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TECHNICAL NOTE

Reliability, accuracy and ecological validity of a wireless pressure sensor for swimming performance analysis

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Abstract
Pressure measurements are a valuable approach to evaluate swimming performance. However, the traditional cabled pressure devices could affect the swimming technique. In this study, the performances of a wireless and wearable pressure sensor were investigated in terms of i) reliability and accuracy, comparing hydrostatic and hydrodynamic pressures with the theoretical ones, ii) ecological validity, comparing performance when wearing or not sensors in free-swimming. Excellent test–retest, intra-, and inter-sensor reliability were observed for both hydrostatic and hydrodynamic pressures (ICC $\geq$ 0.96) with low bias (MAE $\leq$ 0.1 kPa, RMSE $\leq$ 0.11 kPa) compared to theoretical ones. Free-swimming was affected by wearing or not the sensors with a significative reduction in terms of velocity (0.04 ms^{-1}, $p < 0.001$) and stroke length (0.03 m, $p < 0.05$) but not stroke rate ($p = 0.148$). The wireless pressure sensor can measure the actual pressure in the aquatic environment with high accuracy and reliability, providing an ecological approach for monitoring hand pressure in swimming.

1 Introduction

The assessment of propulsive force during swimming is an ongoing debated topic [1]. Over the last decades, several indirect and direct methods have been developed to assess propulsive forces during swimming [2]. Simulation methods involve computational or numerical estimates and, in the most cases, require data acquired from multiple cameras or particle image velocimetry. In contrast, experimental methods assess the exerted force without the need for complex equipment or setup, relying instead on a one or a few wearable devices on the swimmer [2]. The advantage of one of these latter approaches, which uses couples of sensors placed on both sides of the hand, is that unsteady flow effects are accounted in the swimmer's propulsion. In particular, the resultant force exertion was assessed by multiplying the differential pressure on the hand (calculated as the pressure difference between the palmar and dorsal sides of the hand) by the hand's surface area [3]. Subsequently, to obtain the force previously estimated in the direction of propulsion, a kinematic analysis of hand orientation using video-based analysis [4] or inertial measurement unit (IMU) is required [5].

Early versions of pressure sensors included three or four pairs of sensors with wired connections [3, 4, 6]. Kudo et al. [7] suggested that the optimal number of sensors to obtain an accurate measure of exerted force was twelve. However, the presence of multiple sensors, gloves, or tapes may have ecological implications for the swimmer who has to wear them. In recent years, the development of new wireless devices has enabled the measurement of pressure using one pair of sensors, thereby affording swimmers a more natural and less constrained technique [8–10]. Although this approach reduces accuracy due to pressure being estimated at a single point on the palm, it facilitates practical application and improves swimmer's comfort.

The validity of the pressure sensors in swimming remains a topic of ongoing research as only a few studies have performed reliability or accuracy evaluations [10, 11]. One

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pair of wired pressure sensors revealed excellent day-to-day reliability in measuring the resultant force exerted by the hand on the water [10]. On the other hand, Santos et al. [11] compared the differential pressure approach to the load cell output in tethered swimming, finding differences probably due to the nature of measurements (i.e. only hand force exertion versus whole body force exertion). Given the absence of a force reference measure, and given the availability of the pressure gold standard, which also remains unaffected by variability in swimmer technique, the primary focus should be the pressure measurement. In this context, theoretical pressure can be used as a benchmark for sensor validation. Furthermore, precise measurement of pressure is essential for obtaining accurate estimates of the resultant force exerted by the swimmer's hand. However, without kinematic analysis, it is not possible to distinguish between propulsive and non-propulsive components.

Thus, the first aim of the present study was to evaluate the sensitivity, reliability and accuracy of a wireless and wearable pressure sensor system by conducting two validation tests for hydrostatic (P_s) and hydrodynamic pressure (P_d). The reliability was investigated in terms of intra-sensor, inter-sensor, and test–retest reliability. The accuracy was evaluated by considering the theoretical hydrostatic pressure (P_{sT}) and the theoretical hydrodynamic pressure (P_{dT}) as the gold standard. Furthermore, the wireless devices offer advantages for field application compared to the previously mentioned single-pair pressure sensors [10, 11], such as the absence of wired connections. Therefore, the second aim was to examine the ecological validity of the device in terms of performance during free-swimming conditions.

2 Materials and methods

2.1 Experimental design

This is a validation and observational research study. For the two purposes, three different protocols were performed: i) to test instrumentation's sensitivity and to validate the reliability and accuracy of P_s measured by sensors, ii) to test reliability and accuracy of P_d measured by sensors, iii) to explore the ecological validity of the device during free-swimming. In the first two set-ups, P_{sT} and P_{dT} were considered as reference systems, while in the third set-up, the experimental data from 16 swimmers were exploited. In the first protocol, a bucket of water (20 °C) was used to test sensitivity and reliability, whereas the accuracy evaluation of the first protocol and the other two protocols were performed in a 25-m indoor pool (27 °C), adding in the last a 1000-m warm-up at low-to-moderate intensity. The test order was randomized across all trials. Participants read an information sheet and signed an informed consent form. The project, in accordance with the Declaration of Helsinki, was approved by the local Bioethics Committee (Approval code: 0025066). The same wireless pressure sensor devices were used for all the experimental protocols: SEAL system (Platysens, Hong Kong) consists of an armband that surrounds the hand and incorporates two uniaxial pressure sensors (WxHxD = 52 × 32x7 mm; mass = 25 g; Fs = 50 Hz) placed on both sides of the hand (Fig. 1). Data were acquired and stored in sensors' on-board memory, while downloading of raw pressure data or post-processed estimated force was handled via Bluetooth through a dedicated Android app (SEAL, version 1.0).

2.2 Hydrostatic pressure assessment

To test sensitivity, four sensors were submerged in a water-filled bucket starting from the surface down to a depth of 14 cm (0.5 cm step intervals) to identify the minimal detectable change in pressure due to depth variation. The immersions were performed using a tripod and calibrated bar beneath it (Fig. 2a). Twelve trials were conducted (three per sensor).

To test P_s reliability, one sensor at a time was submerged in the same bucket from the surface down to 50 cm depth (5 cm step intervals, and 5 s static for each step). Six static immersions were performed for a total of eight different sensors, repeated over two days. To test P_s accuracy one sensor at a time was submerged in a swimming-pool down to 120 cm depth (5 cm step intervals, and 5 s static at each step). One static immersion was performed for each of the

Fig. 1 Palmar and dorsal side of the wireless pressure device

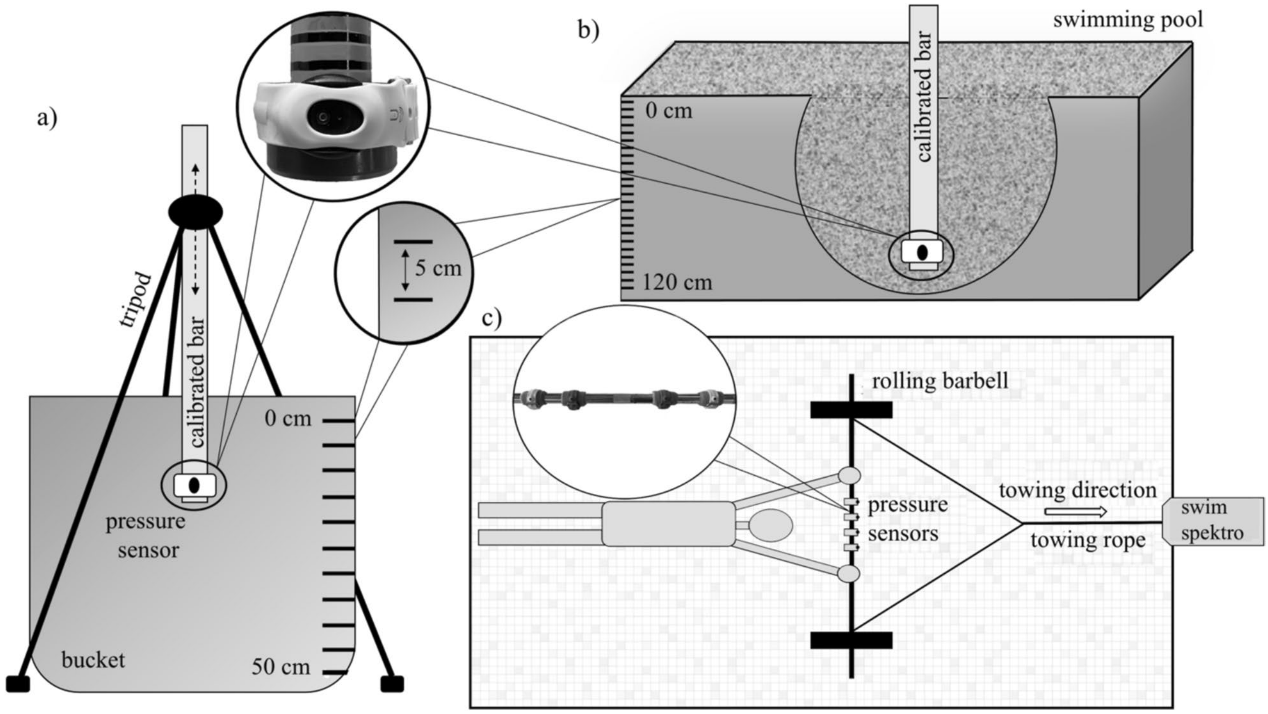

Fig. 2 Panel **a** hydrostatic pressure reliability set-up. Panel **b** hydrostatic pressure accuracy set-up. Panel **c** hydrodynamic pressure set-up

four sensors utilized. The mean value (± standard deviation) of P_s at steady state was compared to P_{sT} calculated as $P_{sT}=P_{atm}+\rho gh$, where P_{atm} is the atmospheric pressure in situ (102.04 kPa), ρ is the water density at 27 °C (996.53 kgm^{-3}), g is the gravitational acceleration (9.81 ms^{-2}), and h is the depth from the water surface.

2.3 Hydrodynamic pressure assessment

P_d of four sensors was measured during eleven passive towing trials (0.5 – 1.5 ms^{-1}, 0.1 ms^{-1} interval) using the Swim Spektro system (Talamonti Spa, Ascoli Piceno, Italy). Sensors were attached to a barbell that had been rolled on the pool bottom at 1.08 m depth, held by an operator to ensure stability (Fig. 2b). Pressure between 10 and 5th meter from the starting wall was used to calculate mean P_d (± standard deviation) at each towing velocity steady state. To isolate P_d, P_s at 1.08 m depth (112.56 kPa) was subtracted from the total sensor pressure. Then, P_d was compared to P_{dT} (kinetic energy per unit volume) calculated as $P_{dT}=0.5\bullet\rho\bullet v^2$ where ρ is the density of the fluid at 27 °C (996.53 kgm^{-3}), and v is the towing velocity. This procedure assumes that the sensors are consistently aligned perpendicular to the flow direction, without considering potential artifacts arising from slight misalignments between the sensor and the flow, or flow separation (i.e. due to the sensor geometry).

2.4 Ecological assessment

Sixteen young swimmers (four Females) aged 16.6 ± 1.0 years, with a stature of 177.6 ± 6.8 cm, body mass of 68.6 ± 6.9 kg, with over five years of swimming experience and a weekly training volume of 30 ± 6 km were involved. Their 50-m front crawl personal best time in short-course corresponds to 512.06 FINA points. Each participant completed two free-swimming trials recorded by a sagittal camera (GoPro, Hero 7, 60 Hz, 1080p). They swam with and without pressure sensors on their hands, performing front crawl arms-only without breathing, using a pull buoy and a calf band. Maximal velocity (v_{MAX}) in free-swimming was assessed by video analysis, measuring the time to cover from 10 to 20 m from the starting wall, with stroke rate (SR) checked. Stroke length (SL) was estimated as v_{MAX}/SR.

2.5 Statistical Analysis

For P_s and P_d, the intra-, test–retest- and inter-reliabilities were tested in terms of intra-class correlation [ICC (3,1)], coefficient of variation (CV%), standard error of measurement (SEM), and minimal detectable change based on a 95% confidence interval (MDC). Inter-sensor reliability was examined on eight sensors for P_s, and four sensors for P_d. Only for P_s, intra-sensor and the test–retest (day 1 vs. day 2) reliability of eight sensors was checked. The P_s and P_d accuracy compared respectively to P_{sT} and P_{dT} was verified using mean absolute error (MAE) and root mean square error (RMSE). To ensure ecological validity, paired t-tests were conducted to investigate differences in v_{MAX}, SR, SL between trials with and without wearing pressure sensors. Cohen's d was used as the standardized effect size, with the following interpretation: i) trivial effect for $|d| \leq 0.25$, ii) small effect for $0.25 < |d| \leq 0.5$, iii) medium effect for $0.5 < |d| \leq 1.0$ and iv) large effect for $|d| > 1.0$ [12]. The ICC, CV%, SEM and Pearson's r were classified as proposed by Koo et al. [13], Scott et al. [14], Buchheit et al. [15], and Hopkins et al. [16], respectively. Prior to the statistical analysis, the Shapiro–Wilk test was performed, and the statistical significance level was set to $p < 0.05$. Statistical analysis was carried out using JASP (version 0.16.4.0).

3 Results

The pressure sensor's sensitivity was estimated at 0.1 kPa with a minimum detectable displacement of 1 cm. P_s showed excellent intra-, inter-, and test–retest reliability with ICC (always ≥ 0.96) and CV% (always $< 0.13\%$). SEM compared to MDC was classified as 'good' (see Online Resources Table 1 and Table 2 for more details). Accuracy analysis showed low errors between P_s and P_{sT} for each depth (MAE ≤ 0.1 kPa, RMSE < 0.11 kPa, Fig. 3).

P_d analysis reveals excellent inter-sensor reliability: ICC (≥ 0.97), CV% ($< 6.9\%$, for velocity larger than 1.0 ms^{-1}), SEM (< 0.02 kPa), and MDC (< 0.06 kPa), with the exception of CV% for velocities ranging from 0.5 to 1.0 ms^{-1} (respectively 34% for 0.5 ms^{-1}, 38% for 0.6 ms^{-1}, 23% for 0.7 ms^{-1},13% for 0.8 ms^{-1}, 4% for 0.9 ms^{-1} and 11% for 1.0 ms^{-1}). Figure 4 shows agreement between P_d and P_{dT}, with MAE (< 0.06 kPa) and RMSE (< 0.07 kPa) for each velocity.

During free-swimming trials, significant differences, with large or moderate effect size, were found for v_{MAX} and SL between conditions ($p < 0.001$, $d = 1.318$ and $p < 0.05$, $d = -0.662$, respectively) with higher values without sensors (1.45 ± 0.10 ms^{-1} vs. 1.49 ± 0.09 ms^{-1} for v_{MAX}, 1.53 ± 0.12 m vs. 1.56 ± 0.12 m for SL). Conversely, SR showed no significant difference, with similar results without and with sensors 57.01 ± 3.29 cycle/min and 57.51 ± 2.67 cycle/min respectively ($p = 0.148$, for more details in Online Resources Table 5 and Table 6).

4 Discussion

This study investigated the performance of a wireless and wearable pressure sensor system for swimming analysis, focusing on i-ii) sensitivity, reliability and accuracy through validation tests of hydrostatic and hydrodynamic pressures using theoretical pressure as the gold standard, and iii) ecological validity, examining the impact of sensors on performance in free-swimming. Results confirmed that the present wireless pressure sensor are reliable and accurate for measuring pressure in aquatic environments. Furthermore, although the sensor reduces v_{MAX} and SL, the absence of wires and the reduced weight (25 g) could enhance the ecological benefits compared to cabled device (226 g, [10]) or multiple pair of sensors.

Regarding sensitivity, reliability and accuracy, the results of both hydrostatic and hydrodynamic protocols highlighted

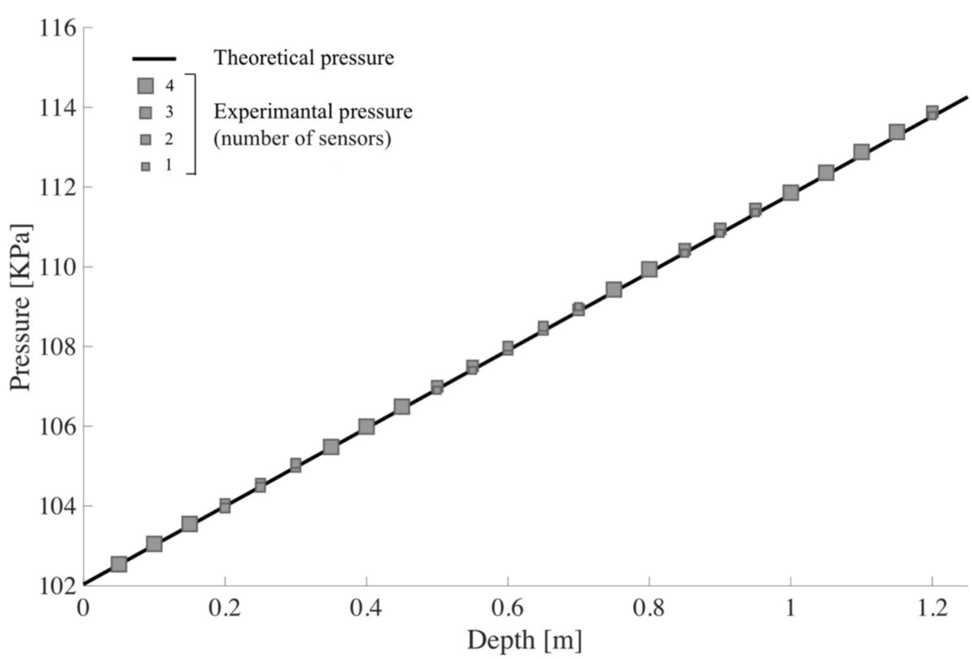

Fig. 3 Relationship between theoretical hydrostatic pressure represented by the black line and hydrostatic pressure measured by sensors represented by grey squares. The legend uses different square sizes to represent the corresponding number of sensors with the same results in pressure measurement. See Online Resources Table 3 for more details on experimental data

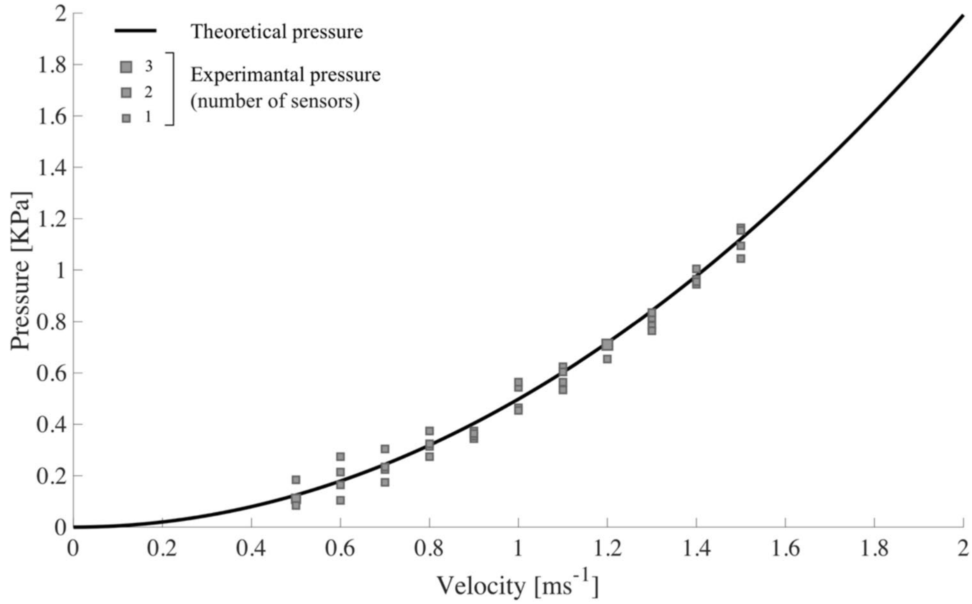

Fig. 4 Relationship between theoretical hydrodynamic pressure represented by the black line and hydrodynamic pressure measured by sensors represented by grey squares. The legend uses different square sizes to represent the corresponding number of sensors with the same pressure measurement. See Online Resources Table 4 for more details on experimental data

that test–retest, intra- and inter-sensor evaluations were excellent (ICC ≥ 0.96). When comparing test–retest reliability with literature, similar findings were reported by Santos et al. [10], who observed ICC values greater than 0.9 for peak and mean force measurement using one pair of pressure sensors (not wireless) during front crawl. However, hydrodynamic pressure assessment for velocities below 1.0 m·s^{-1} showed high CV% values (up to 38%), indicating low reliability. The low values of pressure observed at these speeds (0.12 – 0.5 kPa) are close to the device's sensitivity (0.1 kPa), and this may affect our results. Nevertheless, since the palmar pressure during swimming generally exceeds 1 kPa [4, 6, 17] the sensitivity could be considered adequate for this purpose. In addition, the accuracy showed good results, with no significant difference between experimental and theoretical pressure. Thus, the wireless pressure sensors can be considered a reliable and accurate method to assess the pressure in aquatic environment, and to discriminate the hydrostatic from hydrodynamic pressures for applied purposes. Wireless sensors have several applications, including research on the mechanism that generate propulsion in swimming [1].

Regarding ecological validity, no significant differences were found in *SR*, indicating that the pressure sensors did not alter the stroke rate (decrease of 0.9 ± 2.2% wearing the device). Conversely, significantly lower values, with large or moderate effect size, were observed for v_{MAX} and SL when wearing the pressure sensors during free-swimming. Despite these significant differences, the reduction in v_{MAX} (2.6 ± 2.0%) and *SL* (1.8 ± 2.6%) would correspond in a 50 m simulated performance decline of 0.9 s over 33.6 s in our participants. Whereas the slight change in SL would result in less than one additional stroke cycle to complete a simulated 50-m front crawl, equivalent to a reduction of less than one meter over 30 strokes. Washino et al. [18] investigated the impact of wearing reflective markers during swimming and reported a significant negative influence on v_{MAX} (− 0.06 ms^{-1}, 3.3%), *SR* (− 0.01 Hz, 1.2%) and *SL* (− 0.05 m, 2.1%) compared to the free condition. In contrast, our results suggest that the wireless pressure sensor system has a smaller impact on performance than 25 reflective markers attached to the body. Given the lack of an ecological evaluation of other pressure sensors, direct comparisons are challenging. However, the evolution of such devices appears to be moving towards a reduced impact on swimming technique.

While using one pair of pressure sensors may result in lower measurement accuracy, the key lies in achieving high accuracy with an unobtrusive design that preserves the athlete's movement and technique. Minimal impact on swimming technique is essential for practical applications, thus it is crucial to balance the number of sensors with their influence on swimmers' performance. Additionally, the proper placement of the sensor between the third and fourth metacarpals of the hand may contribute to a good approximation of the force vector [19]. A further limitation of the present device is the low sampling rate (50 Hz). This may affect the instantaneous force measurement, but it should be sufficiently accurate for assessing average force and identifying the typical force pattern of the stroke. Moreover, other single-pair (cabled, Fs = 100 Hz) devices have demonstrated reliability on mean and peak force exertion during swimming [10], highlighting the potential of these types of instruments. Notably, ease of use is the most important requirement for swimming analysis tools according to coaches, as well as the accessibility is another key prerequisite [20]. In this regard, the wireless and cable free nature of the device, combined with its ecological design, makes it well-suited for coaches aiming to monitor the hydrodynamic pressure exerted by their swimmers.

5 Conclusion

The present wearable and wireless pressure sensor is reliable and accurate in measuring the real value of hydrostatic and hydrodynamic pressure. However, these results cannot be extended to the swimmer's propulsive force due to kinematics and kinetics assumptions, thus further investigations are required. The reduced spatial constraints for analysis, and a time-efficient procedure, confirm that the wireless pressure sensors could offer a useful approach for monitoring swimmer's performance in the training context.

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Data availability Supplementary data to this article can be found online at: https://osf.io/asmpd/?view_only=2e862a7ecc98402fb2ced88c958d8533

Declarations

Conflict of interest The authors have no conflict of interests to declare.

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