index (nPVI; Sandnes and Jian, 2004) and the percentage of signal outside the confidence interval (CI) of Bland & Altman were computed. For the first experiment, no smoothing or filtering was applied to the data, whether from the inertial measurement system or from the machining centre. Therefore, the comparison concerns the raw signals on the entire lengths of the acquisitions.

For analysis of the second experiment the discrete relative phase was computed (Zanone and Kelso, 1992). Two maximum and two minimum local peaks by cycle were taken into account.

Results

Experimentation 1.

The rotation test showed excellent agreement: 0.82 < r < 0.84 (p < 0.0001), 1.08 < nPVI < 1.21 and the percentage of signal outside CI from 2.67 to 3.16% (3418 samples). As did the translation test: 0.18 < r < 0.28 (p < 0.0001), 2.11 < nPVI < 4.25 and the percentage of signal outside CI from 2.01 to 2.63% (3455 samples). Figures 2 and 3 present respectively rotational speeds and translational accelerations by means of the MIKRON machining tool and CIREN.



Figure 2: Rotational speeds by means of the gold standard (MIKRON machining tool, red line) and the prototype (blue line).



Figure 3: Translational accelerations by means of the gold standard (MIKRON machining tool, dark dashed) and the prototype (grey line).

Experimentation 2.

Figure 4 presents longitudinal speeds of the hip in breaststroke for speedometer and CIREN. The analysis of 28 consecutive local peaks shows that speedometer's signal was slightly in advance (6.7 °) and the mean discrete relative phase was $21.2 \pm 16.8^{\circ}$.



Figure 4: Longitudinal speeds of the hip in breaststroke for the gold standard (speedometer, dark dashed) and the prototype (grey line)

Experimentation 3.

Figure 5 presents longitudinal speeds of the hip in crawl for 3D kinematics and CIREN. Point by point comparison revealed r = 0.49 (p < 0.0001), nPVI = 0.11 and the percentage of signal outside CI = 3.57%.



Figure 5: Longitudinal speeds of the hip in crawl for the gold standard (3D kinematics, dark dash) and the prototype (grey line)

Discussion

When compared to well-tried mechanical system, CIREN provides rotational speeds and translational accelerations that are in excellent agreement, validating the system under the tested ranges of motion.

In swimming, the longitudinal speed computed by CIREN appears more sensitive and presents smaller amplitudes than the speedometer's signal, presumably because of the speedometer's design (a motor used as generator that measures the speed of wire unwinding) and also because a torque is applied to keep the cable tight, reasons that could mask some of the more subtle high speed variations related to the extra amplitudes apparent in the CIREN signal. Furthermore, speedometer's average speed appears to be lower than CIREN's average speed got by timing. However, the CIREN's drift correction conceals any change in the average speed during the test, nevertheless the magnitude and pace are not affected.

The third experiment showed good agreement between the signals from CIREN and 3D kinematics. The longitudinal speed computed by CIREN can be considered as valid in the context of high-level swimmer analysis. Indeed, the speed curve clearly shows the stroke cycles and a simple check of frequencies confirm this conclusion.

Conclusions

CIREN provides a good estimation of the instantaneous speed of the swimmer and, beyond that, allows consideration of movement variability (stroke frequency).

Compared to conventional systems, additional features lie not only in the analysis of roll, but also in the continuous analysis over the entire length of the pool, even for tests for which the distance to swim is greater than one pool length. Furthermore, CIREN improves the low frequency of conventional video analysis system, facilitates the implementation of the study (no complicated setup), limits the inconvenience caused by wearing a measure system, and finally speeds up the feedback to the operator (coach, sport scientist, etc.).

In perspective, it would be interesting to compare, in a laboratory situation, our prototype with another mechanical systems able to reproduce the 3D motion of the swimmer along with translation in order to further confirm the validity of the CIREN protocol for the evaluation of speed.

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