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A SYSTEM FOR MONITORING THE PROGRESS OF REHABILITATION OF PATIENTS WITH MUSCULOSKELETAL DISORDER

Abstract. The work is **devoted** to the development of a system for monitoring the rehabilitation process of patients with musculoskeletal disorders, as well as identifying possible postural distortions in both children and adults based on anthropometric data, which confirms the **relevance** and **practical significance** of the work during the period of military operations in Ukraine and a large number of people with musculoskeletal injuries. The paper **proposes** a model of a system consisting of two subsystems: a subsystem for collecting pododynamic parameters based on a dynamic baropodometric platform and a visual posture monitoring subsystem. The combination of different gait and posture analysis methods in a single system provides high diagnostic and prognostic value. The main **purpose** of the proposed system is to monitor the progress of patient rehabilitation using hardware and computer-optical diagnostic methods without radiation exposure with the ability to easily transport the created system, the possibility of high-precision diagnostics in real time, as well as the ability to store and analyze changes in the musculoskeletal system over time. For the collection and analysis of pododynamometric parameters, computer data visualization **methods**, methods of statistical and dynamic data analysis, and data segmentation methods were used. To collect and analyze anthropometric parameters, **methods** of detecting objects in the image, methods of computer classification, segmentation and image processing, methods of analyzing graphic information were used. In addition, the paper **researches** the influence of marker characteristics (shape, color model of representation) and lighting conditions during the acquisition of kinematic parameters on the accuracy of marker detection for further determination of the angles of the pelvis and shoulder line. The **results** obtained by using the hybrid marker detection algorithm show that the representation of any of the used shapes in all the colors under study in the presence of additional lighting gives 100% marker detection accuracy, only in the HSV color model for a simple scene. The RGB model provides 100% accuracy in detecting only yellow markers with additional lighting. In the absence of the possibility of using additional lighting, only round markers in all the studied colors represented in the HSV color model can achieve 100% accuracy. For a complex scene, representing the input images in the RGB color model does not allow achieving 100% accuracy for any of the marker shapes and colors, even with additional lighting. The highest accuracy for a complex scene is also shown by round markers colored in green or orange, regardless of the presence of additional lighting. **Further research** will focus on expanding the range of system parameters necessary for diagnosing the patient's condition and analyzing the course of treatment using electromyographic indicators.

Keywords: system, model; method; monitoring; rehabilitation; image; spine; analysis; anthropometry; baropodometry; curvature.

Introduction

The investigations in the development of systems to support the rehabilitation of patients with musculoskeletal disorders are relevant in the present time. In the context of the war in Ukraine, this topic is extremely important for both the military and the civilian population. According to the Ministry of Health of Ukraine, from February 2022 to November 2023, more than 50,000 people lost one or more limbs as a result of the war. Restoration of body parts that have been lost or damaged due to injury, disease, or congenital pathologies is possible through the process of prosthetics. The state of the art in lower limb prosthetics makes it possible to create the most functional and comfortable prostheses. As of August 2023, there were more than 80 prosthesis manufacturers in different parts of Ukraine that produce auxiliary (technical) means of rehabilitation, including functional and cosmetic prostheses of the upper and lower extremities.

The purpose of prosthetics is to compensate for the missing or treat the impaired function of the support and movement organs with the help of special mechanical devices – prostheses. However, the consequences of limb prosthetics should also be noted, including the following:

– improving the user's mobility and independence;

– reduction of pain and discomfort after amputation;

– improved psychological state due to increased activity;

– phantom pains;

– posture disorders.

The latter two consequences are negative, as they are a manifestation of the continued psychological and physical feeling of losing a limb. Patient recovery needs consistent training, physiological procedures, and monitoring of the patient's gait by an orthopedist to perform various activities, as the shape and size of the remaining limb will change and prostheses will fail [1–3]. Therefore, rehabilitation systems are required for these patients.

However, it is not only lower limb prosthetics that can lead to postural disorders (Fig. 1).

Depending on the type of posture disorders, the following consequences might develop [4, 5]:

– tension and pain in the neck, upper back, lower back, and shoulders;

– the risk of circulatory disorders in certain parts of the body, as the musculoskeletal system is unevenly involved in the loads;

– impaired lung function, as the constant forward bending leads to a decrease in lung capacity and inhalation depth. It also puts pressure on the heart;

– compression of the abdominal organs, which can negatively affect the functioning of the gastrointestinal tract;

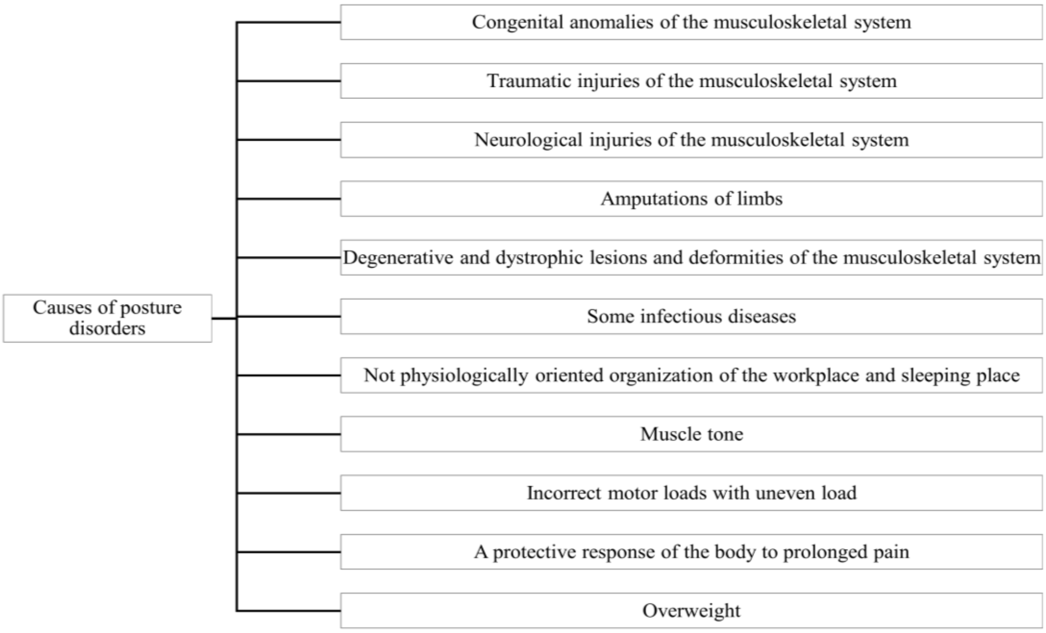


Fig. 1. Causes of posture disorders

– nerve endings may be pinched and neuralgia may develop;

– structural diseases of the musculoskeletal system.

Understanding the possible consequences of posture disorders, great attention should be paid to rehabilitation aimed at correcting posture, as well as to methods for monitoring the progress of rehabilitation and improving the patient's condition.

Rehabilitation efficiency can be increased by the use of support systems developed according to the tendencies of Medicine 4.0 or precision medicine [6]. The principal goal of Medicine 4.0 is the personalization of a patient treatment based on different types of data, including genomic. The use of different data types causes the exploitation of Artificial Intelligence (AI) methods and approaches [7, 8]. AI-based methods, including, machine learning methods, can analyze medical images, patient data, and other clinical sources to help doctors make quick and accurate diagnoses [9, 10]. They can also predict disease risks and the effectiveness of treatment [11]. Conception of Medicine 4.0 includes other directions from IT too (Table 1).

Table 1 – Areas of medical automation and AI application in diagnostics

The direction of automation	Example of application
Robotics	– robotic surgical systems [12]; – AI-enabled exoskeletons [13, 14]; – robot assistants.
Artificial intelligence methods	– analysis of medical images (X-rays, MRI, CT, etc.) [15, 16]; – decision support and providing recommendations based on patient data analysis [17]; – personalized medicine to create personalized treatment plans [6].
Telemedicine	– virtual visits to doctors online for people who live in remote areas or have limited mobility; – remote monitoring of patients' health status.

In this study, the development of a system to support patient rehabilitation is proposed. This system allows monitoring of the rehabilitation process of patients with musculoskeletal disorders, as well as identifying possible postural distortions in both children and adults based on anthropometric data. And needs to be noted, that the system has a higher demand for the period of military operations in Ukraine which have been going on for three years and have led to an increase in the number of patients with combat injuries, explosion injuries, burn marks, injuries due to building collapses, etc.

Research task rationale

The spine is called the "supporting structure" of the human body. It holds the entire skeleton, it's responsible for motor functions, and protects the spinal cord. Unfortunately, more than 80% of the world's working population suffers from some degree of spinal disease. Among the most common diseases are osteochondrosis, scoliosis, sciatica, and herniated disc. Other reasons that create an additional unbalanced load on the spine, shoulders, shoulder blades and pelvis are shown in Fig.1. Spinal diseases develop gradually and manifest themselves as sharp pains when the disease has already been progressing for a while, so it is very important to monitor the condition of the spine.

Among modern methods of diagnosing the spine, the position of the shoulders, shoulder blades and pelvis, we can distinguish: neurological examination, X-ray examination, computed tomography (CT) scan, magnetic resonance imaging (MRI), anthropometry (Fig.2) [18, 19]. The most common and objective method of monitoring the spine in orthopedic practice, in particular in corset therapy, is X-ray examination. However, taking into consideration the impact of radiation exposure on humans, the use of X-rays should be limited, especially when multiple controls are required to determine the effectiveness of treatment and assess the dynamics of changes in the spine and the position of the shoulders, shoulder blades and pelvis. Therefore, in such cases, it is important to use non-invasive, harmless methods of spinal examination, including an anthropometer.

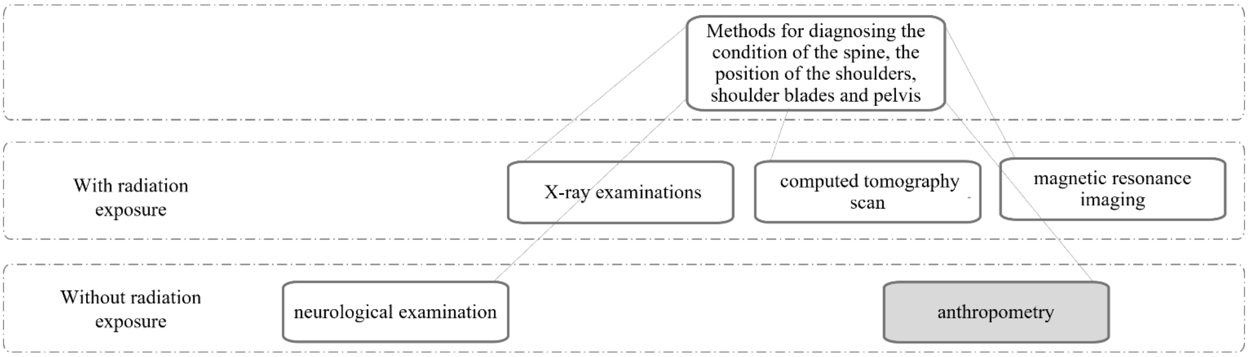


Fig. 2. Overview of methods for examining the position of the shoulders, shoulder blades and pelvis and the position of the spine in the frontal plane

To assess the nature of pathological spinal curvature and postural disorders, anthropometric studies are used, which measure the spatial coordinates of control points on the human body in the sagittal and frontal planes [20, 21]. The readings are taken from the bone protrusions of the skeleton, which serve as reference points (Fig.3). In the case of an unchanged anatomical structure of the spine, bone protrusions can be easily palpated or determined visually. Knowing the topography of the vertebrae and, respectively, finding out their place on the torso, the patient is examined with an anthropometer.

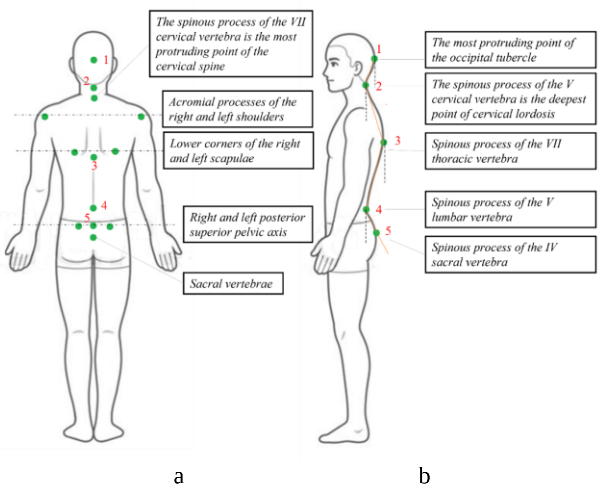


Fig 3. Schematic location of reference points on the torso:
a – during the examination in the frontal plane;
b – during the examination in the sagittal plane

To determine the sagittal curvature of the spine, the defined points are sequentially connected by imaginary straight lines and the angles that are formed between the lines and the vertical that are drew from each point are measured (Fig.3b). The results of measuring the value of each angle in the sagittal plane of the patient are automatically compared with the norm for his or her age.

Lateral curvature of the spine in the frontal plane is a deviation of the spine from a straight line, and can have different localization of the apex of the angle of primary curvature (cervical-thoracic, thoracic, lumbar-thoracic, lumbar and combined), which affects the condition of the chest and pelvic bones. Curvature of the spine in the frontal plane leads to a violation of the correct positioning of internal organs and, respectively, to malfunctions in their work. The manifestation may be that the shoulder blades, shoulders and pelvis on the right and left sides are located at different levels. Thoracic scoliosis is recognized by a pronounced asymmetry of the spinal column and waist, different levels of shoulders and shoulder blades. When the pelvis is displaced (tilted) from its normal position, the axis of load distribution changes during movement. In the absence of muscle imbalance, the pelvis and shoulders are aligned. The biomechanics of movement is balanced and the distribution of load vectors is also uniform.

Changes in the anatomical structure of the spine can be examined by computer-optical video recording of human movements, a characteristic feature of which is the presence of only an optical communication channel between the recording equipment and the subject [22–26].

Since almost any orthopedic traumatic pathology is a motor pathology, the focus of doctors (orthopedists, traumatologists, prosthetists) exclusively on anatomical categories does not allow for the full restoration of the patient's functional component. The formation of a functional type of clinical thinking is possible on the basis of clinical analysis of human movement. It is possible to automate the process of functional diagnosis of motor pathology, planning of the treatment process, dynamic observation during rehabilitation and its management, assessment of long-term results and long-term prognosis using dynamic baropodometric platforms, which are one of the methods of gait analysis (Fig. 4) [27, 28].

By kinematic parameters we mean a large family of parameters that characterize the spatial movements of the pelvis, axial movements of the lower leg and thigh, trajectories and amplitudes of movement of various body segments, including the torso, upper limbs, and head [29, 30]. Dynamic parameters mean the force of interaction with the support during walking with the subsequent construction of vector diagrams, trajectories of the center of pressure under the foot, etc. It is also possible to measure the load on individual points of the sole of the foot or on its entire area with different discreteness for further analysis of load distribution.

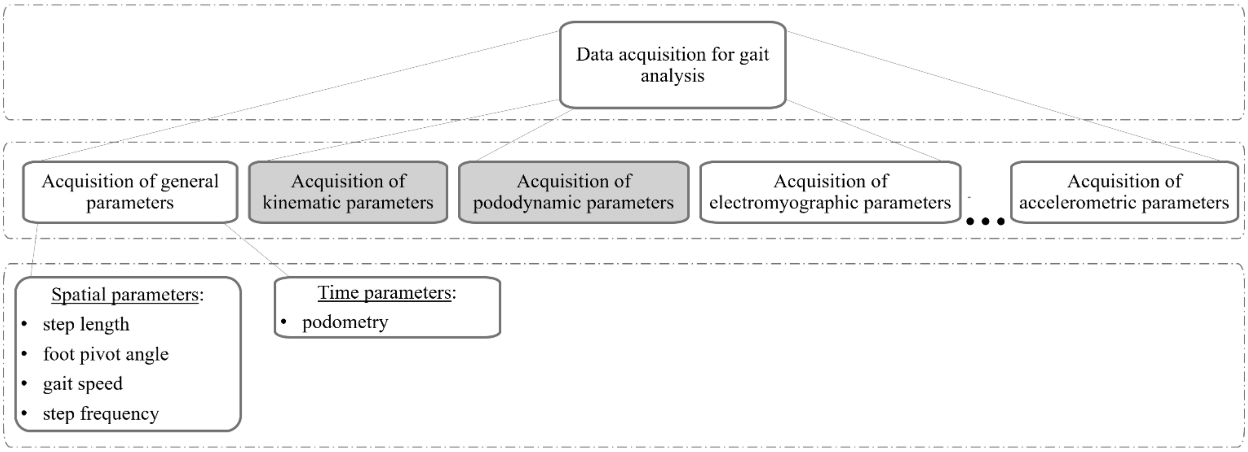


Fig. 4. Gait analysis methods

The analysis of the move is especially useful when solving the following tasks [29–32]:

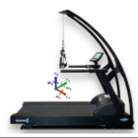
– diagnostic: diagnosis and quantification of asymmetry, balance of the musculoskeletal system, the state of the coordinative and motor abilities, diagnosis of motor pathology and the degree of recovery of damaged organs and tissues;

– dynamic observation: assistance in choosing a treatment method, determining the nature of the dynamics of the disease, determining the effect of medical procedures and manipulations, evaluating the therapy being performed;

– expert tasks: assessment of treatment results, determination of the adequacy of health restoration devices (including prostheses).

The combination of these gait analysis methods (Fig. 4) in a single system will ensure high diagnostic and prognostic value of the examination.

Table 2 – **Overview of dynamic baropodometric platforms on the market**

Platform	Device description	Platform	Device description
Zebris PodoScan II 	Measurement type: pressure distribution, pressure force, gait speed, cadence Additional features: wide range of functions, high accuracy	Gaitway 3D with/without elevation 	Measurement type: pressure distribution, pressure force, gait speed, cadence, balance Additional features: multifunctional, used in many scientific studies
Novel Pedar X 	Measurement type: pressure distribution, pressure force, gait speed, cadence Additional features: easy to use, clear display	BTS Biodex System 3 	Measurement type: pressure distribution, pressure force, gait speed, cadence, balance, coordination Additional features: wide range of functions, used in rehabilitation centers
Footscan Dynamic 	Measurement type: pressure distribution, pressure force, walking speed Additional features: portable, affordable price	Bertec Corporation 	Measurement type: pressure distribution, pressure force, gait speed, cadence Additional features: easy to use, clear display, affordable price

Platform	Device description
AMTI (Advanced Mechanical Technology Inc) 	Measurement type: pressure distribution, pressure force, gait speed, cadence, balance Additional features: multifunctional, used in many rehabilitation centers

Methods for processing and interpreting studies on dynamometric platforms are currently being actively developed in biomechanical laboratories, preparing to enter the diagnostic and treatment market.

The problem formulation

The objective of the work is to develop a system for monitoring the progress of rehabilitation of patients with musculoskeletal disorders using hardware non-radiation and computer-optical diagnostics with the possibility of easy transportation of the created system, the possibility of high-precision diagnostics in real time, as well as the ability to store and analyze changes in the musculoskeletal system over time.

To achieve this objective, the following tasks have to be solved:

– analysis of systems for collecting kinematic parameters of patient;

– analysis of systems for collecting pododynamometric parameters of patient;

– creating a model of the proposed system for monitoring the progress of rehabilitation of patients with musculoskeletal disorders;

– development of a portable barpododynamometric platform;

– researching the effect of marker characteristics and lighting condition during the acquisition of kinematic parameters on the accuracy of marker detection for further determination of pelvis and shoulder lines angles.

Further research will focus on expanding the range of parameters needed to diagnose the patient's condition and analyze the course of treatment using electromyographic indicators.

Results and Discussion

The paper proposes to assess the presence of spinal curvature with subsequent monitoring of the rehabilitation status using hardware non-radiation and computer-optical diagnostic methods, which are combined in the proposed model of a system for monitoring the progress of rehabilitation of patients with musculoskeletal disorders (Fig. 5).

The advantages of the proposed system are that it is absolutely harmless to the body (no radiation exposure), representative and reproducible.

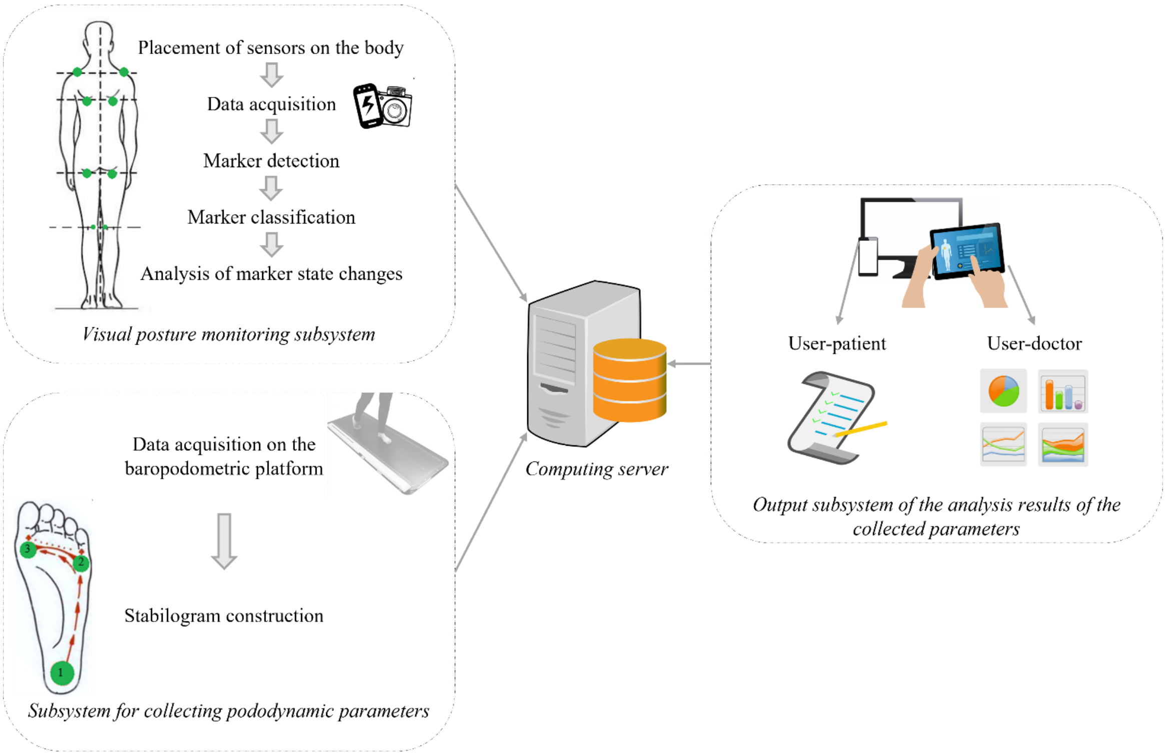


Fig. 5. Model of a system for monitoring the progress of rehabilitation of patients with musculoskeletal disorders

The subsystem for collecting pododynamometric parameters is designed to assess the symmetry of foot pressure and is represented by a platform with force-measuring sensors on which the subject walks. The force applied to each sensor allows calculating the projection of the total center of mass of the body onto the support plane.

The general power supply of the device is provided by the 3V3 Out and GND outputs of the microcontroller. Diodes and resistance are connected to the pressure sensors. Semiconductor diodes 1N5399 are used as protection against reverse current in the circuit, and resistors with a resistance of 10 kOhm are used to limit the current on the pressure sensors to prevent their rapid failure. Changes in sensor resistance are converted by ADS1115 analog-to-digital converters (ADCs). They read the voltage changes on the sensors during pressure changes and convert this information to digital form. The project includes an SSD 1306 display for displaying simple error information, the current IP address of the device, etc. The use of ADCs reduces the number of used microcontroller inputs/outputs to two, which increases the number of sensors or new equipment that could be connected to microcontroller (Fig. 6).

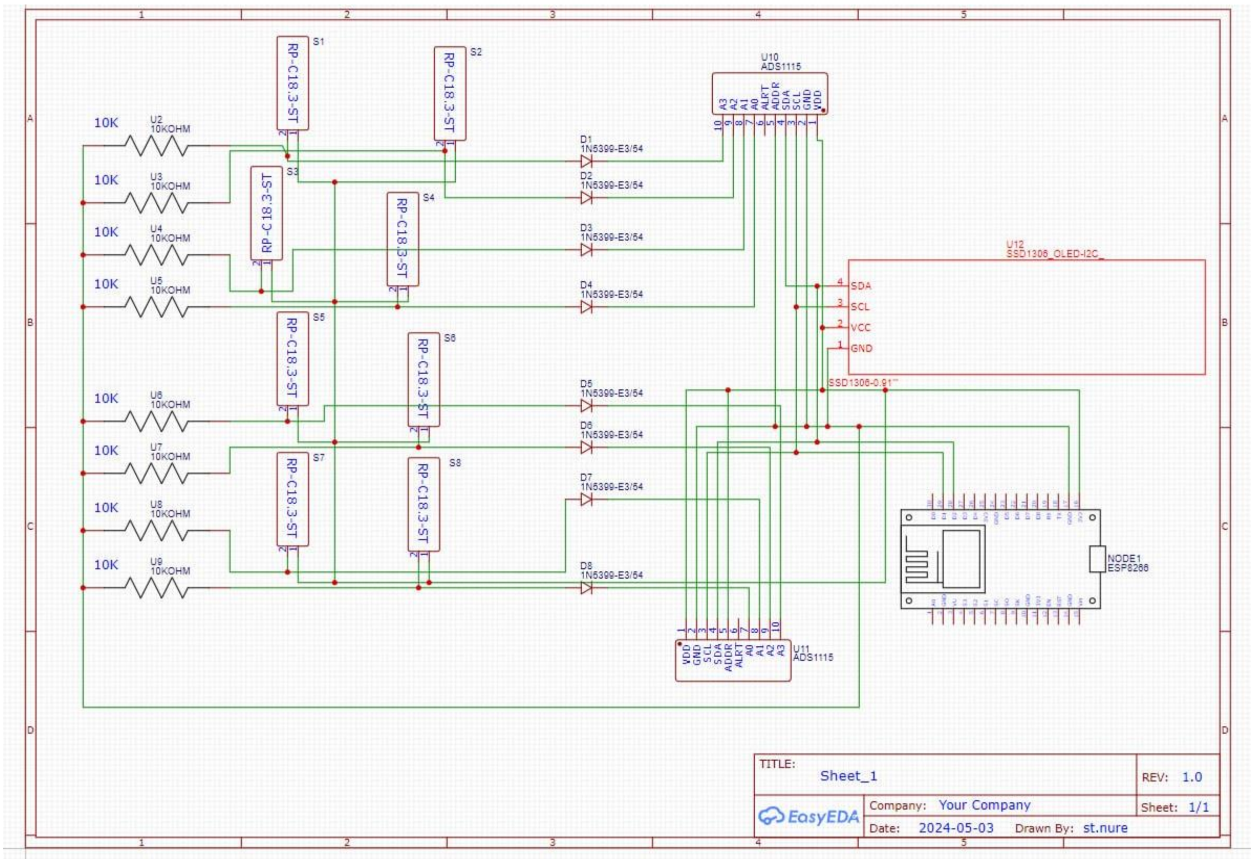


Fig 6. Schematic diagram of the foot pressure symmetry assessment subsystem

The use of the ESP8266 microcontroller allows to quickly transfer data from the sensors via Wi-Fi wireless technology using the built-in interface (Fig. 7). Within the context of the visual posture monitoring subsystem, a number of research studies were conducted into the choice of markers for recording kinematic parameters to improve the accuracy of determining the line angles of the pelvis and shoulder line.

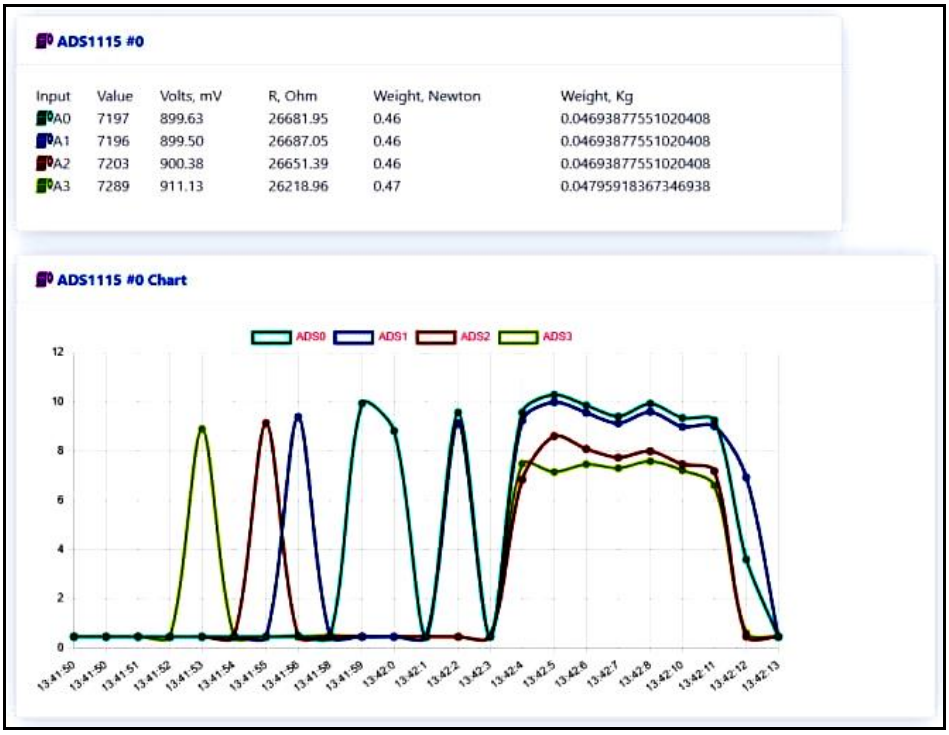


Fig 7. The result of the foot weight/pressure measurement, available to the doctor for analysis

So far, there are a number of major approaches to detecting objects:

– various artificial intelligence methods: machine learning, deep learning, convolutional neural networks, etc [33, 34];

– methods based primarily on the use of computer vision: geometric matching methods, grouping methods, and feature-based methods [35, 36].

However, the detection methods proposed above are well suited for detecting complex objects, but require a large amount of computation, which may be redundant for detecting simple markers that differ in color and shape. Therefore, it’s proposed to consider simpler methods: color-only, shape-only, and hybrid detection.

To create software model, the open source library OpenCV was used, which contains a large number of ready-made solutions for image processing and analysis.

Results of the Study

The paper proposes a hybrid approach to marker detection based on the algorithm shown in Figure 8, which combines color and shape detection. First of all, the algorithm builds on the presence of contours of the found shapes because they have only two states: found or not.

The color contours, in turn, can be partially detected, divided into several contours due to the difficulty of selecting a range of colors.

The hybrid detection algorithm (Fig. 8) is a combination of color and shape detection algorithms. It starts by retrieving all contours with the required shape, but without filtering by size. Next, it retrieves the centers of all the contours with the required color, but without filtering by size. After this preparatory stage, the algorithm performs a step-by-step analysis of the four possible cases:

– case #1: the contour of the required shape is found with the center(s) of the required color contour(s) on its area;

– case #2: no shape contour is found, but a color contour is found that perfectly matches the required shape;

– case #3: a shape contour is found, but there are no color centers on its area;

– case #4: no shape contour is found, but a color contour is found; it is necessary to check for neighbor contours to avoid the situation of interpreting one object as two (or more) different ones.

The algorithm for analyzing case #1 involves comparing each shape contour with all the centers of the color contours. If the center of a color contour is located on the area of a particular shape contour, it is interpreted as the required marker; otherwise, it is interpreted as a possible candidate.

Case #2 involves finding a color contour with a required shape that fits perfectly; to do this, a shape identification algorithm is applied to the contour. If the result is positive, the constraints are checked. The constraints include: minimum area; a reference value of the area that can be obtained if one ideal candidate (the required marker) is found after case #1.

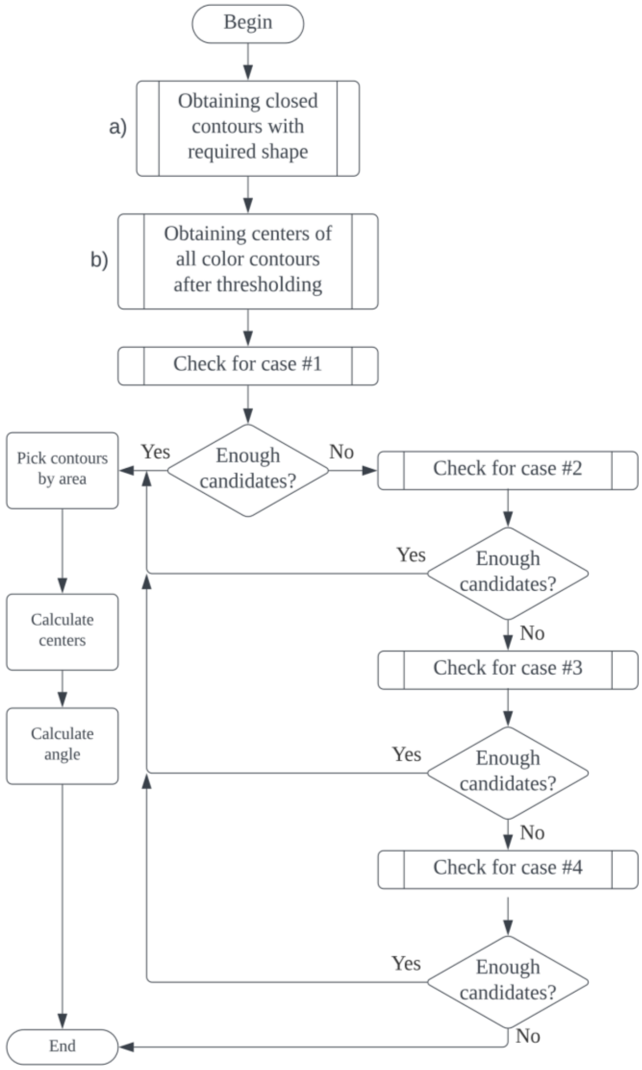


Fig. 8. Hybrid algorithm for marker detection

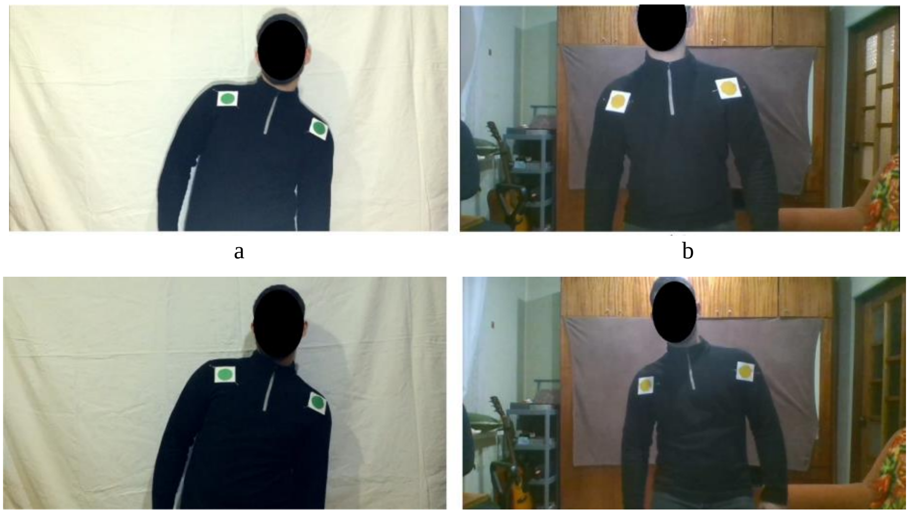
In the case #3, the analysis of the candidate contours obtained after case #1 is performed. An identical constraint check is performed as well.

The analysis of case #4 occurs when there are no shape contours and perfect matching color contours. Its purpose is to find neighbor color contours to avoid false-positive detection. The idea is based on the breadth-first search algorithm.

For the experiment, 64 videos were recorded in HD (1280x720 pixels), 30 frames per second, with two markers attached to a person's shoulders; the person moves, tilts his or her body, approaches and moves away from the camera during the video.

Each video was pre-processed to correct the white balance and cropped so that the two markers on each frame of the video are presented. All videos can be divided into two large groups according to the complexity of the scene: simple and complex. The experiment involves the use of 4 colors of markers: yellow, green, orange, blue; 4 shapes of markers: octagon, square, circle, triangle. Each video also has two variants: with and without additional lighting directed at the person (Fig. 9).

For each color format and color, probably the best color ranges (lower and upper) were selected.



a b c d

Fig. 9. Video groups by complexity: a – simple scene with additional lighting, b – complex scene with additional lighting, c – simple scene without additional lighting, d – complex scene without additional lighting

The criteria for evaluating the results of the research are the accuracy and error of detection, which are calculated using formulas (1) and (2), respectively:

$$a_d = \left(f_d / f_\tau \right) \cdot 100\%; \quad (1)$$

$$e_d = \left(f_{md} / f_\tau \right) \cdot 100\%; \quad (2)$$

where a_d is the detection efficiency or accuracy, f_d is the number of frames that were correctly detected, f_t is the total number of frames in the video, f_{md} is the number of frames that were misdetected, e_d is the detection error. The results are presented in the format shown in Table 3.

Table 3 – **Format of results presentation**

Marker detection accuracy without additional lighting, %.
Marker detection accuracy with additional lighting, %.
Marker detection error without additional lighting, %.
Marker detection error with additional lighting, %.

Analyzing the detection results shown in Table 4, we can conclude that the detection accuracy changes significantly under different lighting conditions (if the RGB color format is used). It can also be seen that the average detection accuracy of octagonal markers is the lowest (80.59% without additional lighting, 82.27% with additional lighting), and the error is the highest (32.56% and 17.17%, respectively), which may be due to the similarity of the shape to a circle, which eliminates the part of the hybrid algorithm's work related to shape detection.

Analyzing the detection results in Table 5, it can be seen that, unlike the RGB color format, the HSV format demonstrates stable detection accuracy under different lighting conditions and higher detection accuracy in general. It can also be seen that the detection error is higher for such shapes as octagon and circle.

Table 4 – **Results of marker detection on a simple scene, RGB**

Color/Shape	Octagon		Rectangle		Circle		Triangle	
Blue	75.93%	50.69%	99.32%	99.41%	90.64%	94.51%	98.37%	99.40%
	59.93%	42.19%	10.38%	1.94%	6.61%	3.21%	9.59%	0.15%
Orange	78.49%	89.49%	80.06%	92.91%	76.42%	85.00%	71.29%	95.85%
	15.97%	26.10%	4.15%	16.56%	6.86%	28.93%	11.90%	12.26%
Green	70.33%	88.90%	83.81%	99.44%	75.35%	71.01%	71.94%	80.27%
	53.66%	0.00%	4.27%	0.14%	6.80%	0.43%	6.98%	2.98%
Yellow	97.59%	100.00%	97.28%	100.00%	100.00%	100.00%	97.34%	100.00%
	0.69%	0.40%	2.02%	0.47%	0.00%	0.15%	5.79%	0.46%

Table 5 – **Results of marker detection on a simple scene, HSV**

Color/Shape	Octagon		Rectangle		Circle		Triangle	
Blue	98.34%	100.00%	100.00%	100.00%	100.00%	100.00%	97.89%	100.00%
	0.28%	1.53%	0.00%	0.00%	1.75%	2.17%	0.17%	0.00%
Orange	100.00%	100.00%	99.86%	100.00%	100.00%	100.00%	100.00%	100.00%
	10.83%	13.72%	0.29%	0.00%	1.89%	1.76%	0.00%	0.29%
Green	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
	1.11%	0.00%	0.00%	0.42%	1.52%	0.31%	1.18%	0.00%
Yellow	100.00%	100.00%	99.85%	100.00%	100.00%	100.00%	100.00%	100.00%
	0.00%	0.13%	0.15%	0.00%	0.00%	0.46%	2.50%	1.23%

This can be explained by the naturalness of this shape (such shapes can appear when light is reflected, etc.) and the fact that the circle is detected using a heuristic algorithm. In most cases, the error of the octagon may be due to its similarity to a circle in some points of time.

The detection results in Table 6 show that detecting markers in a complex scene using the RGB color format is a non-trivial task, since in most cases the detection accuracy decreases significantly in both cases: with and without additional lighting. This can be explained by the problem of the color range selection, when changing the threshold of one of the channels leads to the capture (removal) of an unnecessary (necessary) color or shade into the range. This may raise the question of the fundamental impossibility of selecting a range that can be used to distinguish a single color at different degrees of lighting.

Analyzing the detection results shown in Table 7, we can conclude that the use of the HSV color format is a more effective approach for detecting markers in a complex scene.

However, the detection accuracy is not equal to 100% in all cases, which is primarily due to the large number of objects of different colors and shapes in the background, which obviously affects the result.

Table 6 – **Results of marker detection on a complex scene, RGB**

Color/Shape	Octagon		Rectangle		Circle		Triangle	
Blue	37.46%	68.28%	49.68%	88.38%	64.14%	76.27%	39.74%	87.48%
	44.78%	5.81%	1.27%	1.29%	3.53%	0.93%	12.58%	1.67%
Orange	5.25%	88.28%	14.38%	90.07%	34.35%	54.30%	9.42%	68.93%
	51.43%	1.90%	0.00%	0.00%	4.21%	3.25%	0.00%	3.43%
Green	26.28%	68.14%	63.18%	84.94%	69.82%	79.13%	11.64%	29.61%
	92.31%	5.47%	19.06%	0.41%	4.52%	2.10%	46.67%	13.68%
Yellow	0.56%	78.25%	51.20%	97.61%	11.37%	20.37%	0.00%	43.30%
	100.00%	0.32%	0.00%	0.00%	3.80%	11.89%	0.00%	6.19%

Table 7 – **Results of marker detection on a complex scene, HSV**

Color/Shape	Octagon		Rectangle		Circle		Triangle	
Blue	74.92%	99.50%	99.68%	100.00%	94.02%	100.00%	96.15%	97.60%
	1.96%	0.00%	1.11%	0.00%	2.58%	0.00%	3.73%	0.27%
Orange	67.47%	100.00%	96.77%	100.00%	100.00%	100.00%	95.72%	97.04%
	6.89%	0.00%	0.00%	0.00%	0.32%	0.00%	1.94%	1.37%
Green	96.58%	98.76%	100.00%	98.03%	100.00%	100.00%	71.67%	75.84%
	9.50%	0.00%	0.35%	0.24%	1.65%	0.00%	7.94%	10.68%
Yellow	100.00%	100.00%	95.88%	100.00%	98.56%	100.00%	65.57%	98.85%
	83.62%	4.25%	6.99%	0.00%	8.47%	1.65%	59.58%	12.66%

The paper shows the results for the hybrid marker detection algorithm (Fig. 10) depending on the type of scene (simple or complex scene), the selected color model (RGB and HSV), the shape of the marker (circle, square, triangle, octagon), and the presence of additional lighting.

Analyzing the difference between RGB and HSV formats when using the hybrid detection algorithm, it can be seen that even in a clean scene condition, the average detection accuracy of the RGB format is 87.85% with an error of 10.69%, while the average detection accuracy of the HSV format is 99.87% with an error of 1.37% (+12.02% and -9.32%, respectively).

The results can be explained by the structure of each format: RGB format has 3 channels, each of which is responsible for all color characteristics at once; HSV, in turn, has 3 channels, each of which is responsible for an individual color characteristic, which makes this color representation more resistant to changes in lighting, provided that the range is well chosen.

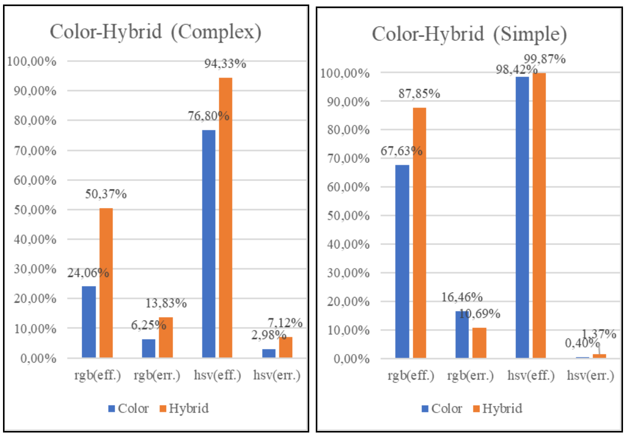


Fig. 10. Comparison of algorithms: by color and hybridThus, the HSV format is better suited for detecting markers by color

Conclusions

The relevance of developing a computer system for monitoring the progress of rehabilitation of patients with musculoskeletal disorders is confirmed by its high practical importance in Ukraine and is due to the growing number of people with musculoskeletal disorders and injuries as a result of military operations in the country; the need to create portable systems with long-term data storage for further analysis of the progress; the advantages of a computer monitoring system to provide a more objective and accurate assessment of rehabilitation progress.

The paper analyzes the systems for collecting kinematic pododynamic parameters of a patient and proposes a model of a system for monitoring the progress of patient rehabilitation using hardware and computer-optical non-radiation diagnostics methods with the possibility of further analysis of anthropometric and pododynamic data, the possibility of easy transportation of the created system, the possibility of high-precision diagnostics in real time, as well as the possibility of storing and analyzing changes in the musculoskeletal system during the time, which is safe both for children and adults. The proposed model of the system consists of two subsystems:

– a subsystem for collecting pododynamic parameters, which is designed to assess the symmetry of foot pressure and is represented by a dynamic baropodometric platform with force-measuring sensors, on which the subject walks. The force applied to each sensor allows calculating the projection of the total center of mass of the body onto the support plane;

– a visual posture monitoring subsystem, which is designed to record the kinematic parameters of the subject for further determination of the angles of the pelvis, shoulder blades and shoulder line at the control points marked with markers. A characteristic feature of computer-optical video recording of human movements is the presence of only an optical communication channel between the recording equipment and the subject.

The combination of different methods of gait and posture analysis in a single system allows for high diagnostic and prognostic value.

As part of the research, the influence of marker characteristics (shape, color model of representation) and lighting conditions during the acquisition of kinematic parameters on the accuracy of marker detection for further determination of the angles of the pelvis and shoulder line was analyzed. The research is of great practical importance, since the accuracy of determining the angle of the pelvis, shoulders, and shoulder blades depends on the accuracy of detecting markers on the subject's body and leads to further research:

– the influence of the choice of the color model of the marker representation on the detection accuracy;

– the influence of the marker shape on the detection accuracy;

– the impact of indoor lighting quality on detection accuracy.

The results obtained by using a hybrid marker detection algorithm, which is a combination of color and shape detection algorithms, show that the detection accuracy significantly depends on the selected color format and lighting conditions. Compared to the RGB format, the use of HSV allows for more stable accuracy regardless of the lighting conditions. It was also found that even under difficult scene conditions, the HSV format shows higher accuracy, which is also achieved due to better resistance to changes in lighting and the ability to decompose colors into separate characteristics. The lowest accuracy is observed for octagonal markers, which may be due to their similarity to a circle, which complicates the process of marker detection at the stage of shape analysis.

These results confirm the advantage of using the HSV format for accurate marker detection by color in different lighting conditions, scene complexity, and confirm the influence of marker shape on the accuracy of its detection.

Further research will focus on expanding the range of system parameters necessary to diagnose the patient's condition and analyze the course of treatment using electromyographic indicators.

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Система моніторингу прогресу реабілітації пацієнтів із порушеннями опорно-рухового апарату

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Анотація. Робота **присвячена** розробці системи контролю процесу реабілітації пацієнтів із вадами опорно-рухового апарату, а також виявленню можливих викривлень постави, як у дітей, так і у дорослих на основі антропометричних даних, що підтверджує **актуальність** та **практичну значущість** роботи у період військових дій на території України та великої кількості людей із травмами опорно-рухового апарату. В роботі **запропонована** модель системи, яка складається з двох підсистем – підсистема збору пододинамометричних параметрів на основі динамічної бароподометричної платформи та підсистема візуального моніторингу постави. Поєднання різних методів аналізу ходи та постави у єдиній системі дозволяє забезпечити високу діагностичну та прогностичну цінність роботи. Основною **метою** запропонованої системи є моніторинг прогресу реабілітації пацієнтів за допомогою методів апаратної та комп'ютерно-оптичної непроменевої діагностики із можливістю легкого транспортування створеної системи, можливістю високоточної діагностики в режимі реального часу, а також можливістю збереження та аналізу змін опорно-рухового апарату протягом часу. Для збору та аналізу пододинамометричних параметрів використані **методи** комп'ютерної візуалізації даних, методи статистичного та динамічного аналізу даних, методи сегментації даних. Для збору та аналізу антропометричних параметрів використані **методи** виявлення об'єктів на зображенні**,** методи комп'ютерної класифікації, сегментації та обробки зображень, методи аналізу графічної інформації. Крім того, у роботі проведено **дослідження** впливу характеристик маркерів (форма, кольорова модель представлення) та освітлення при реєстрації кінематичних параметрів на точність детектування маркерів для подальшого визначення кутів нахилу ліній тазу та плечей. **Результати**, отримані при використанні гібридного алгоритму детектування маркерів, показують, що представлення будь-якої із наведених форм в усіх досліджуваних кольорах при наявності додаткового освітлення дає 100% точність детектування маркерів, лише у кольоровій моделі HSV для простої сцени. Модель RGB забезпечує 100% точності детектування лише жовтих маркерів за умови додаткового освітлення. За відсутності можливості використання додаткового освітлення, досягти точності 100% дозволяють лише круглі маркери в усіх досліджуваних кольорах, поданих в HSV кольоровій моделі. Для складної сцени, представлення вхідних зображень в кольоровій моделі RGB не дозволяє досягти 100% точності для жодної із форма та кольорів маркерів навіть при додатковому освітлення. Найвищу точність для складної сцени також показують маркери круглої форми, пофарбовані у зелений або помаранчевий колір незалежно від наявності додаткового освітлення. **Подальші дослідження** будуть зосереджені на розширенні діапазону параметрів системи, необхідних для діагностування стану пацієнта та аналізу перебігу лікування, завдяки електроміографічним показникам.

Ключові слова: система; модель; метод; моніторинг; реабілітація; зображення; хребет; аналіз; антропометрія; бароподометрія; викривлення.