Hardware-Software Complex to Restore Finger Movement Coordination and Color Perception

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***Abstract*—** After the damages of the cervical-thoracic spine and hand nerves, the motor and/or sensory functions are impaired, especially fine motor skills of each finger individually or a group of fingers. The results of injuries in the cervical spine can also lead to atrophy of the optic nerve. In this case, it becomes quite difficult to distinguish colors, color perception is distorted. This is especially true of red color. The work presents the results of the development and testing series of diagnostic and training (DT) devices “Reflex-Txx” for the physical rehabilitation program (therapy) of these patients. As a working element of the device, a movable zone, rotating on a servo drive, with Hall sensors or touch buttons for contact with hand fingers in different DT device models of the series “Reflex-Txx” has used. The electronic components and architecture of the developed devices are described as the minimal cost of hardware implementation. For this purpose, an Arduino platform is used in the developed DT devices. The average-moving method was used to research the effectiveness of training techniques. The statistics of a current training session is displayed on the LCD screen of a DT device. The total results are accumulated, displayed and analyzed on the microservices of the developed hardware and software complex. The mobile application was developed to visualize training data on the user's gadgets in real-time.

***Keywords*—**cervical-thoracic spine/hand damages, diagnostic-training devices, Arduino, microservice architecture.

I. Introduction

In accordance with the Classification of American Spinal Injury Association Impairment Scale motor and/or sensory functions are impaired after spinal injuries [1]. In this case, muscles and joints are lost strength and mobility. Damage to the fingers of the hands can also occur as a result of congenital anomalies, office work, strokes, etc. For example, carpal (“tunnel”) syndrome can begin with a decrease in the motor functions of the fingers, muscle weakness, etc. [2].

Rehabilitation programs have to combine physical therapies with exercises toward muscle strengthening and redeveloping fine motor skills. According to medics, strategies for recurring episodes of spasticity are very important. Post-stroke spasticity of the limb is one of the most frequent motor disturbances. Spasticity is reported in more than 12 million people worldwide [3]. The most common are lesions from injuries of the upper extremity (UE) pains with a rate of 26% to 96% [4].

Therapeutic exercises and a gradual increase in motion, including apparatus treadmill, loads play a leading role in the treatment of spasticity [5]. Adaptive devices also may help people with spinal cord injury and hand nerve damage to regain independence and improve mobility and quality of life. Such devices may include computer adaptations and other computer-assisted technology.

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II. Analytical Review of the Literature

It is important in time, before the development of contractures (“clawed paw”, “monkey paw”), to identify affected fingers (Fig. 1) and to provide the necessary hardware to carry out the training programs to overcome muscle weakness and to develop fingers.

It is advisable to follow the Management of carpal tunnel syndrome evidence-based clinical practice guidelines, adopted by the American Academy of Orthopaedic Surgeons (AAOS) in 2016 [2]. In addition to medical tests and health surveys using sophisticated equipment (Ultrasound scan, CT or MRI, X-rays, etc.), these Recommendations also provide for special simple mechanical tests. These recommendations also give examples of strong evidence that supports no benefit to routine postoperative immobilization (splinting). It says about the effectiveness of short-term difference in regards to grip strength, pinch strength, and range of motion up 17.5 months via the 4-week courses of sensory and therapy motion exercises relearning home program. Such an approach calls simple exercises running on simple, inexpensive devices. A treatment with allowing an early range of motion exercises has contributed to the improvement in motion in the short 2-week term in 2-point and 3-point pinch strength. This effect was not present follow-up ordinary immobilization even at the 3-month [2].

Fig. 1 Fingers (groups of fingers) to be diagnosted/trained

Thus, it is important not only to localize the problem, but also to contribute to the decision to train the finger (in case of muscle weakness) or to solve about immobilization the finger to reduce the risk of further complications ((in case of injury or inflammation). For some diagnoses, the doctor may also recommend doing some gentle exercises to stretch the fingers, which may help reduce stiffness and improve mobility even to participants with rheumatoid arthritis [6], [7]. This is possible with the help of special devices for practicing individual movements with your fingers.

The results of injuries in the cervical spine can also lead to atrophy of the optic nerve and as a result, it becomes quite difficult to distinguish colors, color perception is distorted, and the field of vision sharply narrows to red color [8]. Therefore, in diagnostic and training (DT) devices for detecting dichromasia, it is also advisable to include components associated with the determination of the base colors (RGB).

Specific training can improve function, coordination of fine muscle movements, and overall strength and health. Scientists note the relative effectiveness of an intensive task-specific motor training program added to standard rehabilitation compared with standard rehabilitation alone for improving hand function [9]. Early rehabilitation is important to prevent joint contractures of the hand and fingers, as well as the loss of muscle strength [10].

Worldwide, hardware methods for the treatment of degenerative-dystrophic diseases of articular or periarticular tissues are being studied and successfully applied. the extracorporeal shockwave therapy of fingers flexor muscles in poststroke patients [11], phototherapy [12], etc.

However, it should be borne in mind that the above devices are full-scale, designed to treat all parts of the spine and joints, and therefore are characterized by large dimensions and cost.

For the sake of this, it’s relevant to develop small-sized low-cost DT devices, which you need to use regeneration-stimulating the regrowth of axons and targeting their connections appropriately by repeating the coordinated motions with particular fingers and finger groups.

It is also important to accumulate the results of training each individual in the database of the hardware-software complex (HSC) to adjust training regimes and achieve the best possible results. It should be noted that the transfer of a patient's personal data from the DT device to the servers occurs, mainly through the open communication channels. Based on this, vulnerabilities of wireless networks introduce additional risks to ensure the confidentiality and integrity of transmitted data [13]. As a result, the data of diagnosis and testing of patients may be distorted. If dangerous factors cannot be eliminated from communication channels, it is advisable to use methods and tools that indicate error positions in the message and focus on implementation on hardware platforms used in the HSC development [14].

JWT (JSON Web Token) technology is required to authenticate when data processes by HSC microservices. You can also use the Google Firebase Authentication Service to simplify the development process. But it should be borne in mind that in this approach, personal data of users (IP-address, e-mail, user IDs on social networks and other systems, etc.) become partially accessible to third-party service.

III. Object, Subject and Methods of Research

The object of the research is a process for improving the coordination of finger movement through hardware training, as well as data processing on microservice platforms.

The subject of the research is the DT devices, based on information technology, for diagnostic and rehabilitation the patients with damages of cervical-thoracic spine and hand nerves.

The aim of this study is hardware and software implementation of assistive movement technology and training of color sensitivity of patients with damage of the cervical and thoracic spine and hand nerves, as well as the study of the effectiveness of use in the rehabilitation the movements of the hands and fingers of participants.

The tasks for the development of the hardware and software complex (HSC) are:

1. The development of hardware and software for DT devices and microservices.
2. Data collection from sensors in the training complex (from several types of workplaces with developed DT devices or IoT devices of industrial production).
3. View metrics in real-time.
4. Analysis of data collected over a period of time.

The average moving method was used to evaluate the effectiveness of training with the use of DT devices. This allows you to determine the degree of improvement or deterioration of patient outcomes already during training.

IV. Results of Work

A. Development of Diagnostic-Training Devices and Hardware-Software Complex

1)Development of Hardware

Considering the recommendations made above, a series of diagnostic and training devices “Reflex-Txx” was developed. Each device model has a movable working area, in which 3 LEDs

(RGB) and sensors under them are mounted (Fig. 2). The LEDs light up alternately in random order. The patient should touch the colored area near the illuminated LED before the next light signal.

In this way, the patient's perception of RGB colors, the reaction time to the LED flash and coordination of movements are evaluated. Considering that fingers from the 1st to the 4th may need diagnostics and training (see Fig. 1), it is planned to touch the area near the flashed LED by a finger or a magnet, which is held by a pinch of 2-, 3- or 4 fingers (Table 1).

Fig. 2 Diagnostic and training devices of the “Reflex-Txx” series

Table 1 shows that for diagnosing the degree of spasticity of one finger, for example, according to Modified Ashworth Scale (MAS) of muscle spasticity [3], a touch sensor, for example, TTP223, can be placed under the disk working area. At the top, such a touch button on the “Reflex-TT3” (“Training Touch 3 Sensors”) is marked with a circle of the same color as the LED next to it. (see column 3 in Table 1).

If we are talking about the damage of several fingers and the need to train them with 2-point, 3-point and 4-point pinch strength, then it is advisable to use the Magnetic holder as a tool for touching the working area (see columns 2–4 in Table 1). In this case, 3 Hall sensors are attached under the working area, for example, A3144 – one sensor near each LED (Fig. 3). The upper surface of the working area of such a “Reflex-TN3” (“Training Hall 3 Sensors”) device is marked with RGB rectangles.

Arduino software implements an algorithm of a random flash of different colors on each LED, which provides training of the concentration of attention of the patient and promotes the treatment of optic atrophy.

The hardware platform for the developed devices is the widespread Arduino platform. Despite the rapid departure of the microelectronics market towards the STM32 platform, the Arduino platform still holds a fairly strong position in the segment of devices for home use. These include, among others, small-sized finger training devices according to the recommendations of AAOS [2].

The convenience of Arduino for development home training programs is due to the presence of its own ecosystem of the platform, knowledgebase, C ++ programming environment, wide software functionality, accessible shields, ease of use. When equipped with high-quality electronic components from the original vendors, devices based on the Arduino platform can well satisfy the needs of the market of biomedical electronic devices for monitoring, diagnostics and treatment.

TABLE I. Fingers (groups of fingers) to be trained

The count of training fingers	**1**	**2**	**3**	**4**
Fingers position during training				
Magnetic pinch holder	Not required			
Sensor Type	Touch	Hall	Hall	Hall
Start Score on the MAS	2–3	1–2	1–2	From 1+ up to 2
Finish Score on the MAS	1+	0	0	1

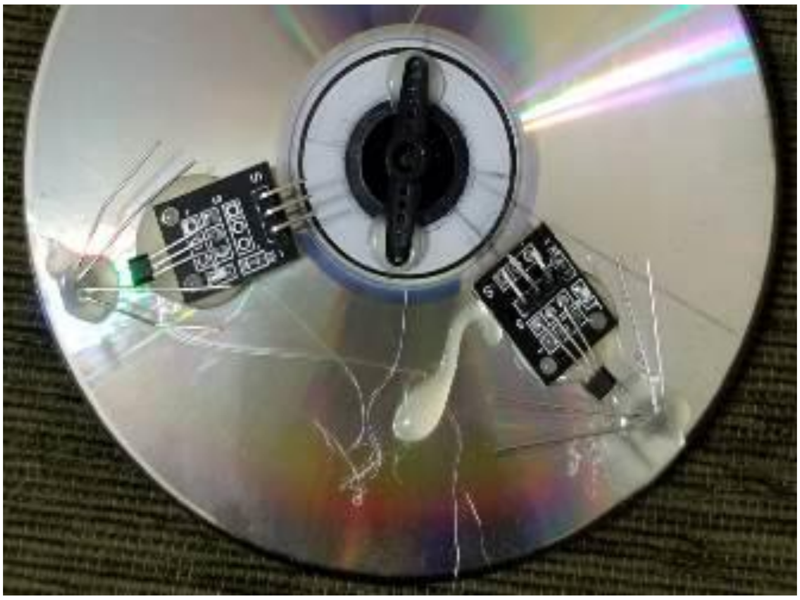
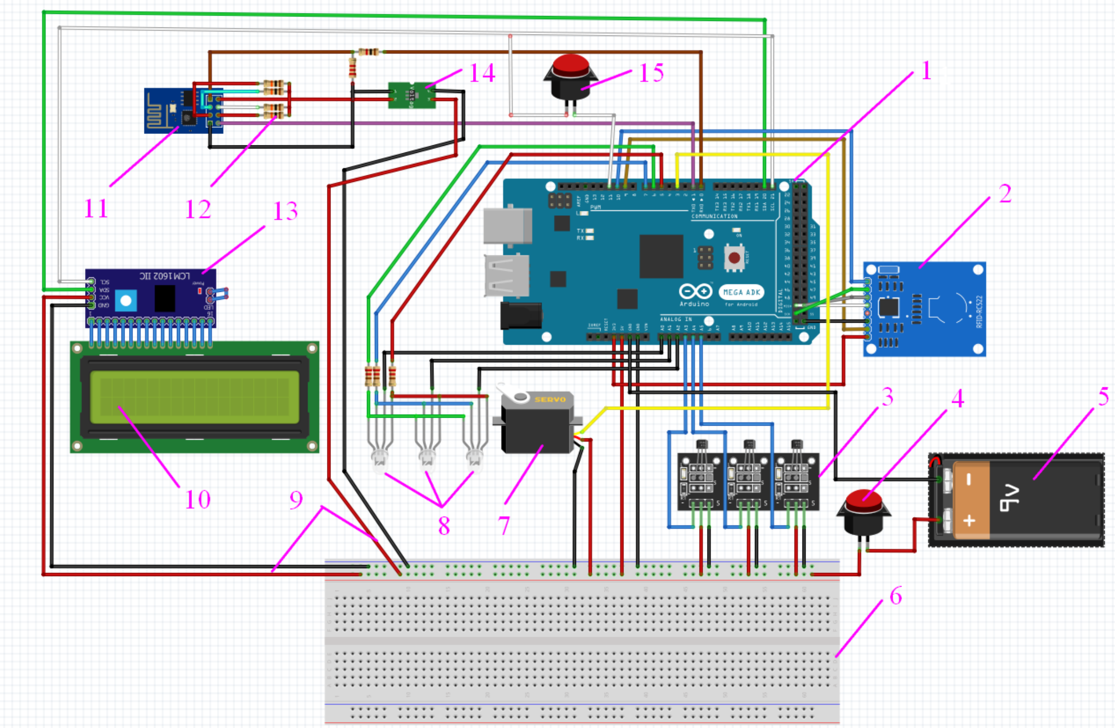


Fig. 3 Hall sensors on the working area of the DT device “Reflex-TH3” (bottom view)

An open-source software tool Fritzing v. 0.9.3 has been used to layout electronic components and document developed prototypes (Fig. 4).

The device “Reflex-Txx” rotates the work zone over a range of 30 degrees while vibrators via servomotor, for example, SG-90. The patient's task is to track the device working area movement turning own hand.



Legend: 1 – microcontroller board (central control) Arduino; 2 – RFID module; 3 – sensors (Hall or touch);4 – power button; 5 – Li-Po Battery 9 V; 6 – circuit board; 7 – servo motor; 8 – LED (RGB); 9 – breadboard Dupont jumper wires; 10 – LCD screen; 11 – Wi-Fi module; 12 – resistors; 13 – I2C module; 14 – DC converter 3V/5V; 15 – start button.

Fig. 4 Wiring diagrams of the modules in “Reflex – Txx” series DT device

Interaction of the DT of the device with the computer or the patient's own gadget is carried out using a Wi-Fi module, for example, ESP-01 of the ESP8266 series via UART using a set of AT commands.

2) The Architecture of Hardware-Software Complex

Developed DT devices of the “Reflex-Txx” series and industrially produced monitoring IoT devices could be considered as the Internet-of-Things nodes for Home Area Network (HAN) [15]. Such devices can connect different sensors that can be substituted further according to the medical recommendation for the patient. In comparison with known solutions, the proposed approach does not require a reprogramming device in case of sensor type has been changed.
The data received from each DT device is transmitted to the services of the developed HSC via a wireless network with the distribution of the data flow separately for each task in the context of each of 5 attempts to complete it [16].
To accomplish the tasks of research, HSC is divided into several services, each of which performs a specific task throughout the system. That is, an approach called service-oriented architecture is used during development [17].
In this case, data is exchanged, for example, between:

- DT devices that collect primary sensors data.
- Monitoring Service for HSC based on Redis Database Management System (DBMS).
- Data Analysis and Storage Service based on WebSocket technology and MongoDB DBMS.
- Single Page Application (SPA) Data Visualization Service [18] and others (Fig. 5).

Messages are JSON files, the structure of which is agreed for each pair of participants in the communication protocol.

Because HSC provides real-time metrics monitoring and long-term data storage for further analysis, it has been decided to create two separate user interfaces. To accelerate the development process for both interfaces, open Nuxt.js framework and open Vuetify component library are used.
The Nuxt.js framework, which contains libraries for Vue.js, was used to build web-based interfaces and a web server with server-side rendering, automatic routing configuration, and state management internal data.
The Vue.js framework was used to create user interfaces and to create sophisticated one-page applications (SPA) in combination with modern tools and support libraries [19].
The monitoring interface solves the problem of displaying real-time data, namely, workload schedules for each DT device and patient, coordination status metrics, and color perception of the user in the last hours of use of the system.

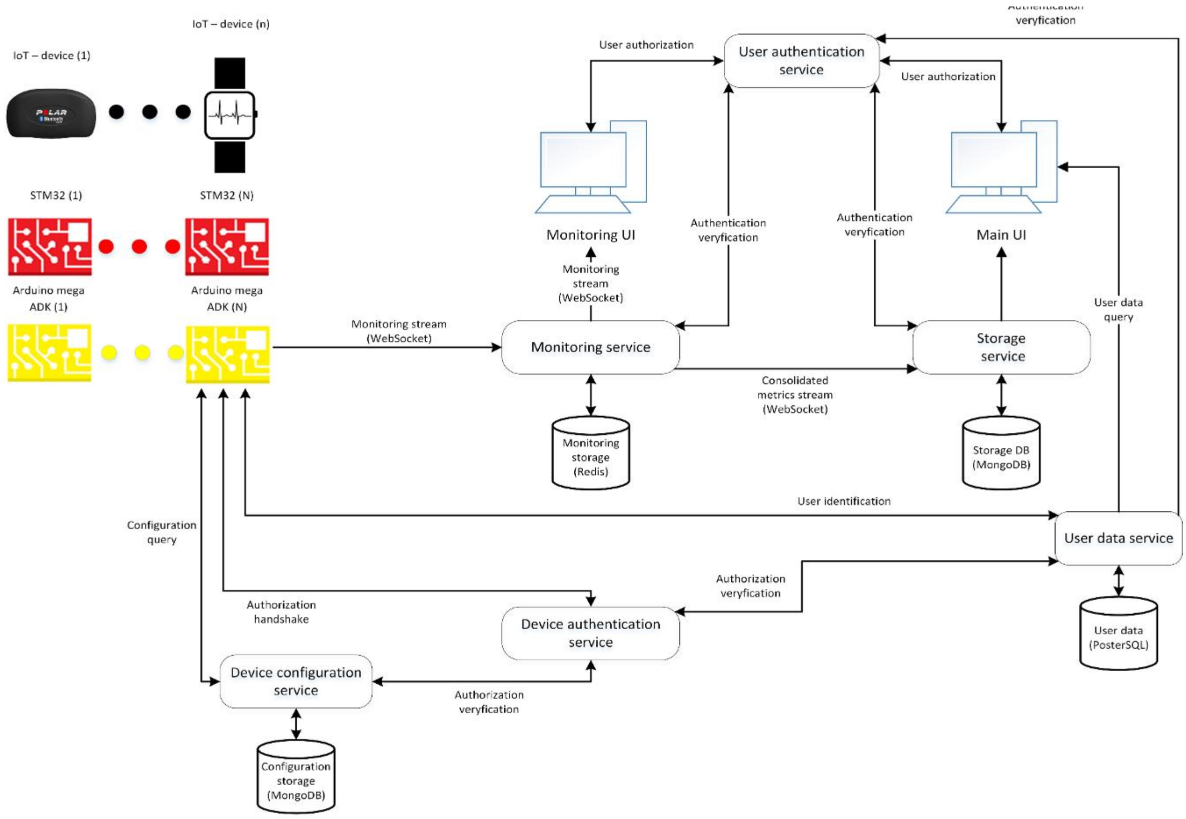


Fig. 5 The architecture of hardware-software complex to diagnostic and rehabilitation the patients

B. Prepare Exercises and Measurement

1) Training mode

Following the medical advice to hold the pinch for up to 30 s before releasing it [20]. One attempt time on “Reflex-Txx” has selected 30 s divided into 20 actions. The attempt repeats up to 5 times with 10-second breaks in between.

Thus, the developed hardware-software complex supplies a series of 20 light flashes with an interval of 1.5 s to the working area of the “Reflex-Txx” device. In the case of a high level of spasticity by MAS and as a result of a slower patient reaction, this interval may be increased.

2). Data Visualization and Processing

During the work of patients with “Reflex-Txx” devices, for each of 5 attempts of a piece of training series, an oscillogram is recorded showing the patient’s reaction speed to the light-emitting diode of a certain color, and average values of training indices are calculated. All results can be seen on the smartphone using the developed mobile application (Fig. 6).

Using the average moving method allows you to determine the degree of improvement or deterioration of results already during training. In this case, at first, the average value of the reaction time AVGi is calculated as:

$$AVG_i = \frac{1}{CurCoAc} \sum_{n=1}^{Att} \sum_{i=1}^{CoAc} TR_{i,n}, \quad (1)$$

where *CoAc* – the total number of actions in the attempt Attn (supposed that is performed *CoAc* = 20 actions in each attempt); *CurCoAc* – the number of actions performed at the current time from the beginning of the attempt; *TRi,n* – reaction time on the RGB LED flash; *Att* – the number of attempts in session (Att = 5).

To evaluate the effectiveness of training over the course of training, the average moving time MOV_AVG_i is calculated by some neighboring actions *NMA* in an attempt (in example *NMA* = 3):

$$MOV\_AVG_i = \frac{1}{NMA} \sum_{i=NMA}^{Ai=NMA} TR_i. \quad (2)$$

If the training is successful, then with its current MOV_AVGi becomes smaller than AVGi. that is, reaction time decreases during training time (Fig. 6).

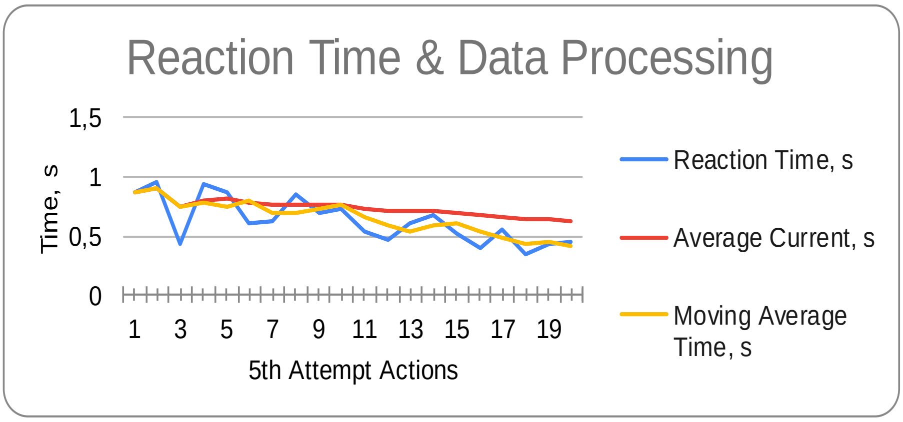


Fig. 6 The training with improving outcomes over time

On the mobile interface, this transition of training to the phase of improving results is marked as “Green Zone” (as in Fig. 7,a).

If it is difficult for the patient to complete the task on time, then the average reaction time AVGi overrun the moving average, and training should be interrupted (“Red Zone” on Fig. 7,b). In this case, it is advisable to increase the interval between flashes of LEDs or to change a number of application points of pinch strength.

At the same time, after successful completion of the test on the DT device "Reflex-Txx" the sound will be accompanied and the message "Test Complete" will be displayed on the LCD screen. The DT device name, main characteristics and statistics of successful attempts during the session will be shown up (Fig. 8).

a.

b.

Fig. 7 The visualization of the successful training (a) and failed training (b) results

3). Data analysis on a specialized microservice

Based on the data obtained from the long-term storage service, it is possible to analyze the work of the complex and some users for a certain period of time, using the obtained metrics (Fig. 9).

For example, from the analysis of Figs. 9, and it can be concluded that the "Reflex – TH3" DT devices are used more efficiently than the "Reflex – TT3" devices. The TH3 DTs have trained 443 users (Visits) more than the TT3, and they have opened on the TH3 for 681 sessions (Sessions) more than the TT3. That is, patients showed a greater interest in devices in which the work area based on Hall sensors than in devices with touch buttons.

In addition, the number of attempts for TH3 during the analyzed period is reduced compared to the allowed maximum of 1622 attempts (Attempts), i.e., training to obtain the desired result was faster. It should be noted that patients of TH3 DTs exhibited greater DT devices interest, as there are new users (Unique Users) 522 fewer than TT3 patients. That is, patients did not leave the training site until testing was completed with a positive result. Thus, it can be noted that the workloads and training regimes at NTC are selected correctly. Also, from Fig. 9,a, it is possible to estimate the monthly number of users on the TH3 and TT3 DTs separately.

From Figs. 9,b shows that the performance of patient PVH-13-408 from December 16 to December 22 was 18% higher than that of patient HMD-04-408. During the specified training period, the first user showed a 12% shorter average time to complete the tasks. In addition, its average sliding time was 16% better. That is, over the course of training, his speed of PVH-13-408 reaction to the random inclusion of RGB LEDs and movement coordination has improved

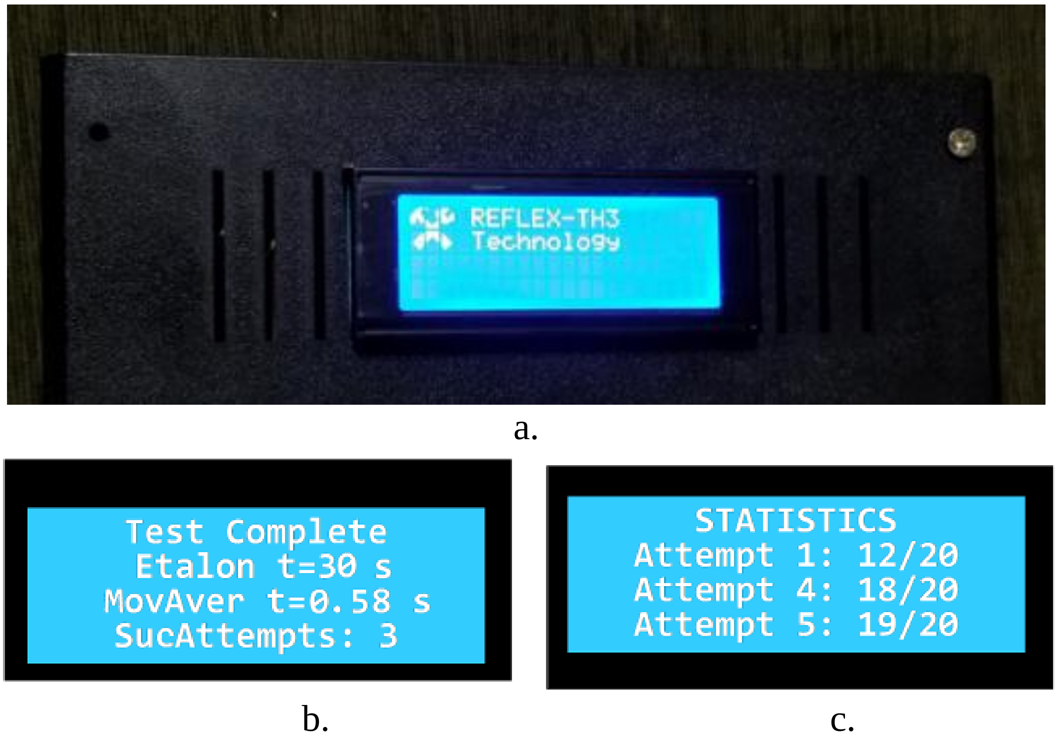


Fig. 8 Device Logo (a) and test results after training: b – move average time; c – test statistics (unsuccessful / successful actions of each attempt)

significantly. From Fig. 9,b it could also be concluded that such positive training results are achieved by greater persistence, since PVH-13-408 has opened for 42 sessions more than the HMD-04-408 during the analyzed time period.

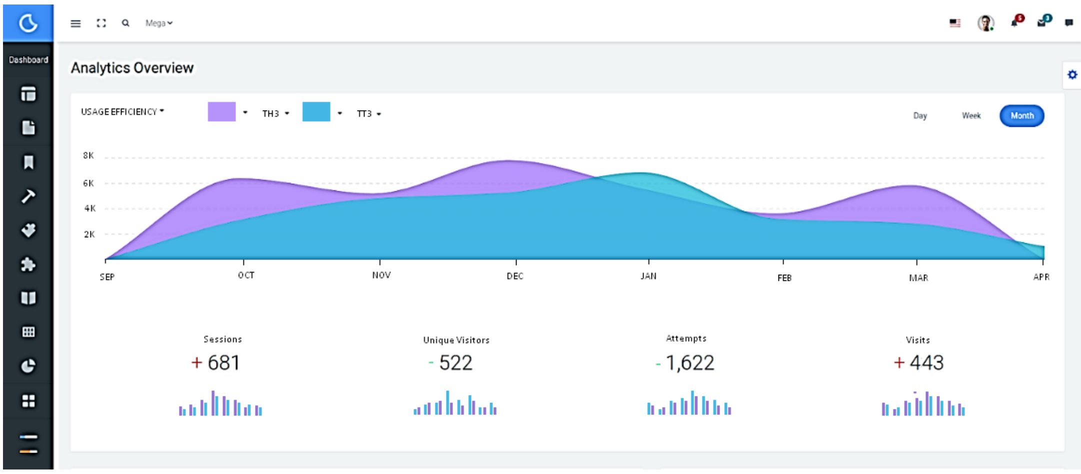
The main argument in favor of using the developed “Reflex-Txx” series is that as a result of increasing the intensity of motor loads with the involvement of gripping movements of the fingers in the patients trained on the DT devices, by 3rd week there was observed a decrease in spasticity of the hand by 2 points according to the MAS of muscle spasticity [3].

V. Conclusion

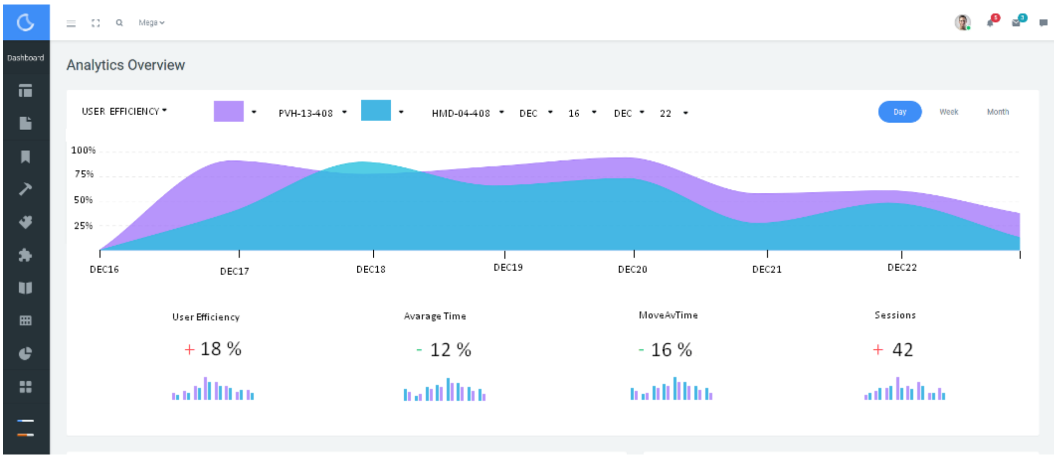
Thus, medical studies and training on the developed “Reflex-Txx” series indicate that passive therapy with robotic devices for rehabilitation of the stroke and spinal trauma requires further analysis and cost-effectiveness compared to standard therapy. It is proven that such treatment is well tolerated without side effects. The use of diagnostic training devices, in addition to conventional physiotherapy, gives positive shifts in treatment after a total of 150 minutes of the entire trial.

In the absence of positive changes in the developed hardware and software complex (HSC), reprogramming of intervals between light flashes, the pauses between attempts to rest the patient according to medical recommendations is provided. The HSC also provides for connection to the IS of personal IoT devices to monitor the general condition of the patient to prevent overloading his.

As your skills grow, muscle strength increases, and patients' response rates increase, you will find that the Arduino platform will no longer cope with the amount of computing you want to get from it. It may be corny to lack performance in calculations, updating information on displays, sending data and other resource-consuming actions, and it may just run out of



a.



b.

Fig. 9 Analysis of the usage efficiency in the HSC of two models of "Reflex-Txx" series devices: a – time load monthly, b – success of training of users

memory. In this case, you can upgrade to a more advanced STM32 platform. However, it should be noted that improving the hardware resources of devices will entail a significant increase in the cost of devices, as well as a significant increase in their power consumption. Therefore, we consider it appropriate to first of all pay attention to optimizing the program code directly for the components of the Arduino platform: analysis of the use of variables of the corresponding types, transition from actions with floating-point numbers to an integer type, replacement of division to multiplication, replacement of the Arduino-function to work with ports, etc.

This approach will save the minimum cost of hard and thus spend on expanding the device fleet. Thereby can be increasing the number of patients who can be assisted with home programs in the course of rehabilitation after cervical spine injuries and damage to the nerves of the hand and fingers.

This study was funded and supported by the Ministry of Education and Science of Ukraine as a part of the science-research work with state registration.

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