International Journal on Robotics, Automation and Sciences

Performance Evaluation of Capacitive Based Force Sensor for Electroencephalography Head Caps

Indhika Fauzhan Warsito*, Alexander Hunold, Jens Haueisen, and Eko Supriyanto

***Abstract*—Accurate electrode signal measurement using EEG head caps can only be achieved through sufficient contact or force. A flexible force sensor is required to obtain accurate force measurement underneath EEG head caps. In this study, we evaluate the performance of a capacitive based sensor including its accuracy, repeatability, hysteresis, and stability. The result shows that accuracy error and repeatability error were 3.03±2.8 % and 3.84±2.92 %, respectively. The stability errors were 2.37±0.15 % (10 gram), 2.54±0.00 % (50 gram), 2.37±0.15 % (100 gram), 5.07±1.16 % (150 gram), 7.27±0.39 % (200 gram). The hysteresis error of the sensor was 4.48±0.47 %. Based on the results, the capacitive based force sensor provides sufficiently low errors in accuracy, repeatability, stability, and hysteresis and is thus suitable for measuring adduction force in EEG cap applications.**

Keywords—Force Sensor, Electoencephalography Head Caps.

I. Introduction

The development of dry electrodes for electroencephalography is a current research topic because gel is not required for dry electrode systems. Thus, there is significantly lower preparation time compared to wet electrodes [1]–[5]. However, due to the lack of gel, sufficient adduction force is required for dry electrodes to ensure low and stable interface impedances [6].

Textile caps with integrated dry electrodes have been developed which provide flexibility and comfort [7]. These electrodes and caps are also used for combined recording and stimulation setups [8]. However, the cap needs to provide optimal adjustment to individual heads with different shapes and sizes, to ensure accurate results. The correct positioning of the cap and the correct adduction force are important to the electrode-skin interface impedance [6].

For verifying stable contact between the cap system and the scalp, an accurate force sensor is needed to determine the actual adduction force on the surface of the scalp. The force data can be used to adjust cap position and tighten the cap accordingly. Moreover, these data serve for designing new caps. However, only thin and flexible force sensors can be used in this application, adjusting to curvy head areas and provide comfort to the user.

There are several types of flexible force sensor. The most common are force sensitive resistors (FSR). The FSR is basically a piezo-resistive force sensor, which changes its resistance relative to the applied pressure. Due to their low thickness, FSRs can be used in textile cap applications. FSRs consist of 2 layers, separated by a spacer. The resistance decreases as it is being pressed. FSRs are relatively cheap [9]–[13]. However, they provide only limited accuracy [14], leading to exclusion for the present application for contact pressure evaluation.

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International Journal on Robotics, Automation and Sciences (2020) 2:1-5
https://doi.org/10.33093/ijoras.2020.2.1
Manuscript received: 20 Jun 2020 | Revised: 10 Aug 2020 | Accepted: 23 Sep 2020 | Published: 30 Oct 2020

Published by MMU PRESS. URL: http://journals.mmupress.com/ijoras

Capacitive force sensors are the other main type of flexible force sensors which may be suitable for this application since they provide high accuracy and high repeatability. Capacitive force sensors are operated based on electrical capacitance changes. Among all types of electrical pressure sensor (including resistive sensors), capacitive sensors are the most precise sensors and are known for their long-term stability, high resolution, drift-free character, and simple structure [15]. In this paper, the performance of a capacitive force sensor is evaluated.

II. Material and Methods

A. Materials

In this study, a SingleTact™ capacitive force sensor manufactured by Pressure Profile System, Inc (Glasgow, UK) was used. SingleTact™ is a capacitive force sensor with a parallel capacitive configuration. SingleTact™ consists of 2 thin round Polyimide electrode plates separated by a sensor dielectric [16]. For this application, a calibrated sensor CS15-4.5 N with a diameter of 15 mm was chosen. It can measure up to 0.45 kg equivalent load.

SingleTact™ includes electronics providing an interface to the main controller. The supply voltage needs to operate between 3.7 V and 12 V with an input current of 2.7 mA. The range of the analog output voltage is between 0.5 V and 1.5 V. In terms of data transfer, SingleTact™ can accommodate more than 100 Hz.

The analog signal produced by the capacitive sensor is digitized with an Arduino Mega 2560 (Ivrea, Italy) and connected to a PC for data processing and analysis.

A weighting set OIML M1 343/344 (KERN & SOHN GmbH, Balingen-Frommern, Germany) is used in this study for evaluation of the force sensor systems.

B. Methods

We evaluated the performance of the SingleTact™ capacitive force sensor. Since weight force is proportional to mass, a weighting set was used to apply controlled force by putting weights on top of the capacitive sensor. The analogue signal is then digitized by an Arduino Mega and transferred for processing in a PC. Figure 1 shows a block diagram of the setup.

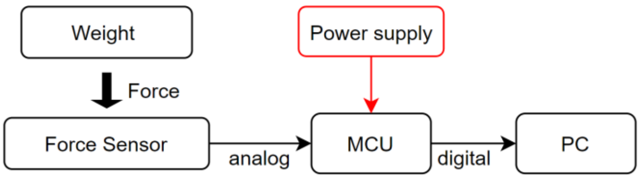

FIGURE 1. Block diagram of the measurement setup.

There are 4 parameters which have been examined in this study: accuracy, repeatability, stability, and hysteresis.

a) Accuracy

Accuracy error is the absolute deviation of the measured value by the sensor from its true value. The Relative accuracy error (1) represents the percentage of the absolute measurement error versus the true value.

$$\text{Rel. Acc. Error } (\%) = \frac{|\text{meas. value} - \text{true value}|}{\text{true value}} \times 100\% \qquad (1)$$

In this study, the relative accuracy error is used. 10 weight scales are randomly selected with a range from 10 g up to 200 g. Each selected weight is repeatedly measured 5 times.

b) Repeatability Error

The repeatability error (2) represents differences in sensor's output in measurements of the same load under identical conditions.

$$\text{Repeatability Error } (\%) = \frac{|\Delta_r|}{\text{FS}} \text{ x } 100\% \qquad (2)$$

With Δr being the value difference between 2 runs and FS is the full span output. In this study, the weight was randomly selected within the range from 10 g up to 200 g. Furthermore, the selected weight was repeatedly measured 10 times.

c) Stability Error

The stability error (3) describes the maximum deviation of the sensor's output with the same input within a specified time duration.

$$\text{Stability Error } (\%) = \frac{\text{Max deviation}}{\text{FS}} \times 100\% \qquad (3)$$

In this study, weights of 10 g, 50 g, 100 g, 150 g and 200 g were selected and repeatedly measured for 3 times. The output voltage was recorded for 120 seconds for determining the stability error across this time interval.

d) Hysteresis

Hysteresis describes a situation where the sensor's outputs are different when measuring the same input quantity with different history. The hysteresis error (4) is here defined as the absolute difference between output values for decreasing and increasing weights (Δh).

$$\text{Hysteresis Error } (\%) = \frac{\text{Max}|\Delta_h|}{\text{FS}} \times 100\% \qquad (4)$$

Here, the weight scale was measured in a certain sequence. First, the lowest weight (0 g) was measured. Then, the measurement was continued with increments of 10 g up to 200 g. After that, the measurement was continued with decreasing the weight by increments of 10 g, from 200 g to 0 g. The increase and decrease sequence were repeated five times. In the end, the average hysteresis error was determined.

III. Results

A. Accuracy and Repeatability test

The grand mean accuracy error and the repeatability error of the sensor (mean ± std.) were (3.03±2.8) % and (3.84±2.92) %, respectively. Figures 2 and 3 show the accuracy error and the repeatability error.

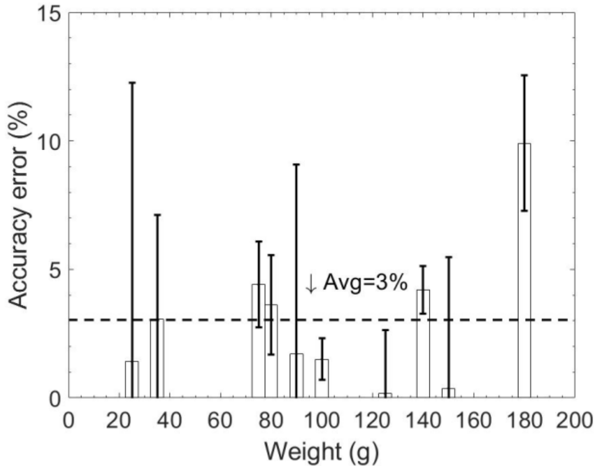

FIGURE 2. Relative accuracy error with respective standard deviation, horizontal line indicates the average.

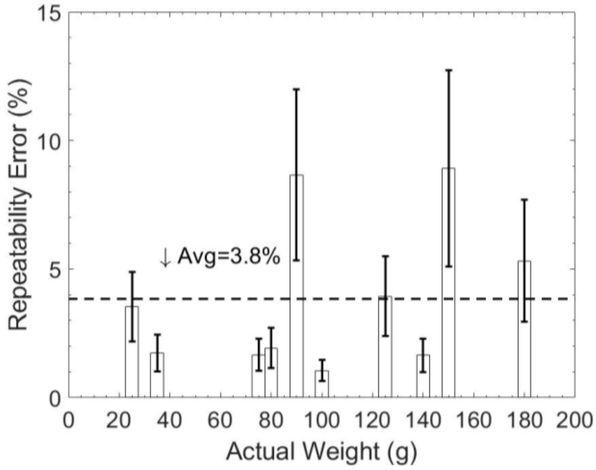

FIGURE 3. Repeatability error with respective standard deviation, horizontal line indicates the average.

B. Stability test

a) Weight: 10 grams

The stability test with 10 g input resulted in overall mean voltage outputs of 0.52 V. Stability errors were on average 2.37±0.15 % (FIGURE 4) across the three repetitions.

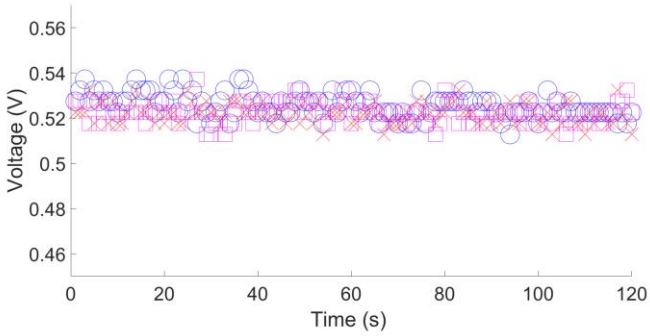

FIGURE 4. Stability test of the capacitive sensor with 10 g, 3 measurement repetitions (1st: circle, 2nd: cross, 3rd: square).

b) Weight: 50 grams

Stability test with 50 g input resulted in average voltage outputs of 0.61 V. Stability errors were (2.54±0.00) % (**FIGURE 5**).

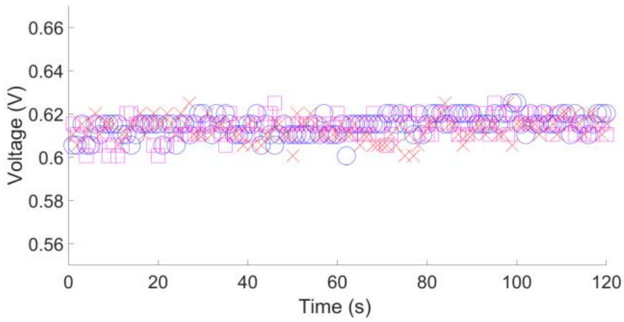

FIGURE 5. Stability test of the capacitive sensor with weight 50 grams, 3 measurement repetitions (1st: circle, 2nd: cross, 3rd: square).

c) Weight: 100 grams

Stability test with 100 g input resulted in average voltage outputs of 0.68 V. Stability errors were (2.37±0.15) % (**FIGURE 6**).

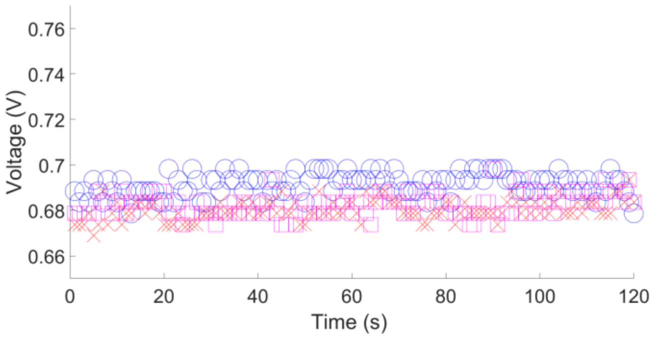

FIGURE 6. Stability tests of the capacitive sensor with weight 100 grams, 3 measurement repetitions (1st: circle, 2nd: cross, 3rd: square).

d) Weight: 150 grams

Stability test with 150 g input resulted in average voltage outputs of 0.77 V. Stability errors were (5.07±1.16) % (FIGURE 7).

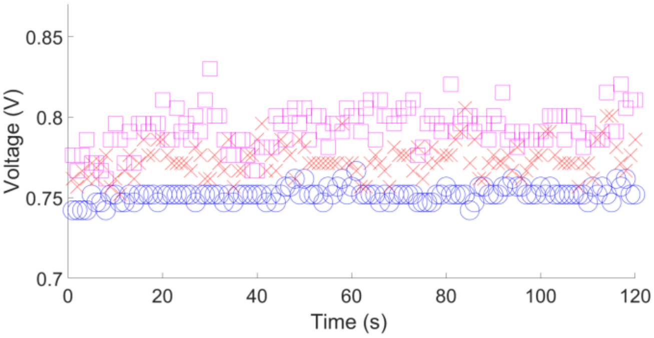

FIGURE 7. Stability test of the capacitive sensor with weight 150 grams, 3 measurement repetitions (1st: circle, 2nd: cross, 3rd: square).

e) Weight: 200 grams

Stability test with 200 g input resulted in average voltage outputs of 0.96 V. Stability errors were (7.27±0.39) % (**FIGURE 8**).

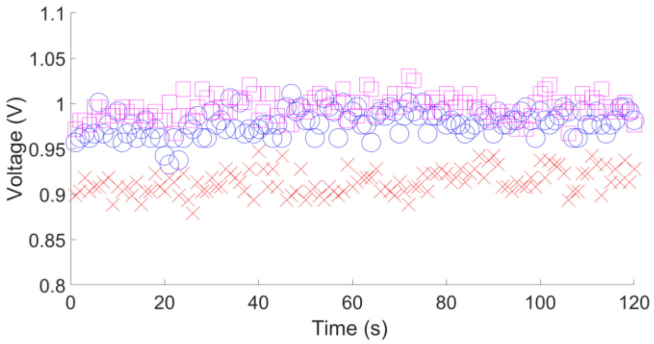

FIGURE 8. Stability test of the capacitive sensor with weight 200 grams, 3 measurement repetitions (1st: circle, 2nd: cross, 3rd: square).

C. Hysteresis Test

The resulting hysteresis error for capacitive sensor was on average (4.48±0.47) % (**FIGURE 9**).

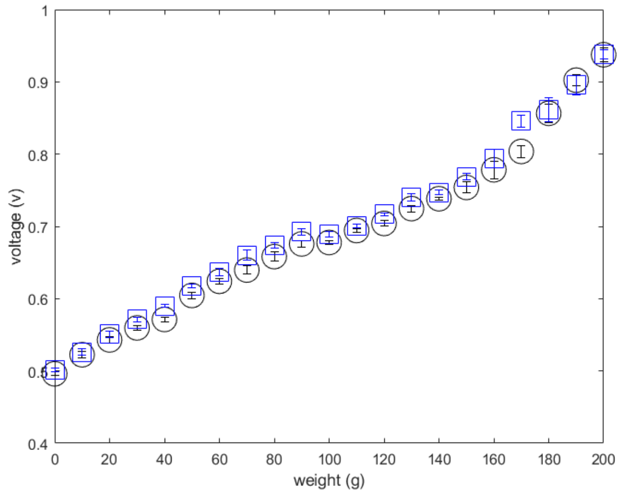

FIGURE 9. Hysteresis test of the capacitive sensor with increasing direction (circle) and decreasing direction(square).

IV. Discussion

The measurements of accuracy, repeatability, stability, and hysteresis resulted in errors below 10 % on average. Thus, the performance evaluation of the SingleTact™ demonstrated its reliability.

Few studies have published performances of flexible force sensors which include repeatability of the system. Piezo-resistive force sensors were investigated by Parmar, et al. (2017) [14]. Peratech SP200 (Richmond, UK), Interlink FSR® (Interlink Electronics Inc., Camarillow, CA, USA), Sensitronics® FSR (Sensitronics LLC., Bow, WA, USA), Tactilus® (Sensor Products Inc., Madison, NJ, USA), and Tekscan® Flexiforce A301 (Tekscan Inc., South Boston, MA, USA) were evaluated in their study. For comparison with the study conducted by Parmar et al. (2017), our study results were adjusted with using following formula [14]

$$\text{Weight (g)} = \frac{\text{Area (cm}^2\text{)x Pressure (mmHg)}}{735.5591} \quad (5)$$

The complete list of relative accuracy error comparison is shown in Table 1. Compared to the referenced piezo-resistive based force sensors (Table 1), the capacitive sensor's Relative Accuracy Error was in general lower.

The increasing stability error to higher loads (150 g and 200 g) might limit SingleTact's applicability in adduction force for certain EEG cap configurations, since at least 200 g (2 N) were desired for satisfying electrode-skin interface impedance [6]. Moreover, systematic differences in stability measurement are noticeable between 1st, 2nd, and 3rd repetition on higher weight especially from more than 100 g. The issue can be caused by the longer time needed for the sensor to restore its shape to initial position after being loaded with higher weights.

TABLE 1. Comparison of our results with previous findings.

Sensor	Relative Accuracy Error (%)			Reference
	Pressure 30.5 mmHg	***Pressure 51.4 mmHg***	***Pressure 72.7 mmHg***	
Paratech	16.3	1.9	4.4	[14]
Interlink	33	25.1	-	[14]
Sensitronics	15.7	12.8	15.1	[14]
Tactilus	-	7.2	10.5	[14]
Tekscan Flexiforce	29.6	3.6	14.2	[14]
SingleTact	4.41	0.16	9.91	Current Study

During measurement, the weights were manually placed directly on top of the sensor. The weights have different diameter for different weight (the diameter of all weights is smaller than the sensor diameter) which may influence the measurement. Moreover, during the performance of the measurements, humidity and temperature were not controlled for.

V. Conclusion

The performance of a capacitive force sensor system has been evaluated. Based on the measurement results from the present study, the capacitive force sensor produced sufficiently low errors in accuracy, repeatability, stability, and hysteresis. Thus, the capacitive force sensor might be suitable for electrode contact pressure in EEG caps applications.

ACKNOWLEDGMENT

We thank the anonymous reviewers for the careful review of our manuscript.

FUNDING STATEMENT

This work was supported in part by Marie Sklodowska-Curie, Germany under grant agreement No. 813483 (project INFANS), Ministry of Higher Education Malaysia, Technische Universität Ilmenau, and Universiti Teknologi Malaysia.

AUTHOR CONTRIBUTIONS

Indhika Fauzhan Warsito: Conceptualization, Methodology, Validation, Writing – Original Draft Preparation;

Alexander Hunold: Literature Review;

Jens Haueisen: Data Curation, Validation;

Eko Supriyanto: Project Administration, Supervision, Writing – Review & Editing;

CONFLICT OF INTERESTS

No conflict of interests was disclosed.

ETHICS STATEMENTS

Our research work follows The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org.

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