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Thermoelectric Heat Meter for the Diagnosis of Neurotrophic Injuries of the Lower Extremities and the Spine

The paper presents the development of a multi-channel portable thermoelectric heat meter with a wireless interface and cross-platform software for the diagnosis of neurotrophic injuries of the lower extremities and human spine. The device provides simultaneous measurement of temperature and heat flux density by four independent channels with the ability to connect via Bluetooth or Wi-Fi interface. Software based on React Native has been developed, running on Windows, macOS, Android and iOS platforms with patient management functions, real-time monitoring, data storage in the Firebase cloud database and the ability to analyze the collected datasets using machine learning methods.

Keywords: thermoelectric heat meter, semiconductor sensor, bismuth telluride-based thermoelectric material, heat flux density, temperature, medical diagnostics, neurotrophic injury, injuries of the lower extremities and spine, computer program, wireless interface, React Native, Firebase, machine learning.

Introduction

General characterization of the problem. Neurotrophic injuries of the lower extremities and spine are one of the current problems of modern medicine, which is due to the widespread prevalence of the pathology and the difficulty of early diagnosis. Diabetic neuropathy, radiculopathy, polyneuropathy and other neurotrophic diseases lead to impaired innervation of

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biological tissues, which is accompanied by changes in local heat generation and temperature characteristics of the affected areas [1–8]. Timely diagnosis of such disorders allows preventing the development of complications, including trophic ulcers, gangrene and disability of patients [1, 4, 5].

Traditional methods of diagnosing neurotrophic injuries, such as electroneuromyography, ultrasound, and magnetic resonance imaging, although informative, have a number of limitations: the high cost of equipment, the need for specialized facilities, the difficulty of conducting mass examinations, and the impossibility of long-term monitoring of the patient's condition over time [3–5].

Semiconductor thermoelectric heat flux sensors [2, 6–15] are an effective tool for studying local thermal characteristics of the human body due to their compact size, high sensitivity, stable operation in a wide temperature range, and compatibility with modern data recording systems [2, 11, 12].

The modern development of information technologies opens up new opportunities for medical diagnostics. The use of wireless interfaces (Bluetooth, Wi-Fi) allows the creation of mobile diagnostic systems, and the use of cloud technologies and machine learning methods provides the possibility of accumulating large amounts of data and their intelligent analysis [16–20].

Therefore, *the purpose of the work* is to develop a multi-channel portable thermoelectric heat meter with a wireless interface and cross-platform software for diagnosing neurotrophic injuries of the lower extremities and spine.

Design and technical characteristics of the device

The multi-channel portable thermoelectric heat meter (Fig. 1) developed at the Institute of Thermoelectricity of the National Academy of Sciences and the Ministry of Education and Science of Ukraine provides simultaneous measurement of temperature and heat flux density with data transmission via a wireless interface. The main technical parameters of the device are presented in Table 1.

Fig. 1. Thermoelectric device for measuring temperature and heat fluxes

Table 1

Technical characteristics of the device

№	Technical characteristics of the device	Parameter values
1.	Number of measuring channels	4
2.	Operating temperature range	0 ÷ +50 °C
3.	Temperature measurement accuracy	± 0.05 °C
4.	Heat flux density measurement range	1 ÷ 100 mW/cm²
5.	Maximum error in heat flux density measurement range	3 %
6.	Overall dimensions of the thermoelectric sensor	(14×14×3) mm
7.	Wireless interface	Bluetooth 5.0, Wi-Fi 802.11 b/g/n
8.	Communication range	up to 10 m (Bluetooth), up to 50 m (Wi-Fi)
9.	Measurement frequency	2 measurements/s
10.	Continuous operating time of the device	24 hrs

The device contains a control unit with a built-in microcontroller, four thermoelectric temperature and heat flux sensors and a wireless communication module. Each thermoelectric sensor consists of a thermistor-based temperature sensor and a thermocouple-based thermopile heat flux sensor. The thermistor has overall dimensions of 2.2 × 2 × 0.7 mm, which provides high locality of temperature measurement. The 10 × 10 × 3 mm thermopile is made of semiconductor thermoelectric materials based on bismuth telluride and provides high sensitivity to heat flux in the range from 1 to 100 mW/cm².

Temperature and heat flux density are measured simultaneously by 4 thermoelectric sensors with the measurement results transmitted via Bluetooth or Wi-Fi interface to a mobile device or personal computer for processing, visualization and storage in the Firebase cloud database in real time (Fig. 2). Electrical signals from thermoelectric sensors are amplified and digitized using a 16-bit analog-to-digital converter with a sampling rate of 2 measurements per second. The microcontroller performs primary signal processing, calibration and conversion into units of temperature (°C) and heat flux density (mW/cm²).

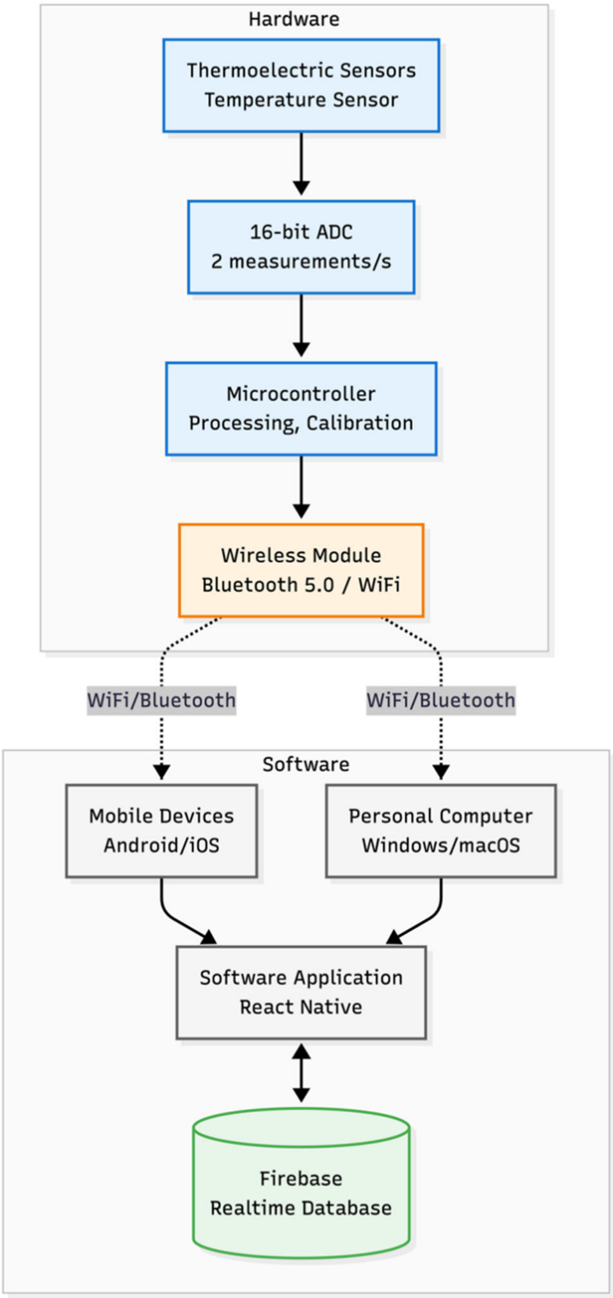

Fig. 2. Block diagram of a thermoelectric heat meter with a wireless interface

The use of a wireless interface provides several advantages over traditional wired systems. First, the ability to perform measurements without restricting the patient's mobility allows for functional load tests, which is important for diagnosing neurotrophic injury in different body positions and levels of physical activity. Second, the absence of wires increases patient comfort during long monitoring sessions, which can last from several minutes to several hours. Third, the ability to simultaneously monitor multiple patients from a single workstation improves the efficiency of medical staff during mass screenings. Fourth, the use of various devices (smartphones, tablets, laptops) to collect and analyze data ensures the system's flexibility and suitability for use in a variety of settings, from hospitals to mobile medical teams.

The device is powered by a built-in 2000 mAh lithium-ion battery, which provides continuous operation for 24 hours at a measurement frequency of 2 times per second. The device is equipped with a battery level indicator and an automatic shutdown system at a critically low charge to prevent battery damage.

The device supports two operating modes: standalone and connected to a mobile device or computer. In standalone mode, measurements can be performed independently of the software, using the device's built-in interface with control buttons and a small display to display current temperature and heat flux density values. Measurement results are automatically stored in the device's internal memory, which allows recording up to 50 hours of continuous measurements. This is especially convenient for long-term patient monitoring in the field or when there is no access to a mobile device. In Bluetooth or Wi-Fi mode, the device transmits data in real time to a smartphone, tablet or personal computer, where the software provides advanced visualization, analysis and data storage in the Firebase cloud database. The data stored in the device's memory can be later downloaded to the program for further analysis and archiving.

Description of the device computer program

The software for the thermoelectric heat meter (Fig. 3) is developed based on the React Native framework, which provides cross-platform compatibility and the ability to work on Windows, macOS, Android, and iOS operating systems without the need to develop separate versions for each platform [21–23]. The program architecture is built on the principle of client-server interaction using the Firebase Realtime Database cloud database for storing and synchronizing data between devices in real time [24–26].

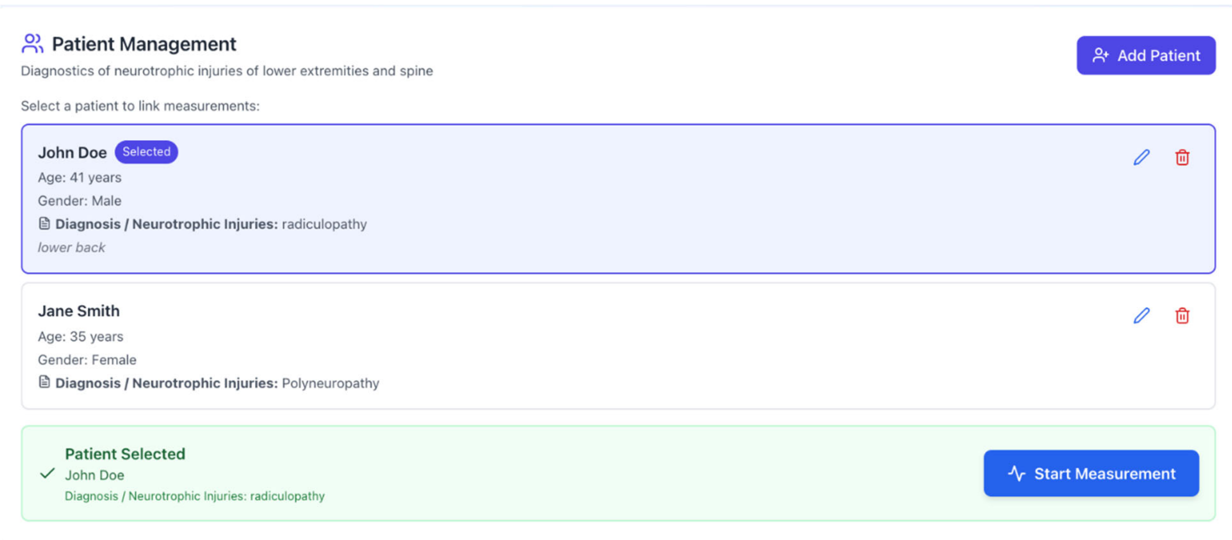

Fig. 3. Patient management module interface

The program provides a full cycle of work with patients from creating a profile to saving examination results. At the first launch, the user goes through the authentication procedure using Firebase Authentication, which supports login via email/password or Google Sign-In. Each user has their own account with personal settings and access only to their data, which meets the requirements of medical ethics and personal data protection [20–22].

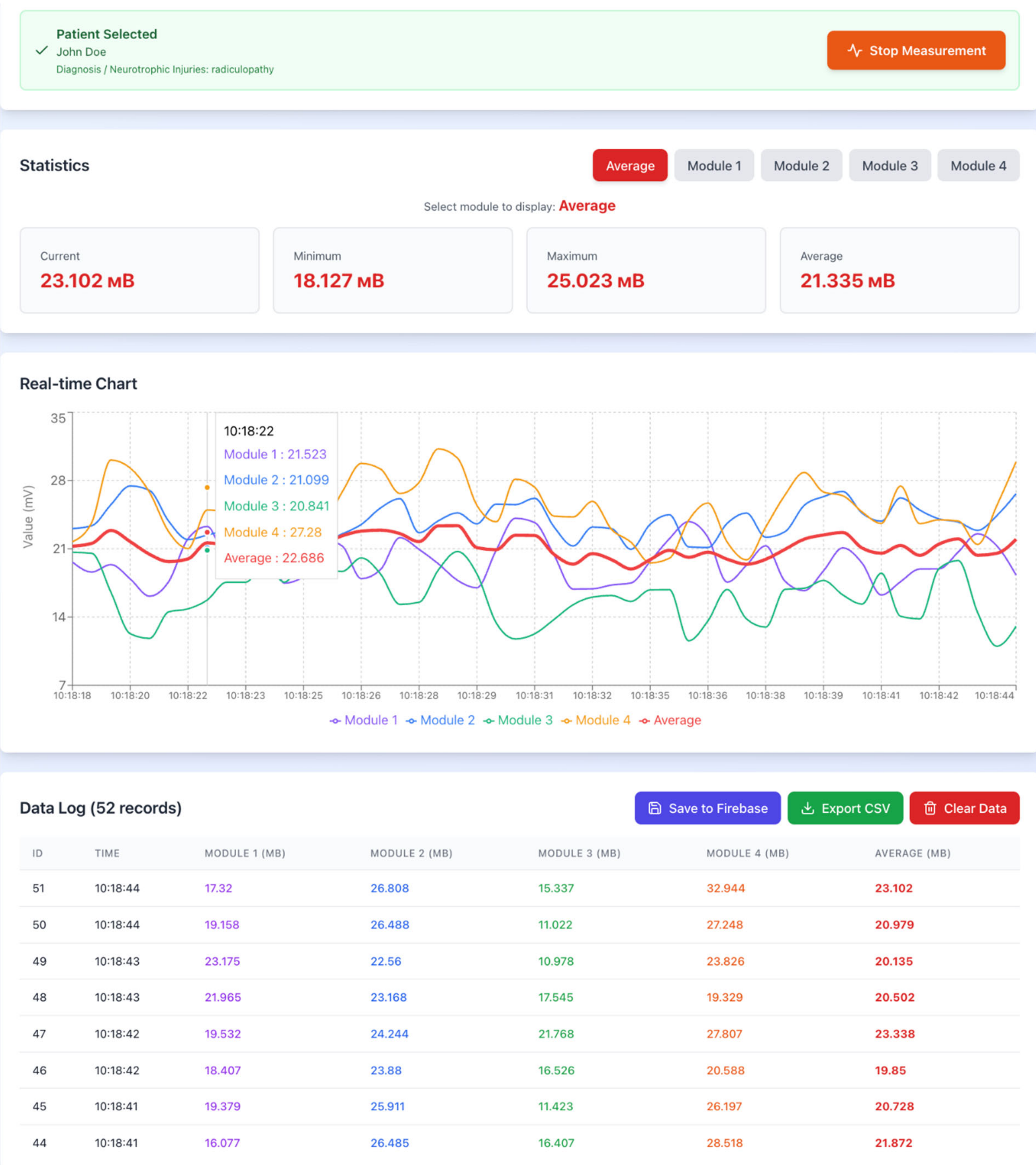

Fig. 4. Program interface for monitoring and saving measurement results (displays real-time graph of active measurement channels and statistics)

After authentication, the user has the opportunity to create patient profiles with detailed information: last name, first name, middle name, age, gender, main diagnosis and notes on the nature of the injury. For patients with neurotrophic injuries, there is an opportunity to indicate the localization of the injury (left or right leg, lumbar or thoracic spine), the degree of injury, the intensity of the pain syndrome, sensory disorders and motor disorders. All patient data is stored in a structured form in a cloud database with complete isolation between users.

To perform measurements, the user selects a patient from the list and establishes a connection with the thermoelectric heat meter via Bluetooth or Wi-Fi. The program automatically detects available devices within range and establishes a connection after confirmation by the user. During the measurement, data from four channels are displayed on the screen in the form of interactive graphs in real time (Fig. 4). The user can select individual channels for detailed viewing, change the scale of the graphs and observe the current values of temperature and heat flux density, as well as statistical indicators (minimum, maximum and average values) for each channel.

During measurements, data is accumulated locally on the device at a rate of 2 measurements per second. After the measurement session is complete, the user has the option to save all collected data in one package to the Firebase cloud database. Each saved session contains metadata (user ID, patient ID, patient name, diagnosis, measurement start and end time, connection type), a complete array of measurements with time stamps, and calculated statistics for each channel. This storage structure minimizes the number of database write operations, which reduces the cost of using cloud services and ensures the integrity of the session data.

In addition to saving to a cloud database, the program provides the ability to export collected data in CSV format for further analysis in specialized data processing programs (Microsoft Excel, MATLAB, Python, etc.). Exported files contain complete information about the patient, measurement parameters and all recorded values, which allows for detailed statistical analysis and comparison of results from different measurement sessions.

Measurement methodology and data analysis

The methodology for conducting measurements using the developed complex includes several sequential stages. At the preparatory stage, the medical professional creates a patient profile in the software, entering basic data (full name, age, gender) and detailed information about the nature of the neurotrophic injury. For patients with diabetic neuropathy, the duration of diabetes mellitus, glycemia level, and the presence of concomitant complications (retinopathy, nephropathy, angiopathy, etc.) are indicated. For patients with radiculopathy, the localization of the injury (L4, L5, S1), the intensity of the pain syndrome on a visual analog scale, and the duration of the disease are recorded. Such detailed documentation allows for further statistical analysis of the data, taking into account the clinical characteristics of the patients.

Measurements are recommended to be performed in standardized conditions at a room temperature of 22 ± 2 °C and a relative humidity of 40–60 %. The patient should be at rest for at least 15 minutes before the measurement to achieve thermal equilibrium of the body with the environment. Thermoelectric sensors are installed on the studied areas of the body using elastic clamps that ensure uniform contact of the sensor with the skin surface without excessive pressure. For the diagnosis of neurotrophic injuries of the lower extremities, symmetrical placement of sensors on both extremities in the projection of the plantar surface of the foot and calf muscles is recommended, which allows detecting asymmetry of heat release between the healthy and affected extremities.

After installing the sensors and connecting the device via Bluetooth or Wi-Fi interface, the healthcare professional initiates a measurement session in the software. During the first 2–3 minutes, the sensors undergo a thermal adaptation process to the skin surface temperature, which is accompanied by a gradual stabilization of the indicators on the graphs. After reaching a stable state, the main measurement phase begins, lasting 5–10 minutes, during which the temperature and heat flux density are recorded with a frequency of 2 measurements per second. Such a high sampling frequency allows you to detect short-term fluctuations in heat release associated with blood pulsation in superficial vessels, which may have additional diagnostic value when assessing the state of microcirculation.

The software displays real-time graphs of temperature and heat flux density changes for each of the four channels, and also calculates the average, minimum, maximum and standard deviation. The user can select individual channels for detailed viewing, change the scale of the graphs and add text notes to the measurement session. After the measurement is completed, all data is stored in the Firebase cloud database with a link to a specific patient, which allows you to further track the dynamics of changes in indicators during repeated examinations.

The analysis of the collected data includes several levels. At the first level, the absolute values of temperature and heat flux density are compared with reference values for healthy individuals of the corresponding age and sex. A decrease in the temperature of the foot surface below 30°C and heat flux density below 15 mW/cm² may indicate impaired blood supply and innervation of biological tissues. At the second level, the asymmetry of the indicators between the symmetrical areas of the left and right limbs is analyzed. A difference of more than 10% is considered pathological and indicates a unilateral nature of the lesion. At the third level, the dynamics of changes in indicators during repeated examinations is assessed, which allows monitoring the effectiveness of treatment and progression of the disease.

Exporting data in CSV format allows for in-depth statistical analysis using specialized software packages. Researchers can use correlation analysis methods to identify relationships between heat release rates and clinical characteristics of patients, analysis of variance methods to compare groups of patients with different types of neurotrophic injuries, and regression analysis methods to build predictive models for the development of complications. The accumulation of large data sets creates the prerequisites for the application of machine learning methods to automate the diagnostic process and increase the accuracy of detecting early stages of neurotrophic injuries.

Conclusions

1. A multi-channel portable thermoelectric heat meter with a wireless interface has been developed for the diagnosis of neurotrophic injuries of the lower extremities and spine, which provides simultaneous measurement of temperature with an accuracy of ± 0.05 °C and heat flux density in the range of 1–100 mW/cm² with an error of 3 % by four independent channels. The use of Bluetooth 5.0 and Wi-Fi 802.11 b/g/n interfaces allows measurements to be made without limiting the patient's mobility at distances of up to 10 m and 50 m, respectively.
2. Cross-platform software based on React Native has been created, running on Windows, macOS, Android and iOS operating systems with patient management functions, real-time monitoring and data storage in the Firebase Realtime Database cloud database. The computer program provides a full cycle of work from creating a patient profile with detailed information about the localization and nature of neurotrophic injury to saving examination results and exporting them for further analysis.
3. A method for conducting medical measurements using four thermoelectric sensors has been developed, which includes standardized measurement conditions (room temperature 22 ± 2 °C, relative humidity 40–60 %), symmetrical placement of sensors on the studied areas of the lower extremities, thermal adaptation time of 2–3 minutes and duration of the main measurement phase of 5–10 minutes. A multilevel approach to data analysis has been proposed, which includes comparison of absolute values with reference values, assessment of asymmetry between symmetrical areas and analysis of the dynamics of changes during repeated examinations.
4. A data storage structure is proposed with linking measurement sessions to specific patients and ensuring complete isolation of data between users in accordance with medical ethical norms and personal data protection requirements. The accumulation of large volumes of structured data in the Firebase cloud database creates the prerequisites for the application of machine learning methods (Random Forest, Support Vector Machines, neural networks) to classify types of neurotrophic damage, predict the development of complications, personalized diagnostics and automatic detection of anomalies, which can increase the accuracy and speed of medical diagnostics.
5. The developed complex (device + software) is promising for implementation in clinical practice for early diagnosis of neurotrophic injuries, objectification of the diagnosis, monitoring the effectiveness of treatment in dynamics and conducting mass preventive examinations of patients at risk (patients with diabetes mellitus, osteochondrosis, vascular diseases, etc.). The wireless interface and cross-platform software provide the possibility of using the system both in a hospital setting and in outpatient practice and by field medical teams. Export of data in CSV format allows for in-depth statistical analysis using specialized software packages for scientific research.

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Термоелектричний тепломір для діагностики нейротрофічних ушкоджень нижніх кінцівок та хребта

У роботі представлено розробку багатоканального портативного термоелектричного тепломіра з безпровідним інтерфейсом та кросплатформеним програмним забезпеченням для діагностики нейротрофічних ушкоджень нижніх кінцівок та хребта людини. Прилад забезпечує одночасне вимірювання температури та густини теплового потоку чотирма незалежними каналами з можливістю підключення через Bluetooth або Wi-Fi інтерфейс. Розроблено програмне забезпечення на базі React Native, що працює на платформах Windows, macOS, Android та iOS з функціями керування пацієнтами, реал-тайм моніторингу, збереження даних у хмарній базі Firebase та можливістю аналізу зібраних датасетів методами машинного навчання.

Ключові слова: термоелектричний тепломір, напівпровідниковий сенсор, термоелектричний матеріал на основі телуриду вісмуту, густина теплового потоку, температура, медична діагностика, нейротрофічні ушкодження, травми нижніх кінцівок та хребта, комп'ютерна програма, безпровідний інтерфейс, React Native, Firebase, машинне навчання.

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