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The Wearable Reflectance PPG Optical Sensor Enabling Contact Pressure and Skin Temperature Measurement †

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Abstract: This paper describes design, realization, and application of a wearable sensor based on photoplethysmography (PPG) principle supplemented with a force-sensitive resistor and a thermometer for measurement of contact pressure force and temperature of the skin at the point where the optical part of the PPG sensor touches the finger. Performed experiments confirm essential influence of the applied contact force on the amplitude and ripple of the sensed PPG signal and also on the stability and precision of heart rate values determined from the PPG wave. Preliminary measurements show that the response to the applied contact force is principally different for fingers of male and female tested persons, so different scaling and pressure levels were applied in the frame of main experiments. Contrariwise, differences between left and right hands are not significant. Influence of skin temperature changes could be omitted in these measurements due to short time duration of the PPG signal recording (approx. 1 min).

Keywords: photoplethysmography optical sensor; wearable sensor; PPG wave features; force-sensitive resistor; contact skin pressure measurement

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1. Introduction

It is well known that the actual state of the skin surface including a color, a temperature, and other factors have an influence on properties of the sensed PPG signals. We have developed a wearable PPG sensor with a contact thermometer to carry out a measurement of the skin temperature. The precision of the determined PPG wave features depends also on the position of the optical sensor and the contact pressure force exerted in the place of the sensor. Many experimental studies confirmed that too low or too high contact pressure applied on the skin of the finger (wrist) by the worn PPG sensor causes degradation (decrease of the heart pulse amplitude and distortion of the systolic peak wave) of the sensed PPG signal [1–3]. The highest amplitude of the PPG signal can be achieved when the contact pressure is equal to the transmural pressure defined as the pressure difference between the inside and outside of the blood vessel. Higher or lower pressure exerted by the probe leads to decreased amplitude caused by collapsing and fluttering of vessel walls [4,5]. The localized physical pressure can be successfully measured by force-sensitive resistors (FSR) [6,7]. Also tension or deformation sensors working on a similar principle as FSR components are usable to measure and monitor the heart pulsation on the wrist radial artery as fully complementary tools to PPG sensors working on an optical principle (typically worn on fingers) [8].

Motivation of the current work was to analyze influence of the adjusted contact pressure force on the quality and temporal features of sensed PPG waves. This paper describes realization of a wearable PPG sensor including also an integrated contact thermometer and an FSR element for contact pressure force measurement. The FSR sensor film is mounted on the surface of the cover box near a hole for the light source and the photodetector. All parts of this sensor are shielded by aluminum boxes to enable its application in the weak magnetic field environment [9]. For different contact forces on a finger, we realized measurement of PPG signals to collect a database of PPG wave records. Then, we statistically analyzed the determined PPG wave features to make practical recommendation about setting of the contact force which is important for long-time measurement experiments inside the magnetic resonance imaging (MRI) device, which is our long-term research aim [9].

While our last realization of a wearable two-channel PPG sensor [10] had incorporated also contact thermo-element for direct temperature measurement during the PPG signal sensing, this paper describes design, realization, and performed first-step measurements with a developed special prototype of a one-channel wearable PPG sensor with an FSR component and a thermometer for detection and measurement of contact force and temperature of the skin at the point where the optical part of the PPG sensor touches the finger. Measurements were realized for five different levels of contact force for male and female tested subjects separately. Sensed PPG signal records are next processed to obtain PPG wave parameters (systolic peaks amplitude, signal range, and ripple) and subsequently calculated HR mean values and their variances. Obtained partial and summary results confirm essential influence of the applied contact force first of all on the amplitude of PPG signals which was also manifested by increased variance of HR values. The temperature sensed in parallel during the whole measurement experiment was changed minimally—probably due to relatively short time duration of the PPG signal recording (about 1 min per one pressure level). Other PPG wave parameters seem to be less dependent on the contact force or affected by other physiological factors.

2. Methods

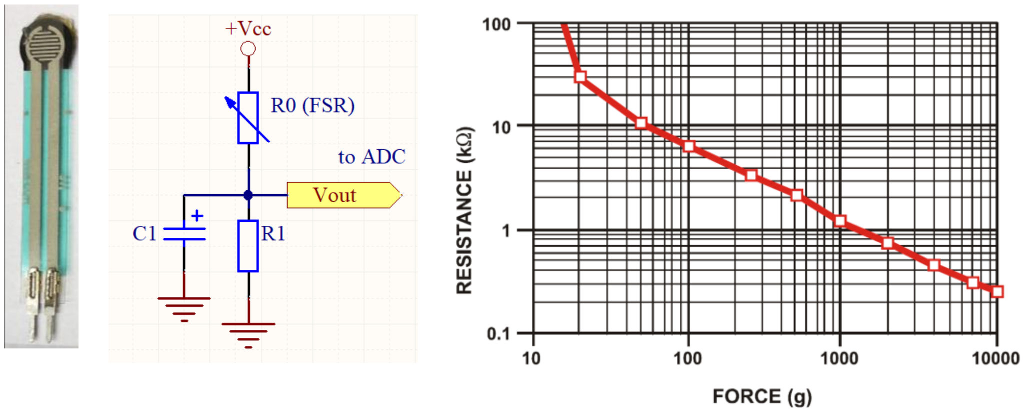
Determination of Basic PPG Wave Properties

For description of basic signal properties of the PPG waves in correspondence with the applied contact force during PPG signal sensing the energetic and statistical parameters can be determined. Currently used methodology of the PPG wave properties including the heart rate determination from the PPG wave was described in more detail in [9,10]. After systolic pulse location, their min/max peak values (Lsp_{MIN}/Lsp_{MAX}) and the signal offset level (L_{OFS}) are determined. Using the mean signal offset the absolute PPG signal amplitude is calculated as $S_{AMPL} = (Lsp_{MAX} + Lsp_{MIN})/2 - \mu\ L_{OFS}$. The bit resolution ($AD_{RES}$) of A/D converter used for digitization of an analog PPG signal can be applied to calculate the relative signal range S_{RANGE} in percentage as $S_{RANGE} = S_{AMPL}/AD_{RES} \times 100$. Finally, the heart pulses ripple in percentage is calculated as $HP_{RIPP} = (Lsp_{MAX} - sLp_{MIN})/Lsp_{MAX} \times 100$. The localized peak positions P_{SYS} are subsequently applied to determine the heart cycle periods T_{HP} and using the sampling frequency f_S [Hz] the heart rate is evaluated as $HR = 60/(T_{HP} \times f_S)$ [min^{-1}]. For further comparison, the mean value and the variance HR_{VAR} (as a squared standard deviation) were also calculated.

For measurement of the contact pressure force based on the FSR component (see the photo in Figure 1a), the voltage divider is usually applied (see the wiring diagram in Figure 1b). There is a non-linear characteristic between the resistance in kilo ohms and the force in grams as shown in Figure 1c. The output voltage from the voltage divider connected to the A/D convertor is defined as

$$V_{OUT} = V_{CC}/(1 + R0/R1)\ [\mathrm{V}], \quad (1)$$

where V_{CC} represents an actual power supply voltage, $R0$ is a resistance of FSR component part, and $R1$ is a pull-down resistor in the voltage divider [11]. An additional capacitor $C1$ connected parallel with the resistor $R1$ suppresses possible peaks induced by step changes of the force applied on the FSR component, so it practically performs partial integration and smoothing of the output analog signal V_{OUT}.



(**a**) (**b**) (**c**)

Figure 1. Principle of function and use of force-sensitive resistors: (**a**) photo of FSR component used in our experiments, (**b**) typical wiring diagram of a voltage divider accompanied by a filtering capacitor (**c**) example of resistance/force conversion characteristics [11].

Using the value V_{ADC} obtained after digitalization by A/D convertor with resolution AD_{RES} the actual resistance of FSR component is given by the formula

$$R_{FSR} = R1 \times (V_{CC}/V_{FSR} - 1) \text{ [ohm]}, \tag{2}$$

where $V_{FSR} = V_{ADC} \times V_{CC}/AD_{RES}$. To express the force in grams the conductance of FSR part is usually calculated as $G_{FSR} = 1/R_{FSR}$. When the current R_{FSR} lays in the linear part of the resistance/force conversion characteristics, the final contact force is given by multiplication with the gravitation constant g (enumerated as 0.00980665 to obtain the force expressed in N)

$$F_{FSR} = G_{FSR} \times \text{g [N]}, \tag{3}$$

Otherwise, some linearization of the parabolic curve part must be applied (see the initial "knee" part of the conversion characteristics in Figure 1c). This step can be done by proper choice of the pull-down resistor R1 [12].

To map potential temperature changes during the measurement with the time duration t_{DUR}, the linear trend (LT) is calculated from the obtained $T1$ temperature sequence by the linear least squares fitting technique. The absolute difference $\Delta\, T1$ between the temperatures $T1$ taken at the start and the end of the measurement can be determined. Next, the gradient parameter T_{GRAD} defined as the ratio $T1_{GRAD} = (\Delta\, T1/t_{DUR})$ [°C/s] is useful for further analysis and comparison. The positive $\Delta\, T1$ and $T1_{GRAD}$ values represent the raising temperature trend; the negative ones signify the falling trend.

3. Objects, Experiments, and Results

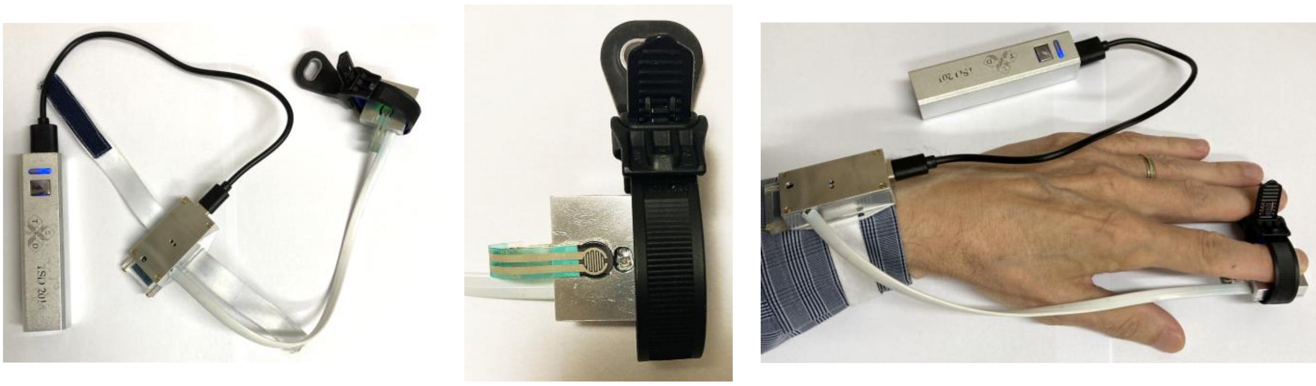
3.1. Description of PPG Sensor Construction and Realization

The currently developed prototype of a wearable one-channel PPG sensor with a thermometer and a FSR component (further call as "PPG-1TSF") consists of:

- the micro-controller board Adafruit Metro Mini 328 (Adafruit 2590) by Adafruit Industries, Brooklyn, NY, USA, based on the processor ATmega328 by Atmel Company, working at f_{CLK} = 16 MHz with eight 10-bit A/D converters, including also the hardware SPI port, the hardware I2C port, and the hardware USART to USB converter [13];
- the bi-directional communication BT module MLT-BT05 by Techonics Ltd., Shenzhen, China, working in the BT4.0 BLE standard at 2.4 GHz;

- the reflectance optical PPG sensors with fully integrated analogue interface—the Pulse Sensor Amped (Adafruit 1093) by Adafruit Industries, Brooklyn, NY, USA;
- the high-precision I2C thermometer based on Adafruit MCP9808 temperature sensors [14] by Adafruit Industries, Brooklyn, NY, USA;
- Force Sensitive Resistor—Small (Sparkfun SEN-09673) [12] by SparkFun Electronics, Niwot, CO, USA.

The whole sensor is powered via the USB port by the 5 V power bank with capacity of 2200 mAh. The applied FSR component consists of a 7.62 mm diameter circular sensing area, enabling detection and measurement of the force from 0.1 to 1.25 N [12]. To use the conversion characteristics with maximum linearity [11], the resistor $R1$ value in the voltage divider was finally set to 3.3 kΩ and the filtering capacitor $C1$ of 6.3 μF was connected in parallel. The integrated thermo-chip MCP9808 enables measuring the temperature from −40 °C to +125 °C with a typical accuracy of ±0.125 °C [14]. While the analogue signal from the optical Pulse Sensor Amped and FSR component are connected directly to A/D converters of ATmega328 processor, the values from MCP9808 thermo-sensor are obtained numerically via I2C bus interface, both located on the Adafruit Metro Mini 328 board. To enable further measurements in a weak magnetic field environment of the MRI device, the whole PPG sensor consists of non-ferromagnetic components and all parts are fully shielded by aluminum boxes against the radiofrequency disturbance—see the photo of sensor's assembling in Figure 2a. The optical part of the PPG sensor including also the FSR part placed on the surface of the Al shielding box is fixed on the measured finger by the special 12.7 mm wide plastic (polyamide) ribbon with a rack fixing binder [15] for easy and precise setting of different pressure forces—see a detailed photo in Figure 2b. The illustration photo of used arrangement for measurement with the PPG-TSF1 sensor is shown in Figure 2c.



(**a**) (**b**) (**c**)

Figure 2. Construction and measurement with the PPG-TSF1 sensor: (**a**) photo of complete assembling with a power bank and a fixing plastic ribbon, (**b**) detail of used plastic ribbon with visible fixing binder tooth system for easy and precise setting of different pressure forces on the finger's skin, (**c**) photo of worn sensor ready for measurement.

3.2. Description of Performed Measurement Experiments

After verifying the sensor's basic functionality, the practical measuring experiment in the normal laboratory conditions was performed. It consisted of real-time sensing of PPG waves and temperature values with different setting of contact forces (CF) and applied on the skin surface of a sensing finger. The tested person was sitting with both hands laid on a table located in a normal laboratory room without any stimuli during the measurement. The measurement was realized for five levels of the applied force (FL1,…, FL5). The sensor was worn on the left and right index fingers, so there were 20 data records per a person in total. Each of data records with a time duration of 64 sec was sensed using the sampling frequency f_S = 500 Hz. In this way we obtained a small database originated from six non-smoker volunteers (four males M1–M4 and two females F1–F2) with a mean age of 56 years. The collected data records were analyzed to obtain PPG wave properties and their statistical parameters.

As the signal from the FSR sensor part is not strictly linear, some pulsation in the rhythm of systolic peaks of the PPG wave is present—expressed mainly in higher levels of the contact force (see an example in Figure 3). So, the mean value and the standard deviation of the F_{FSR} signal must be determined and used for evaluation of the obtained results. In addition, the preliminary measurement has shown that the response to the applied contact force is principally different for fingers of male and female tested persons, so we must apply different scaling and force levels. Therefore the mean CF values in the main measurement experiment were finally set as follows: CF_{MALE} = {0.15, 0.25, 0.45, 0.8, and 1.1 N}, CF_{FEMALE} = {0.20, 0.40, 0.50, 0.60, and 0.75 N}—see bar-graphs in Figure 4. Example of a collection of five sensed PPG waves with applied different contact force levels for a male person M1 are presented in Figure 5. Table 1 shows corresponding partial results of the determined PPG wave parameters. Figure 6 compares final results depending on the used hand (left/right and joined both together) for male and female subjects separately.

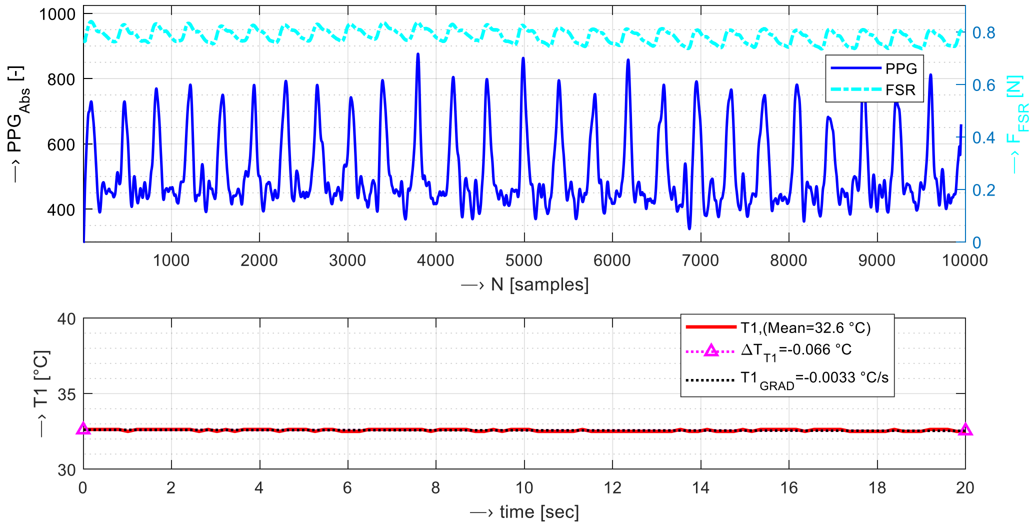


Figure 3. Example of 10-k sample PPG wave with parallel measured analogue signal F_{FSR} from FSR element; f_s = 500 Hz, T1 values taken at each of 0.2 sec, all signals sensed on the left index finger of the male testing subject M1.

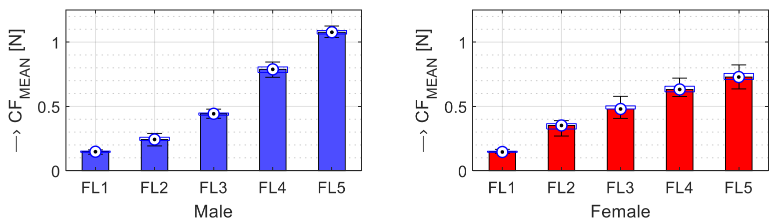


Figure 4. Visualization of practically applied contact force levels (FL1,…, FL5) for male and female tested subjects separately.

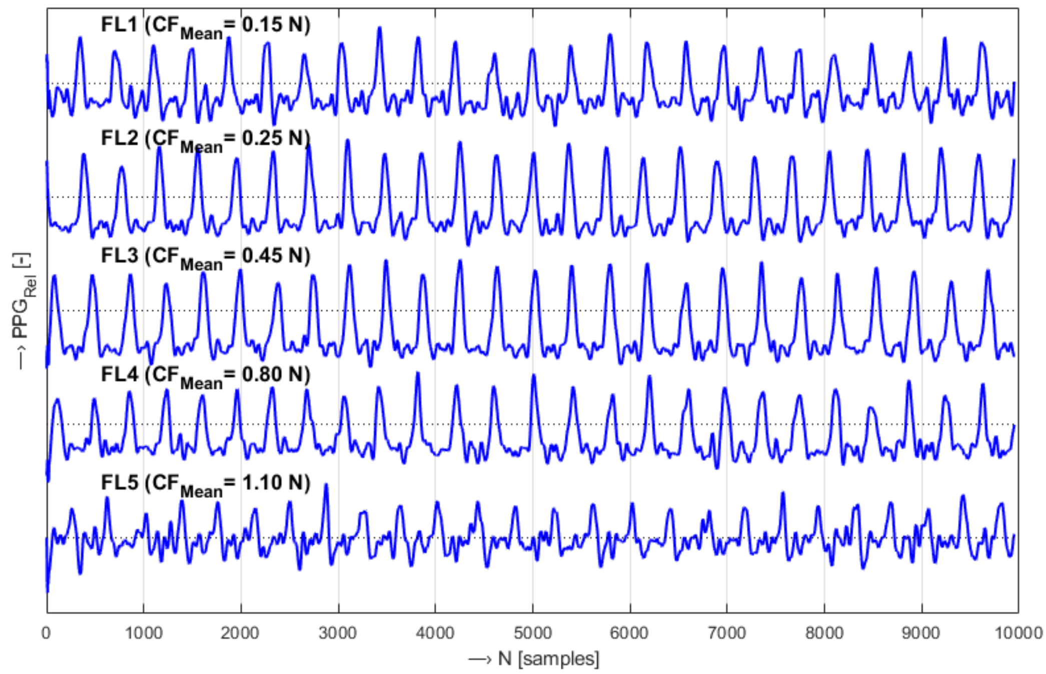
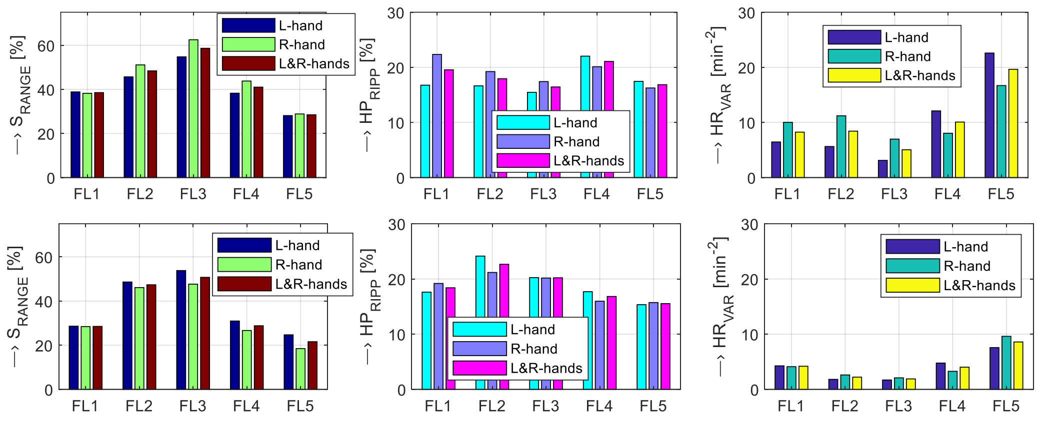


Figure 5. Examples of 10-k sample parts of PPG signals sensed on the left hand's index finger with applied different contact force during wearing of optical sensor part; f_s = 500 Hz, male M1.

Table 1. Results of determined PPG wave parameters corresponding to the PPG signals presented in Figure 5.

Contact Force Level	Lsp_{MIN} [-]	Lsp_{MAX} [-]	μ L_{OFS} [-]	S_{RANGE} [%]	S_{RIPP} [%]	HR_{VAR} [min^{-2}]	CF_{MEAN} [N]
FL1	705	847	378	38.9	16.8	6.46	0.147 ± 0.007
FL2	761	913	369	45.7	16.6	5.64	0.245 ± 0.018
FL3	825	976	340	54.8	15.4	3.12	0.445 ± 0.019
FL4	683	876	388	38.3	22.1	12.1	0.785 ± 0.025
FL5	624	756	402	28.1	17.5	22.6	1.082 ± 0.009



(**a**) (**b**) (**c**)

Figure 6. Summary results—bar-graphs of selected parameters of PPG signals for: (**a**) S_{RANGE} values, (**b**) S_{RIPP} values, (**c**) HR_{VAR} values for left/right and both hands together; male subjects (upper set of graphs) and for female tested persons (lower set).

4. Discussion and Conclusions

The performed measurement experiments confirm practical functionality of the developed special prototype of a wearable PPG sensor supplemented also with a contact thermometer and FSR sensor film. The chosen type of FSR element appears to be suitable for our current experimental purpose—to map the response of the contact pressure force applied on the skin at the point where the optical part of the PPG sensor touches the finger. It has been demonstrated by significant changes in the PPG signal properties as well as in stability and accuracy of subsequently determined HR values.

Testing within the preliminary phase has shown that principal differences between fingers of male and female tested persons must be considered in arrangements and methodology of practical realization of measuring experiments. Female fingers have generally slightly thinner capillaries, so the pressure effect is manifested with application of lower levels of the contact force in comparison with the male ones. Therefore, we must apply different scaling and force levels for males and females and also the obtained results must be analyzed and compared separately. Contrary to our expectation, differences in PPG wave properties between left and right hands are not significant (see the summary results in Figure 6).

The temperature sequences sensed in parallel with the PPG and F_{FSR} signals show minimal changes in $T1$ values (difference ΔT, T_{LT} as well as T_{GRAD} are close to zero—see the lower graph in Figure 3) due to relatively short time duration of the performed individual measurements. Hence, the $T1$ values were practically not considered nor evaluated in the main experiments.

Currently realized measurements were performed in the basic experimental conditions, when the contact force on the measured skin was incrementally increased in five steps. We plan next investigations of the process of regeneration of the pressed skin after stopping application of the contact force. In this case, the longer time duration of the whole experiment will be applied, so the temperature effect may also be shown. Finally, it is necessary to perform more measurements with the aim to collect a larger database of measured data records—which will allow obtaining more representative results that can be generalized.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this paper will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflict of interest.

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