The Impact of the Protective Materials on Strain Gauge Deformation When Simulating Rowing and Canoeing Scenarios

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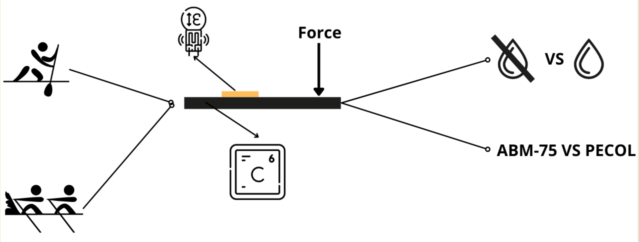

***Abstract*—Technological advancements in water sports, such as rowing and canoeing, have led to the increased use of strain gauges for improved structural analysis. However, the humid conditions inherent to these sports can affect strain gauges' performance, requiring waterproofing materials. This study aims to evaluate the effect of protective materials on strain gauge deformation in both dry and submerged conditions. Two types of protective materials were selected: one from the sensor manufacturer (ABM75) and the other for general applications (PECOL brand). The tests were conducted using a setup designed to apply a constant displacement to five carbon beam samples equipped with two parallel strain gauges for approximately 35 cycles. Inferential statistical analysis revealed no significant differences between the dry ABM75 and the control. However, differences were noted under other conditions. ANOVA tests with statistical parametric mapping (SPM) compared the materials' performance, showing variations in their response throughout the cycles, though less pronounced in dry conditions.**

***Index Terms*—Biomechanic, carbon sample, dry environment, instrumentation, sport, submerged environment.**

I. INTRODUCTION

IN ROWING and canoeing, athletes must prioritize training that hones both efficient technique and optimal power generation, which requires a detailed understanding of biomechanical principles [1], [2]. Integration of these principles into an athlete's training regimen is crucial for achieving a combination of technique and power [3]. This integration is supported by the accuracy and consistency of biomechanical measurements, which serve as the foundation for understanding, analyzing, and optimizing movement mechanics [4], [5]. These measurements are derived from biomechanical devices that become vital tools to provide essential insights into athlete performance. By studying and analyzing biomechanical variables, athletes and coaches can refine their strategies, leading to better performance and competitive results [6]. These biomechanical devices incorporate sensors that capture force, position, and acceleration data. Among these sensors, strain gauges are among the most prevalent and fundamental [7]. Strain gauges were designed to accurately measure minimum deformations, allowing the instrumentation of sports equipment and offering information to coaches, athletes, and researchers regarding variables, such as forces on the oar or paddle [8], [9], [10], [11]. The significance of strain gauges is particularly pronounced in water sports, such as rowing and canoeing, where precise measurement of forces and movements is critical for optimizing performance and ensuring safety.

However, it is crucial to recognize a significant limitation when using strain gauges: their measurements can be affected by external environmental factors, such as changes in temperature, humidity levels, and ambient vibrations [12]. This susceptibility can inadvertently introduce noise into the data

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collected, potentially compromising the integrity and reliability of the measurements [13]. Recognizing this vulnerability, the research field has adopted various mitigation strategies aimed at safeguarding the fidelity of strain gauge data. These strategies include thermal insulation, calibration techniques, signal filters, and the application of protective materials [14]. These protective coatings protect the strain gauge from environmental elements, increasing their resilience and ensuring reliable measurements despite challenging conditions.

Further emphasizing the importance of these protective coatings, some civil engineering studies have explored the influence of external factors, such as temperature and humidity on these sensors [15], [16]. To protect the sensors, these studies have used materials, such as polyurethane sealants [17], epoxy layers [18], silicon rubbers, and other adhesive and protective coatings [15]. The harsh and varying environmental conditions encountered in water sports make the effective protection of strain gauges even more critical. Conditions, such as prolonged exposure to water, fluctuating temperatures, and varying humidity levels, pose significant challenges to the accuracy of strain gauge data in these sports.

Even though these materials are used, to the best of our knowledge, there are no studies in the literature in which the effect of protective materials on strain gauge measurements has been studied.

In this study, the protected strain gauges with ABM75 (HBM Brand) and PECOL sealing material (Pecol Brand) were used. ABM-75 is a protective film that the manufacturer recommends for use in adverse conditions, such as humidity or submersion in water. PECOL sealing, on the other hand, is a polymer sealant that is mainly used for boat repairs and is not intended to protect the sensors. This study aimed to analyze how different protection materials influence strain gauge measurements under constant displacements, which are commonly encountered in rowing and canoeing under dry and submerged environments.

Thus, this study hypothesized that there would be differences between the two materials selected; however, the material with the behavior closest to the control sample is expected to be the one suggested by the sensor manufacturer, ABM-75.

II. METHODS AND MATERIALS

This section describes the materials used and the methods adopted to conduct the research. It details the experimental procedures and the analyses carried out to ensure the validity of the results obtained.

A. Experimental Setup

This study designed and implemented an experimental setup to simulate the real-world conditions encountered during rowing or canoeing training, focusing on the magnitude of the applied force and on the test environment, such as immersing the sensor in water. Fig. 1 presents a schematic view of the developed system for the implementation of experimental tests.

The specialized configuration involved a motor (model ST4209S1006-B, Nanotec) and a rotating screw to apply controlled forces and induce the desired displacements in the clamped-free beam. Precise and controlled displacements were imposed on the free end of the beam using a slider synchronized with the screw rotation. A linear guide was incorporated to facilitate smoother operations and reduce friction between the carriage and the threaded shaft. In addition, a specially designed cart geometry allowed the simultaneous testing of two samples, thereby optimizing the efficiency of the experimental setup. Fig. 2 shows the experimental setup actual model, depicting the version of the tests in dry conditions [Fig. 2(a)] and the setup adapted with a container that holds the water to carry out the submersion tests [Fig. 2(b)].

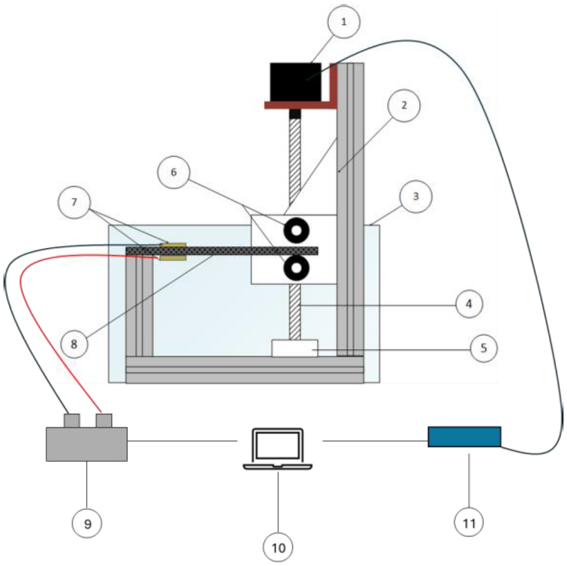


Fig. 1. Schematic view of the developed system for experimental tests. Legend: 1–motor, 2–bearing trolley, 3–water container, 4–threaded screw, 5–spindle bearing, 6–trolley bearings, 7–strain gauges, 8–carbon sample, 9–NI module, 10–computer, and 11–Arduino Uno.

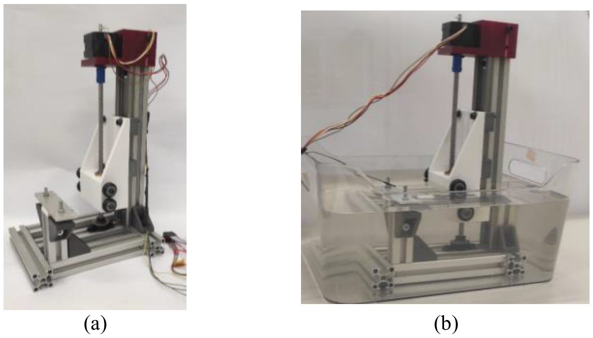

(a) (b)

Fig. 2. Experimental setup in (a) dry conditions and (b) wet conditions.

As depicted in Fig. 1, the motor is directly connected to the Arduino Uno and is programmed to manage motor actuation and ensure the physical manipulation required by the experimental requirements. This management includes initiating the motor movement, adjusting the screw rotation, and precisely controlling the slider displacement.

The strain gauges that instrument the sample are used to measure the deformation. These components are linked to the data acquisition module [national instruments (NI) 9219], which can capture analog signals in real time at a frequency of 10 Hz. The collected data are then transmitted to a computer and processed using LabVIEW software.

During calibration, the gauge factor information of the strain gauge and its connection board configuration is entered; in

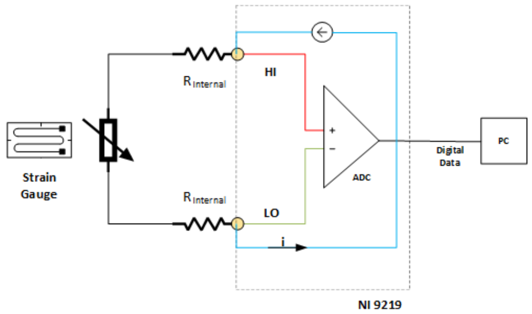


Fig. 3. Configuration of the quarter Wheatstone bridge.

TABLE I
MECHANICAL PROPERTIES OF THE SAMPLE MATERIAL

Mechanical Properties	$\bar{x}$ ± SD
Longitudinal modulus of elasticity [GPa]	104.64 ± 10.32
Transverse modulus of elasticity [GPa]	7.63 ± 0.68
Poisson Coefficient *xy*	0.27 ± 0.011
Poisson Coefficient *yx*	0.12 ± 0.008

this case, the configuration corresponds to a quarter bridge I. Each strain gauge was connected to the board using a quarter Wheatstone bridge in a differential configuration (Fig. 3).

B. Samples

During the initial phase of the study, mechanical tests were performed to evaluate the mechanical properties of materials with properties similar to those of oars or paddles. Specifically, a carbon-fiber-reinforced epoxy composite was selected because of its similarity to the materials used in such applications. This composite, prepared by autoclave/vacuum bag molding using a high-strength unidirectional carbon prepreg (Texipreg HS 160 REM, SEAL, Legnano, Italy) [19], aligned closely with the materials used in oars and paddles.

Furthermore, it is noteworthy that BRAČA-SPORT®, a manufacturer of oars and paddles, favors the use of fine-grained high-modulus unidirectional carbon (HMC) in their products. This information underlines the relevance of the material choice, emphasizing its proximity to industry-preferred materials utilized by leading brands in the field.

Tension tests were meticulously conducted on this composite material using Shimadzu AGS-X 100 kN testing equipment. These tests strictly adhered to the ISO 527-5 standard to ensure precision and consistency. Detailed insights from these experiments encompass the material's mechanical properties obtained from three samples, as seen in Table I.

Five samples were instrumented using two HBM strain gauges, reference K-CLY4-0060-3-350, with a measurement factor of 2.09. The dimensions of the samples, the section, and the instrumentation in relation to the embedment are shown in Fig. 4.

A procedure was employed to prepare instrumentation samples using strain gauges to obtain accurate and reliable strain measurements. The procedure began with delimitation of the gluing area using a 3-D printed template designed for this purpose. Model aids, as illustrated in Fig. 5, facilitated the positioning of strain gauges on the sample surfaces, ensuring a uniform and consistent state between the samples.

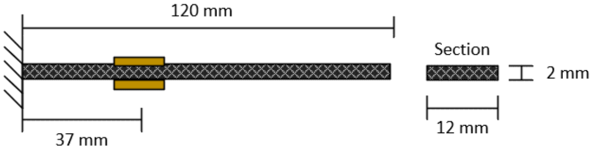


Fig. 4. Diagram showing the dimensions of the sample, section, and instrumentation area.


(a) (b)

Fig. 5. Sample with template aid. (a) Three-dimensional model and (b) real model.

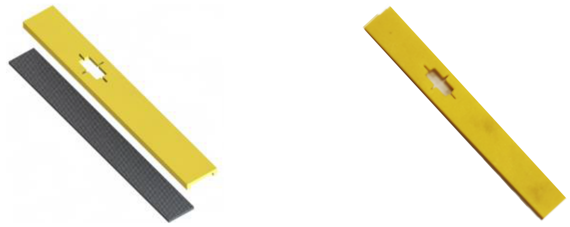

(a) (b)

Fig. 6. Gluing template. (a) Three-dimensional model and (b) real model.

The instrumentation follows the rules to get the perfect adhesion of the strain gauges with the beam surface and the same researcher performed all the experimentation. After delimiting the gluing area, the gluing surfaces were treated with sandpaper. This step was performed to obtain a uniformly smooth surface and remove any coating on the surface, which is a critical factor for ensuring the adhesion of the strain gauges. The gluing area was neutralized with an HBM cleaning agent, to eliminate potential contaminants or residues that could compromise the gluing process. Fig. 6 shows the gluing template used to outline the area and reference guides that assist in subsequent gluing processes.

Sample instrumentation requires maximum precision because it directly affects the strain measurements. Before being glued, a drop of superglue was placed to cover the gluing surface, and the strain gauge was glued, aligning the guides marked in the previous step with the guides present on the sensor itself.

The samples were identified with the strain gauges installed. Each sample was assigned a unique identifier ranging from 0 to 4, where 0 represented the control sample. The strain gauges were labeled A–J to accommodate multiple strain gauges attached to each sample.

The mass of each sample was assessed to establish a baseline for subsequent analysis. This initial weight measurement served as a reference point, allowing monitoring of possible weight variations during the experimental process.

Fig. 7. Sample with the filling template.

TABLE II
SAMPLE WEIGHT (N/A: NOT APPLICABLE)

Samples	**Mass [g]**		
	Without protection	PECOL	ABM-75
Control	5.90 ± 0.14	N/A	N/A
1	6.06 ± 0.16	8.16 ± 0.08	9.87 ± 0.16
2	5.95 ± 0.54	8.10 ± 0.33	9.62 ± 0.07
3	5.88 ± 0.17	7.73 ± 0.15	9.83 ± 0.33
4	6.20 ± 0.65	7.30 ± 0.18	9.55 ± 0.08

The protective material was applied within predetermined limits using a filling template (Fig. 7) to apply the same volume of protective material to each sample. First, the PECOL material was placed on one side, and after drying, the ABM-75 material was placed on another strain gauge on the same sample.

After each application of the protective material and drying, the samples were weighed (Table II). The instrumentation yielded a control sample (two strain gauges) and four samples of each material (ABM7-75 and PECOL).

C. Experimental Procedure

The experimental procedure began by fixing the samples in the experimental setup and positioning them securely between the cart bearings. It is important to ensure that the bearings do not touch the sample, thereby preventing them from exerting pretension on the samples. The samples were then connected to the acquisition board in alphabetical order for streamlined identification and data collection.

The strain gauges were then calibrated using the LabVIEW interface. In the block for entering information about the strain gauges, there is a function for calibrating. Once calibrated, the program starts a test protocol procedure. This process began by triggering a program in the Arduino system, prompting the start of the test cycle.

During the test cycle, a controlled displacement was applied at a constant speed of 5 rotations/min, resulting in deformation values ranging from a minimum of 0 $\mu\varepsilon$ to a maximum of 3000 $\mu\varepsilon$. Each test was performed for 15 min, corresponding to 35 complete cycles between loading and unloading the displacement.

Upon the completion of the test, the samples were inverted, a procedural step necessitated by the presence of a strain gauge on each side of the sample. This inversion allowed for an equitable distribution of the testing conditions across both sides of the sample for subsequent tests.

Additionally, a structured test sequence was used throughout the experiment.

After the inversion, a 10-min interval was observed before the subsequent test began. This interval period was intended to nullify any remaining stress concentration on the samples, ensuring an ideal baseline condition for each subsequent test.

This standardized procedure, encompassing controlled displacement, specific strain values, and sample inversion, was consistently applied to all the samples throughout the experiment. Channel connections remain unchanged for each sample, ensuring continuity and consistency in data acquisition.

All the samples were submerged in water using the same test procedure applied to dry environments. The dry tests were performed in a control laboratory room with a temperature of 23 °C. The water bath is held at the same temperature as the room.

Once calibrated, the program starts a test protocol procedure. This process began by triggering a program in the Arduino system, prompting the start of the test cycle.

During the test cycle, a controlled displacement was applied at a constant speed of five rotations/min, resulting in deformation values ranging from a minimum of 0 $\mu\varepsilon$ to a maximum of 3000 $\mu\varepsilon$. Each test was performed for 15 min, corresponding to 35 complete cycles between loading and unloading the displacement.

D. Data Processing

All data were processed using MATLAB version 2022b (MathWorks Inc., Massachusetts, USA) to allow further data analysis. The first test cycle, subject to significant variability during movement initiation, was excluded from the dataset to ensure consistency and reliability of the analyzed data.

In the initial processing phase, unique values from the deformation datasets were isolated and compiled into new matrices, eliminating redundant data points and refining the dataset for accurate analysis.

After the initial cleaning, the data were segmented into cycles based on the minimum peaks identified. These were determined by inverting the data curve and using the MATLAB findpeaks function, which consists of the algorithm for finding peaks with a specified minimum peak prominence.

Each identified cycle was then subjected to a resampling routine, ensuring uniformity in the length of the data segments and smoothing of irregularities. This resampling process involved normalizing the data to a range between 0% and 100%, which is consistent with the data collected.

Finally, the datasets from each test were individually plotted to facilitate comprehensive analysis, allowing for the identification and removal of outliers. This step preceded the subsequent statistical analysis.

E. Data Analysis

Data were statistically processed using IBM SPSS Statistics 26.0 (IBM Corporation, New York, NY, USA).

Descriptive analysis was used to calculate the mean and standard deviation (x¯ ± SD) and coefficient of variance (CV) for each type of material (Control, ABM-75 and PECOL), as well as for the different scenarios, dry and submerged conditions to analyze the peak value of each curve for the total samples. Normality (Shapiro-Wilk) and homogeneity (Levene) tests were also carried out for the peaks of the curves, from

TABLE III

MEAN ( ), STANDARD DEVIATION (SD), COEFFICIENT OF VARIATION (CV), SIGNIFICANCE VALUES (P) OF PEAKS, AND NUMBER OF CYCLES (N)

		n	$\bar{x}$ ± SD [µε]]	CV [%]	P
Control		78	1736.18±81.24	4.68	-
Dry	ABM-75	124	1875.20±91.46	4.88	0.000
	PECOL	129	1684.79±154.88	9.19	0.001
Water	ABM-75	94	1751.28±115.52	6.60	0.350
	PECOL	84	1576.26±171.29	10.87	0.000

which it was concluded that nonparametric tests (Wilcoxon) were used to study the significance between groups, that is, to understand which material would be almost identical to the control sample for both conditions.

Before conducting any further analysis, the data were normalized. The aim of normalization is to achieve uniformity and standardization of the data, so that comparisons between different series are based on a standard frame of reference. The normalization method involved symmetrical extension, i.e., each time series was extended at both ends, mirroring the data and inverting its values. This procedure standardizes the context for each data segment, mitigating potential distortions during resampling. The data were then resampled to a fixed number of points, ensuring that each segment was the same length, regardless of its original size. Finally, a central section of the resampled data was selected, excluding the extended parts. This process results in normalized data segments that are ready for analysis.

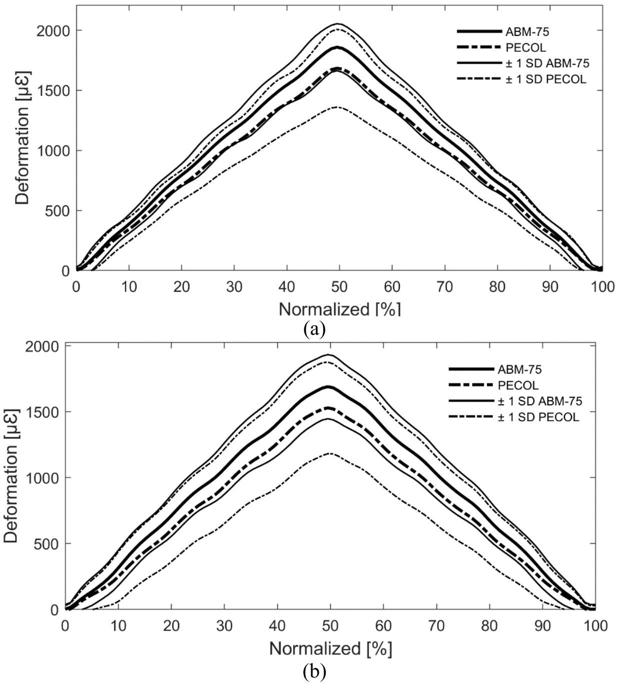
To study the behavior of the curves through comparison, a continuous data analysis methodology, statistical parametric mapping (SPM), was used. SPM is an advanced tool for analyzing data that vary in space and time and is commonly used in areas, such as biomechanics [20]. Its main advantages include preserving the spatiotemporal biomechanical context of the data, allowing a more intuitive and direct interpretation of statistical results, and the ability to process data with imprecise limits without prior simplification, thus avoiding potential biases. SPM uses traditional statistical tests, such as SPM {F} and SPM {t}, respecting the multidimensional complexity of the data and facilitating the detection of significant changes throughout the cycle without reducing the richness of the information [20], [21].

Two-sample t-tests were carried out to compare the behavior of the curves for the two materials under the two conditions and determine whether external factors, such as submersion in water, were influenced. SPM one-way ANOVA and Bonferroni tests were carried out for both the dry condition and the submersion in water condition to analyze the differences throughout the cycle in relation to the control.

The significance level for both nonparametric tests and SPM was set at $p < 0.05$.

III. RESULTS

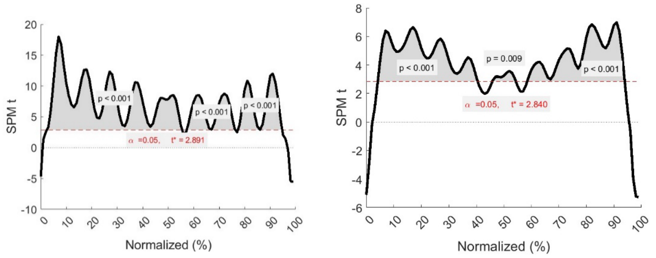
Table III shows the descriptive analyses and significance values ($p < 0.05$) between the control and the two materials under dry and water conditions.



(a)

(b)

Fig. 8. Mean curve graphs coupled with confidence intervals for (a) dry conditions and (b) water conditions. The thick lines represent ±1 standard deviation of ABM-75 and PECOL.



(a)

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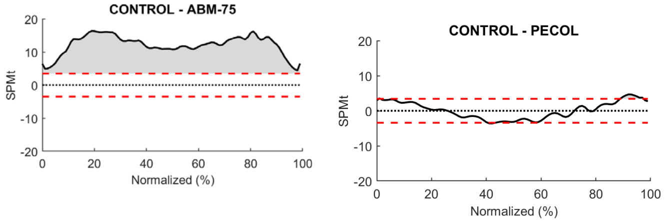
Fig. 9. Statistical results from the SPM analysis throughout the stroke cycle are presented for (a) ABM-75 and (b) PECOL. Gray area marks a significant difference between dry and water conditions.



(a)

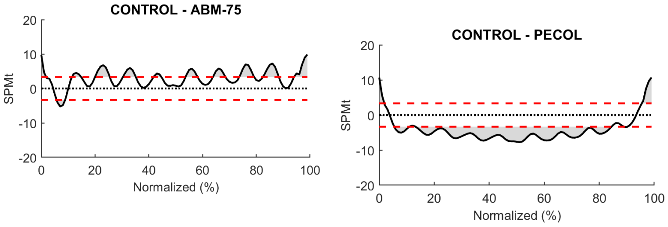
(b)

Fig. 10. Statistical results from the ANOVA analysis throughout the stroke cycle are presented for (a) ABM-75 and (b) PECOL. Gray area marks a significant difference between control and protective material in dry conditions.

Fig. 8 shows the mean curve graphs coupled with the confidence intervals between the dry and wet conditions across ABM-75 [Fig. 8(a)] and PECOL [Fig. 8(b)].

The influence of environmental factors, in this case water, was studied using a comparative analysis between ABM-75 [Fig. 9(a)] and PECOL [Fig. 9(b)].

Fig. 10 presents a graphic based on a one-way ANOVA analysis of SPM, which compares the two different materials under the same conditions: the control with ABM 75



(a) (b)

Fig. 11. Statistical results from the ANOVA analysis throughout the stroke cycle are presented for (a) ABM-75 and (b) PECOL. Gray area marks a significant difference between control and protective material in water conditions.

[Fig. 10(a)] and the control with PECOL [Fig. 10(b)] under dry conditions.

Fig. 11 shows the results of the same analysis carried out in the previous figure; however, in this case, it compares two different materials for water: the control with ABM-75 [Fig. 11(a)] and the control with PECOL [Fig. 11(b)].

IV. DISCUSSION

The study aimed to assess how strain gauge protection materials, namely, ABM-75 and PECOL, influence data accuracy under varying environmental conditions, including dry and submerged conditions. The results showed that in dry conditions, ABM-75 had a significantly higher average deformation (1875.20 $\mu\varepsilon$) compared to the control (1736.18 $\mu\varepsilon$), indicating a notable deviation ($p < 0.05$).

However, this pattern did not persist under submerged conditions, where although variances existed, they did not reach statistical significance ($p > 0.05$). Conversely, PECOL consistently exhibited lower mean strain values than the control in both environments, proving statistically significant ($p < 0.05$). These findings contradict the initial hypothesis and highlight the significant impact of protective materials on strain gauge readings in various environmental scenarios.

It is important to note that previous studies reported in the literature have primarily concentrated on external variables, such as humidity and temperature, which impact sensor performance [15], [16], [18]. Although there has been less examination of the specific influence of protective materials under conditions that simulate real-world sports training, particularly with load application, this study aims to fill this gap by examining the impact of load application on simulating canoeing and rowing training conditions and directly linking material selection to the realistic assessment of athletic performance.

In disciplines, such as canoeing and rowing, where accurate biomechanical analysis is crucial, this study emphasizes the evaluation of peak deformation/force in each cycle and the profile of the deformation curve as important performance metrics [22], [23], [24]. The observed increase in average deformation by ABM-75 in dry conditions suggests a potential alteration in strain gauge sensitivity, which could result in overestimated force or displacement measurements. This insight is particularly significant for sports that require precise force application measurement as it could impact the perceptions of performance for both athletes and coaches. In submerged conditions, the lack of statistical significance in the difference between ABM-75 and the control suggests a potential reduction in the material's impact on sensor readings when immersed in water. This phenomenon can be attributed to water acting as a natural equalizer of external pressures, thus diminishing the influence of the protective material. However, the consistent underperformance of PECOL in both environments raises concerns about its suitability as a protective layer for strain gauges, especially considering the statistically significant lower mean strain values compared to the control. The observed variability, particularly with PECOL, highlights another critical aspect: the reliability and consistency of data collection. The higher standard deviation and coefficient of variation associated with PECOL indicate that this material may introduce an element of unpredictability into the measurements, which is undesirable in high-stakes sports environments, where equipment reliability is fundamental [25].

It is impossible to conclude which is most similar to the control through descriptive and inferential analysis. SPM was used to analyze the deformation curve profiles. The SPM analysis in dry conditions revealed that ABM-75 consistently deviated from the deformation profile of the control, indicating that the strain gauges were able to detect a fundamental change in deformation shape. PECOL, although different, showed the areas of nonsignificant deviation, suggesting that it may occasionally closely resemble the control more than ABM-75.

When underwater, both materials diverged from the control at various points in the deformation cycle, reinforcing the notion that environmental conditions play a crucial role in the interaction between protective materials and sensor performance. These variations in curve profiles are not only academic; they have practical implications for understanding the athlete's technique and the equipment's responsiveness, which are vital for refining training and enhancing performance [23], [24].

For researchers in sports science and equipment manufacturing, these insights highlight the importance of choosing suitable protective materials for strain gauges, especially in sports, such as canoeing and rowing, where environmental conditions can vary significantly. The selection of protective materials can directly impact the accuracy and reliability of performance analytics, thus influencing strategic decisions in training and competition.

This study has some limitations; the laboratory simulations may not fully capture the complexity and variability of real-world canoeing and rowing scenarios, including water salinity and temperature fluctuations. The findings may not apply to the wide range of protective materials available since only two were considered. The experimental design may also affect the strength of the conclusions, including sample size and test repetition. Additionally, the study did not assess the long-term durability of the materials or the impact of wear and tear, which are crucial for evaluating their practical application over time. The findings and limitations of the current study highlight the need for further investigation into these areas and validation of the results under diverse and dynamic conditions.

V. CONCLUSION

This study investigated the effects of the sensor protection materials ABM-75 and PECOL on the accuracy of strain gauge data in environments simulating canoeing and rowing activities. Through data analysis, distinct advantages and disadvantages of each material were identified, leading to valuable insights into their application in nautical sports analytics.

ABM-75 showed greater sensitivity to strains under dry conditions, suggesting its potential for enhanced data accuracy in environments with minimal water exposure. However, its performance advantage decreases under submerged conditions, and its variability across different conditions suggests that ABM-75 might be less predictable in dynamic sports settings.

In contrast, PECOL exhibited lower mean strain values across environments, indicating stable performance but potentially at the cost of reduced strain sensitivity. This stability could make PECOL a versatile option for various conditions, but its significant variability, especially in water, raises concerns about its reliability.

To address these issues, developing calibration protocols and advanced data-processing algorithms that consider and compensate for environmental conditions can enhance the predictability, consistency, and reliability of performance data.

To further boost this field, research into hybrid materials or composite structures that combine the advantages of ABM-75 and PECOL could achieve an ideal balance between sensitivity, reliability, and adaptability to environmental conditions. The nature of the efforts, as well as the amplitude and frequency of the athletes' movements, is also important factors and should be considered in future simulations. Collaboration with materials scientists and engineers is essential to develop solutions that meet the specific requirements of water sports analysis.

In conclusion, this study highlights the importance of selecting appropriate sensor-protection materials for nautical sports analytics. While ABM-75 and PECOL have benefits and limitations, strategic enhancements and innovative approaches can significantly improve their performance. The insights gained from this research are poised to inform the development of more sophisticated sensor systems and enhance the accuracy and reliability of performance monitoring in sports.

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