A preliminary approach for swimming performance analysis of FISDIR elite athletes with intellectual impairment using an inertial sensor

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***Abstract*—People with intellectual impairment show low performances in motor control, especially in complex movements. Performance analysis methods, based on wearable inertial sensor, are often used in typical developed swimmers but have never been used in swimmers with intellectual impairment, for whom the use of quantitative systems would be even more important. This paper presents a case study conducted on freestyle swimmers from the functional evaluation project of the Italian Sport Federation for athletes with Intellectual Impairment (FISDIR). The tests were conducted by five Italian elite swimmers with intellectual impairment using a structured experimental protocol which foresees an inertial sensor located on the wrist. Key freestyle temporal and kinematic parameters were assessed. A high-speed camera was used as a benchmark to validate the inertial-based parameters. The preliminary results indicate that the proposed inertial-based approach correlates over 90% with the performance indices obtained with the camera-based approach, and therefore it could represent a useful tool for monitoring and improving the training.**

***Index Terms*—intellectual impairment; swimming; wearable inertial sensor; performance analysis; sports biomechanics.**

I. INTRODUCTION

Intellectual Impairment (II) is a disorder that includes both intellectual and adaptive functioning deficits in conceptual, social, and practical domains [1]. The most practised individual sports for elite athletes with II are athletics and swimming [2]. For the athletics, several studies of previous literature are focused on running. They show lack of reliability of subjective responses about performance metrics [3], different running patterns (with lower step length and smoothness) [4], and an increased variability in performance, when asked to maintain a steady-state [5]. Indeed, swimmers with II have been rarely studied in the literature. A previous work, using video race analysis, investigated speed, stroke rate and stroke length [6].

To assess key performance indices in swimmers with typical development, recently, wearable inertial sensors have been proposed as an alternative to video-based approaches, which usually require an expertise and are time-consuming [7], [8]. The most popular sensor locations are lower back and wrist [9]. Wrist-worn design are common in commercial devices since they represent the best user-friendly solution. Starting from inertial data of a single wrist-worn sensor, temporal and kinematic parameters can be assessed [9]. This methodology, already used in typical developed swimmers, was never tested before in II swimmers. In particular, this methodology could be even more beneficial for II swimmers, as they present an impaired body understanding and a constrained movement capacity, especially related to synchronized movements [1].

The functional evaluation project of the Italian Sport Federation for athletes with Intellectual Impairment (FISDIR) has been funded with the objective to develop methodologies for a quantitative motor activity assessment of elite athletes with II (practicing athletics and swimming) [10]. In this context, the paper details the methodology and the validation of an inertial-sensor based approach for estimation of swimming performance parameters related to elite swimmers with II.

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TABLE I

DATA COLLECTED RELATED TO SWIMMERS' PERSONAL DETAIL (VIRTUS CLASSIFICATION [11], AGE, PREFERRED HAND, PERSONAL BEST ON 100 METERS FREESTYLE) AND ANTHROPOMETRIC CHARACTERISTICS (STATURE, BODY MASS, BMI).

Swimmer	**Gender**	**VIRTUS Class**	**Age** [year]	**Stature** [cm]	**BMI** [kg/m^2]	**Body Mass** [kg]	**Preferred hand**	**PB 100m** [s]
1	Male	II-3	21	178	25.2	80	Left	58″9
2	Male	II-1	23	157	19.9	49	Right	64″4
3	Male	II-1	25	179	23.4	75	Right	59″7
4	Male	II-1	26	168	19.1	54	Right	59″8
5	Female	II-1	18	168	18.8	53	Right	74″4

II. MATERIALS AND METHODS

A. Participants

Five Italian elite swimmers of FISDIR (four male and one female) participated in the study. After an initial briefing, the informed consent from volunteers as well as the survey form were collected by the test leader. Participants signed the written informed consent, in accordance with the Human Research Ethics Committee of the Griffith University, that approved this study (GU Ref. N° 2019/847). The participants had not any current illness and they had not suffered injuries in the last twelve months (which might affect the performance) before the testing day. Swimmers' personal details and anthropometric characteristics, shown in Tab. I, were collected by the test leader.

B. Experimental protocol

The protocol study consisted in three tests on 100 meters (four laps) freestyle at three different paces (low, medium and high speed). The head coach helped the swimmer to keep the pacing required. Between each trial, to obtain a complete recovery, a rest period of three minutes was guaranteed.

The experimental activity was conducted at the indoor swimming pool (length 25 meters) of the Queensland Sport Academy. To assess temporal and kinematic swimming parameters, an inertial sensor (SABEL Sense, Griffith University, Nathan, Australia [12]) was used. The sensor has dimensions 55 mm × 30 mm × 13 mm (L×W×H) and a weight of approximately 23 g. It includes a tri-axis magnetometer (Dynamic Range (DR): ±7 Gauss), a tri-axis gyroscope (DR: ±2000 deg/s), a tri-axis accelerometer (DR: ±16 g), and it was set to 250 Hz sampling rate. To collect video data from the test, two cameras were used: (i) one fixed video camera (Canon PowerShot G3 X full HD 1080 p) 5020.9 megapixels, for the overall gesture acquisition; (ii) one mobile high speed-camera (GoPro Black Hero4, Woodman Lab) following the swimmer during the test, operating at 240 fps with a resolution of 848x480 in 16:9, for lateral view acquisition. Fig.1 shows the experimental setup.

After a standard warm up session, an inertial sensor was securely attached on the swimmer's right wrist like a wristwatch. The sensor was put in a transparent plastic bag, which was fixed at the swimmer's wrist by waterproof medical adhesive. The inertial sensor reference orientation was defined by anatomical calibration of the athlete/sensor fixing the sensor according to wrist reference system. The orientation of the acceleration sensor is shown in Fig.1. To ensure the familiarization with the sensor and the comfort of the swimmer before the test, some additional warm-up laps were carried out.

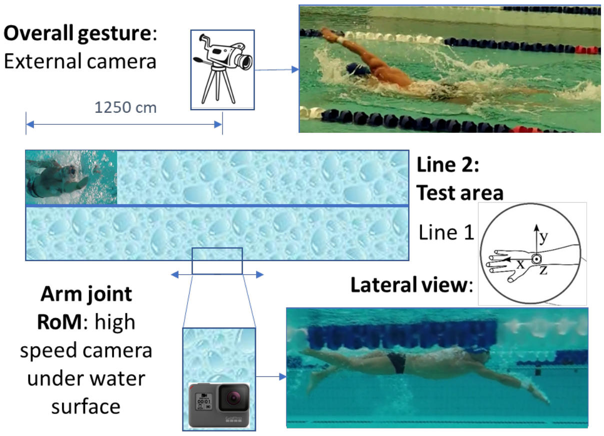

Fig. 1. Design of swimming test setup. In the top the fixed (in the middle of the lap) external camera that allows to acquire the overall gesture. On the bottom a focus on the mobile camera that allows to collect a lateral view of the swimmer to analyze the Stroke Phase. The inertial sensor axis orientation is shown on the right [13].

C. Data Processing

Data processing was performed in MATLAB (MathWork, Natick, MA, USA). The process starts with the assessment of the following temporal parameter events: start time (T_s), swimming phase start time (S_S), swimming phase finish time (F_S), wall contact rotation time (T_t), and finish time (T_e), see Fig.2. The wrist anatomical anterior-posterior acceleration data (a_x, according to sensor's orientation in Fig.1) were filtered (with a zero-phase digital filtering, to delete the phase shift) using a low-pass Butterworth filter (4^{th} order, cut frequency of 10 Hz). It represents the dominant axis and varies around $-2\ g$ in steady-state condition, as in a previous work [13].

Starting from these data, in the first lap, the T_s event was registered at the point of the first falling slope in a_x, whereas a large impact peak and rising slope on a_x signified that the wall contact (W_C) event had occurred. In the last lap, this event represents the finish time (T_e) [13]. The raw data of angular velocity related to wrist anatomical medio-lateral axis (ω_y) allows to detect single arm strokes, through a peak detection method.

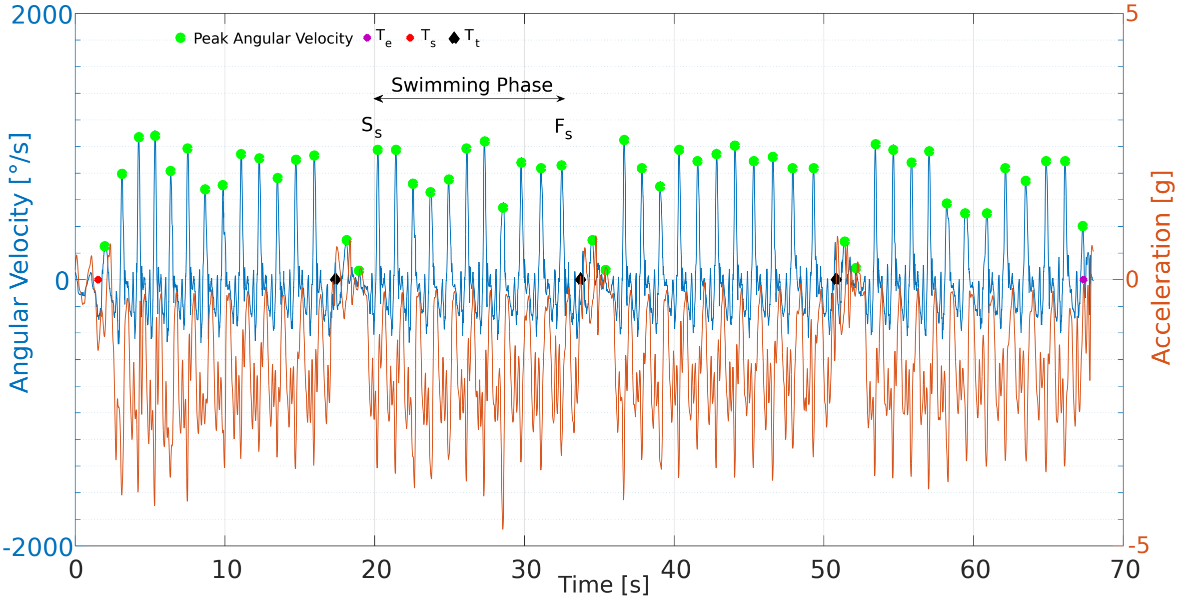

Fig. 2. Raw angular velocity wrist anatomical medio-lateral lap profile (blue) with filtered acceleration anterior-posterior profile (red) related to the swimmer ID4. Main temporal events are assessed on the two profiles.

For the assessment of the swimming phase for each lap (from S_s to F_s event), we excluded the first two strokes and the last one, to evaluate the steady-state gesture. Finally, the ω_y pattern analysis in the normalized stroke cycle allows to detect the key events of the freestyle stroke cycle: hand entry (A); catch (B); hand left (C) [8]; see, e.g. Fig.3.

Starting from the assessment of the previous temporal events, for each lap i the following parameters were calculated: (1) Lap Time (LT); (2) Push Off phase time (PO); (3) Turn phase time ($Turn$); (4) Swimming phase time ($Swim$); (5) Speed mean (S_m); (6) Stroke Count (SC); (7) Stroke Rate mean (SR_m); (8) Stroke Length mean (SL_m); (9) mean percentages of: Pull (Pul_m), Push (Pus_m) and Recovery (Rec_m) phases in the swimming cycle. The corresponding equations are:

$$\begin{aligned} LT_i &= T_{t,i} - T_S;\ for\ i = 1 \\ LT_i &= T_{t,i+1} - T_{t,i};\ for\ i = 2,3; \\ LT_i &= T_e - T_{t,i};\ for\ i = 4 \end{aligned} \tag{1}$$

$$\begin{aligned} PO_i &= S_{S,i} - T_S;\ for\ i = 1 \\ PO_i &= S_{S,i} - T_{t,i};\ for\ i = 2,3,4 \end{aligned} \tag{2}$$

$$Turn_i = T_{t,i} - F_{S,i}; for\ i = 1,2,3 \tag{3}$$

$$Swim_i = F_{S,i} - S_{S,i} \tag{4}$$

$$S_{m,i} = \frac{25m}{LT_i} \tag{5}$$

$$SC_i = length[\omega_{y,max,i}] - 1 \tag{6}$$

$$SR_{m,i} = \frac{1}{n}[\sum_1^n \frac{1}{t(\omega_{y,max,j+1}) - t(\omega_{y,max,j})}] \tag{7}$$

$$SL_{m,i} = \frac{S_{m,i}}{SR_{m,i}} \tag{8}$$

$$\begin{aligned} Pul_{m,i} &= \frac{1}{n}[\frac{B_i - A_i}{A_{i+1} - A_i}] \\ Pus_{m,i} &= \frac{1}{n}[\frac{C_i - B_i}{A_{i+1} - A_i}] \\ Rec_{m,i} &= \frac{1}{n}[\frac{A_i - C_i}{A_{i+1} - A_i}] \end{aligned} \tag{9}$$

where i is the number of the lap in each test, $[\omega_{y,max,i}]$ is the vector of $\omega_{y,max}$ for each lap, j is the number of single stroke, n is the total number of strokes in the $Swim$ phase for each lap. From the high-speed camera data, the key events of the freestyle stroke cycle were manually evaluated, selected through video analysis (Kinovea, Charmant&Contrib.) by an expert according to the definitions in [14]. The following parameters were obtained: (i) Stroke time, obtained as time difference between two consecutive frames related to the A event; (ii) Pull phase, obtained as time difference between the frame of the event A and the frame of the event B; (iii) Push phase, obtained as time difference between the frame of the event B and the frame of the event C; (iv) Recovery phase, obtained as time difference between the frame C and the following event A. Lap times were derived from video as the time from the wall push off event to W_C using external camera.

III. RESULTS AND DISCUSSION

Table II shows an example of the output data for a single swimmer, based on the inertial sensor data processed according to the procedure described in Sec. II-C.

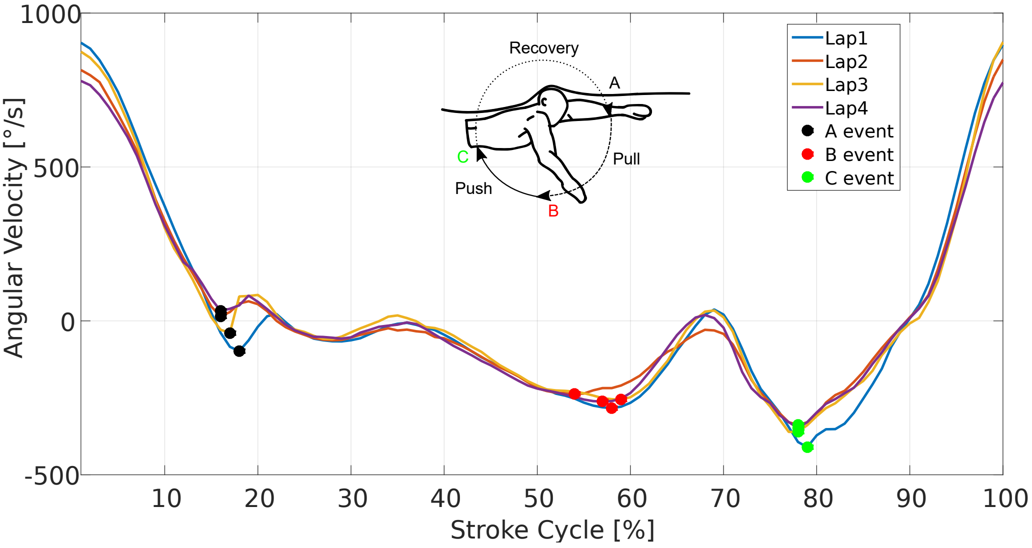

Fig. 3. Mean value for the four laps test of the angular medio-lateral (ω_y) as function of the stroke cycle (swimmer ID4).

TABLE II
TEMPORAL AND KINEMATIC SWIMMING PERFORMANCE PARAMETERS RELATED TO THE SWIMMER ID4.

		LT [s]	**PO** [s]	**Turn** [s]	**Swim** [s]	**S**$_{\mathbf{m}}$ [m/s]	**SC** [-]	**SR**$_{\mathbf{m}}$ [Stroke/s]	**SL**$_{\mathbf{m}}$ [m/Stroke]	**Pul**$_{\mathbf{m}}$ [%]	**Pus**$_{\mathbf{m}}$ [%]	**Rec**$_{\mathbf{m}}$ [%]
Test 1	Lap1	17.66	1.35	1.47	12.05	1.42	12	0.75	1.90	41	19	40
	Lap2	17.77	0.98	1.29	11.72	1.41	12	0.76	1.84	42	19	39
	Lap3	17.08	0.83	1.49	11.51	1.46	12	0.78	1.87	41	20	39
	Lap4	16.70	0.92	-	12.51	1.50	13	0.80	1.86	42	20	38
	Mean	**17.30**	**1.02**	**1.42**	**11.95**	**1.45**	**12.25**	**0.77**	**1.87**	**41.5**	**19.5**	**39**
Test 2	Lap1	15.85	1.59	1.40	11.62	1.58	13	0.86	1.83	40	21	39
	Lap2	16.36	0.74	1.23	10.91	1.53	13	0.83	1.85	38	24	38
	Lap3	17.10	0.84	1.52	11.26	1.46	13	0.80	1.83	42	19	39
	Lap4	16.53	0.57	-	12.71	1.51	14	0.79	1.91	41	21	38
	Mean	**16.46**	**0.94**	**1.38**	**11.63**	**1.52**	**13.25**	**0.82**	**1.86**	**40.3**	**21.3**	**38.4**
Test 3	Lap1	14.96	1.56	1.14	11.04	1.67	13	0.91	1.84	40	20	40
	Lap2	16.36	0.81	1.38	11.27	1.53	13	0.84	1.82	39	22	39
	Lap3	16.31	0.60	1.23	11.09	1.53	13	0.81	1.88	41	21	38
	Lap4	16.83	1.01	-	12.43	1.49	14	0.81	1.84	41	21	38
	Mean	**16.12**	**1.00**	**1.25**	**11.46**	**1.56**	**13.25**	**0.84**	**1.85**	**40.3**	**21**	**38.7**

For the validation of these outputs, we select a set of data related to five different tests, to carry out a comparison of the main parameters with a video-based analysis. Figure 4 shows the regression analysis between inertial sensor and video assessment for the Lap times (n=18) and Stroke Time (n=48). The preliminary results show a strong positive linear relation for each parameter (R^2=0.936 for Lap Time, R^2=0.920 for Stroke Time), as in similar validation processes with typically developed swimmers [15]. Finally, Figure 5 shows the comparison of the assessment for the stroke phases percentage during the cycle. The bar plot (n=48) underlines little difference (usually under 5%); the duration of Pull and Push phases appears to be underestimated, while the Recovery one results overestimated. These differences could be also related to difficult to quantify the exact timings of each phase by video analysis [15]. It is important to underline that, despite in previous work a validation of the parameters was done for typically developed swimmers, no validation is present in the literature for II swimmers.

IV. CONCLUSION

The preliminary results underline the possibility to perform swimming performance assessments in elite II swimmers using a simple system composed by a single inertial sensor located on the wrist. As a matter of fact, this simple system shows an accuracy comparable to video-analysis. The parameters, such as the evolution at the different paces of the stroke rate and stroke distance, could offer a useful description of the main modification in the swimmer's technique at the different pace. The study of the percentage phases of the stroke can potentially allow the coach to identify what is going on under the water and make appropriate recommendations. These parameters are fundamental for swimmers with intellectual impairment where self-reflection feedback is hard to articulate to coaches. Furthermore, this approach could also offer a quantitative method for the classification process of swimmers with II.

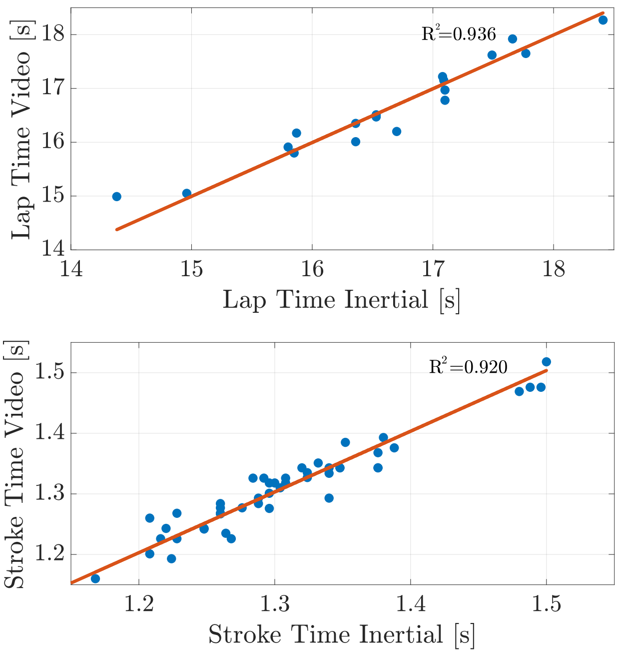

Fig. 4. Regression analysis for Lap Time (top) and Stroke Time (bottom).

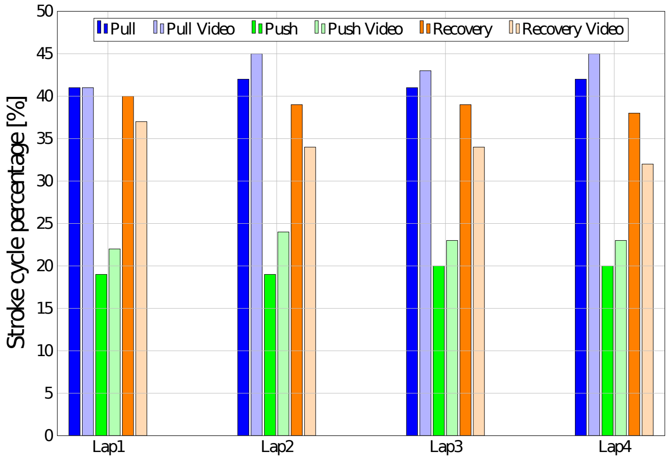

Fig. 5. Inertial-based vs. video-based assessment of the Pull, Phase and Recovery phase cycle percentage).

Starting from these results, future development, using a comparison with typically developed elite swimmers, will be centered on: (i) determination of significant performance parameters based on inertial sensor data useful for improving II athletes' training; (ii) development of synthetic inertial based biomechanical indices [16]–[18] for II swimmers that could offer useful outcome(s) to determine sub-classification criteria.

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