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OPTICAL SENSORS IN DEVICES AND SYSTEMS FOR FUNCTIONAL MONITORING

Abstract

In the conditions of the long-term russian aggression against Ukraine, the number of people with disabilities among the military and civilians is rapidly increasing. This creates a critical need for innovative, objective methods for monitoring the rehabilitation process. A key indicator of functional mobility is gait, whose parameters allow the diagnosis of the consequences of musculoskeletal injuries, amputations, and neuromuscular diseases. Traditional methods are often subjective or too expensive, prompting the search for new technological solutions that leverage optical sensors.

The purpose of the work is to study and systematize existing scientific developments on the use of optical sensors in monitoring gait parameters of people with disabilities.

Results. It is studied that gait analysis is considered as a comprehensive study of functional mobility, which plays a key role in the assessment of physical rehabilitation, diagnosis of disorders, and decision-making regarding further rehabilitation interventions. Two main categories of optical systems are analyzed: marker-based, which have ultra-high accuracy (error<1*mm*), but are limited to

laboratory conditions; and marker-free, based on computer vision, which allow for analysis in the natural environment. Particular attention is paid to fiber-optic technologies, in particular sensors based on Bragg gratings and Fabry-Perot interferometers. It is proven that fiber-optic sensors are the most promising for wearable monitoring devices, since they provide non-invasiveness, lack of physical contact, resistance to electromagnetic interference, and high biocompatibility, implementing real-time monitoring.

Conclusions. The use of optical sensors in devices and control systems fundamentally changes the approach to monitoring rehabilitation effects, providing permanent and high-precision monitoring without limiting the mobility of people with disabilities. The use of optical sensors in devices and control systems provides permanent control without limiting motor activity and wireless data transmission. Miniaturization of devices makes them portable and convenient for long-term wear. High accuracy of measurements of kinematic and kinetic parameters is critical for diagnosing disorders and making decisions about further rehabilitation. Prospects for further research into the use of new materials, such as liquid crystal light guides in optical sensors, to create even more adaptive control systems.

Keywords: gait analysis, optical sensors, fiber-optic optics, marker optical systems, markerless optical systems, Bragg gratings, Fabry-Perot interferometer.

Problem statement

Due to the long-term russian aggression against Ukraine, the number of people with disabilities among military and civilian personnel is constantly growing. As a result, the need to ensure the effectiveness of rehabilitation services in the country is extremely urgent.

Today, the control of the rehabilitation process is the subject of a wide range of fundamental and applied research in various fields of knowledge. Effective

control of the functional mobility of people with disabilities has been recognized by scientists [1, 4] as fundamental, since injuries that cause disability generally lead to impaired locomotor functions for performing most everyday activities.

In this aspect, the analysis of gait parameters is singled out [13, 14] as one of the promising solutions for ensuring the effectiveness of rehabilitation of people with disabilities with a certain list of functional mobility disorders. Such disorders are a direct consequence of injuries and diseases of the musculoskeletal system, cardiovascular and neuromuscular diseases, lower limb amputations, explosive craniocerebral injuries, as well as evidence of the presence of other pathologies, such as ulcers or diabetes [2, 3]. From the point of view of analyzing gait patterns, changes in their normal parameters can reveal key information about the quality of life of people with disabilities or the development of various diseases.

Analysis of recent research and publications

It is argued [1] that objective assessment, diagnosis and prediction of the rehabilitation process requires simultaneous measurement of a significant list of parameters. It has been proven [7, 10] that the creation of new technical modern control tools is aimed at ensuring objectivity and impartiality, analysis and prediction of rehabilitation process data. The use of sensor technologies in monitoring the rehabilitation process has been widely studied in recent years from various points of scientific knowledge [1-3, 14].

The feasibility of using optical sensors in monitoring devices has been established [4]. Optical sensors are considered [12] to be flexible, lightweight, and immune to electromagnetic interference, and therefore suitable for use in wearable monitoring devices [6].

Many sensors in wearable devices can help record walking and running data; spatiotemporal and kinematic variables can be additionally calculated in gait analysis [13]. The use of wearable devices for motion tracking, gait analysis, and

their potential to improve healthcare practices through intelligent data analysis have been reviewed [1, 4, 13].

In motion analysis systems, purely mechanical measurement has been supplemented by optical [2] in recent years. In the context of gait monitoring, they now allow for the highest accuracy in a non-contact manner [13]. Optoelectronic sensors have a key advantage: the complete absence of physical contact [9].

The possibilities of optical sensors are constantly being studied in the direction of their improvement [7, 8]. In particular, today the measurement methodology is based not only on measuring the physical properties of the environment, but also on the analysis of both organic and inorganic properties [11].

It has been studied [2, 12] that optical sensors can detect defects in gait parameters, their deviations, and inconsistencies in patterns with exceptional accuracy. The high resolution of modern optical sensors allows detecting gait disorders at high speed, while maintaining the accuracy standards necessary for the implementation of mass studies [14]. It is extremely important that improved optical sensors are integrated into machine learning programs [13].

However, the analysis of existing approaches to controlling gait parameters led to the conclusion that there is currently no universal solution for controlling disabilities using optical sensors.

Purpose of the article

is to study and systematize existing scientific developments on the use of optical sensors in monitoring gait parameters of persons with disabilities.

Presentation of the main material of the study

The current level of scientific research, which provides an assessment of gait as the basis of human movement, involves a shift in emphasis from a generalized approach to a targeted, individualized, and data-based strategy of rehabilitation interventions, ensuring the effectiveness of such activities. Studying

the spectrum of use of optical sensors in devices and control systems, we aim to clarify the state of their application, purpose, and capabilities that determine the feasibility of this process and its clinical significance. For persons with disabilities, optoelectronic sensors have a key advantage: the complete absence of physical contact.

In recent years, many instrumental systems have been developed to monitor gait parameters of persons with disabilities. In fact, it is the integration of all possible potentials of electronic devices, sensors, and wireless devices, which creates a complex, but at the same time powerful opportunity for the formation of control devices.

In my opinion, gait analysis should be considered as a comprehensive study of functional mobility, which, as noted earlier, plays an important role in the assessment of physical rehabilitation, diagnosis of disorders, and decision-making regarding further rehabilitation interventions. Usually, gait analysis of patients is carried out using video technologies or other expensive platforms based on force-resistive sensors [14].

It is extremely important that optical systems allow for permanent control that does not limit the motor activity of people with disabilities [13]. Optical sensors in devices and systems for controlling gait parameters are divided into two large categories depending on their placement.

Optical motion capture systems, such as Optical Motion Capture, MoCap, Vicon, and OptiTrack. Such systems are based on the use of specialized infrared or video cameras to track light-reflecting passive or light-emitting active markers placed on the human body. These systems record and track reflective markers in real time, reaching frequencies up to 2000 *Hz* Infrared cameras fix the position of the markers in space and record a digital signal of their movements [1, 10].

The principle of operation of such systems involves placing optical sensors around the perimeter of the observation site so as to ensure coverage of the control

object. The sensors are connected without a wire connection to a microcontroller, which controls the sensors and connects in real time to the interface (Fig. 1).

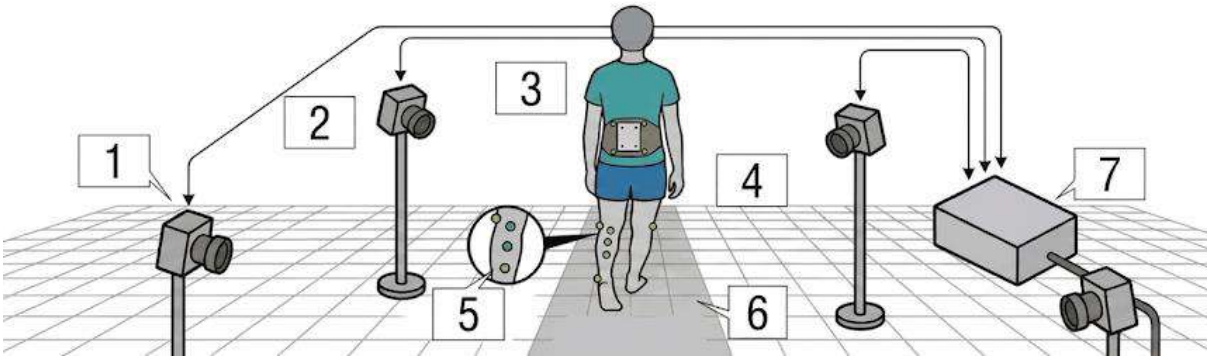


Fig. 1. Scheme optical motion capture systems: 1 – optical sensors; 2 – wire connection; 3 – human; 4 – observation; 5 – active markers; 6 – track 7 – microcontroller

Among the main advantages of such systems is a high level of accuracy: an error of<1 *mm*, which meets the needs of most high-speed motion measurements [10]. In addition, the unlimited range of movements, the absence of cables and mechanical devices make these systems convenient to use.

At the same time, the high cost of optical motion capture systems, the complexity of setup, the influence of soft tissue motion artifacts, and the sensitivity to lighting and reflections of optical sensors complicate their widespread use. Calibration of such systems is also very difficult. And the measurement errors of internal-external rotation of joints during walking can reach 21.8 [4].

Therefore, despite their accuracy, their use is mainly limited to laboratory conditions. This limitation is associated with spatial requirements, the need for precise camera positioning, and the complexity of device calibration [6].

The second group is optical systems without markers (Markerless)

A modern trend based on computer vision and deep learning algorithms. A markerless system does not require the use of reflective markers on the study objects, reducing preparation time and potential discomfort.

Compared to marker-based systems, marker-free technology offers: the use of standard video cameras to determine key points of the skeleton, RGB-D cameras: Cameras that measure the distance to the object (e.g., Microsoft Kinect, Intel RealSense).

The main advantage of such systems is the ability to conduct gait analysis in natural conditions, and the absence of discomfort for control subjects. They provide a re-analysis of control data using updated pose estimation algorithms. Marker-free systems make it possible to collect data, however, as research has shown, the true accuracy of marker-free systems is unknown [4].

In the following, we will detail our scientific search. In control systems and devices, optical sensors are used for:

– an automated method of segmenting body movements during walking;

– a flexible optical fiber goniometer, primarily for monitoring human joint movements;

– a wearable device that integrates sensors based on polymer optical fiber into a knee pad to track knee flexion/extension cycles during walking;

– measurement of joint motion parameters, which allows determining both the bending angle and its orientation using fiber-optic sensors [5, 12].

Special attention will be paid to the use of fiber-optic sensors with Fiber Bragg gratings. In particular, in [2] the development and implementation of a non-invasive architecture of a wearable device for complete gait analysis, provided by optical fiber-optic sensors with Fiber Bragg gratings, is presented.

The developed sensor network provides simultaneous control of gait parameters. Among these are foot pressure, full control of movement in the ankle

and knee joints. At the same time, a high level of accuracy is ensured, without the need for any synchronization with fiber-optic sensors with Fiber Bragg gratings.

Fiber Bragg gratings are sensitive elements of the sensor, the principle of which is to monitor the shift of the wavelength (λ) Bragg, reflected by the grating, as a function of the controlled parameter.

Another type of fiber-optic sensors used in devices and control systems is sensors based on Fabry-Perot interferometers. It has been studied [8] that they have a high level of efficiency and accuracy, are easy to manufacture and inexpensive. Their use in control devices includes kinematic analysis: joint angles, angular velocities and accelerations, and kinetic analysis during gait cycles ((Fig. 2).

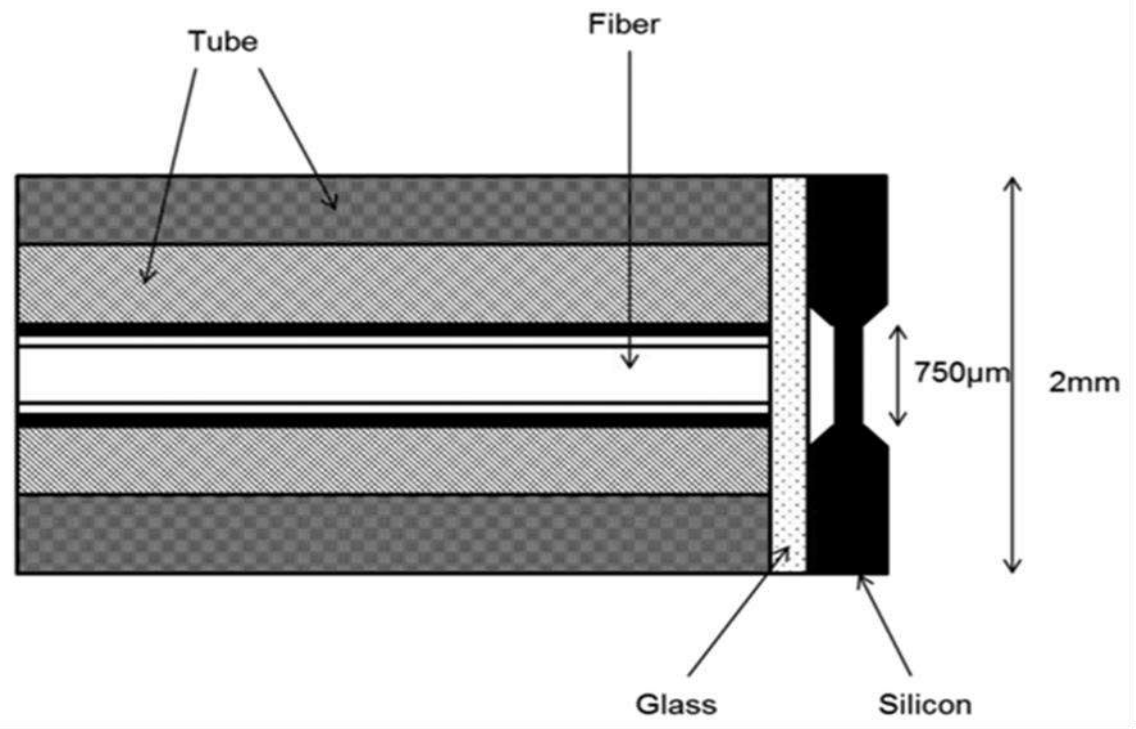


Fig 2. Schematic of a sensor structure. The light is sent and received through the 100 µm core fiber. The cavity length is about 7 µm and the thickness of the membrane is 8 µm [8].

Today, the possibilities of optical signal processing and network technologies will allow creating high-density fiber-optic sensor networks. The production of Fabry-Perot interferometer sensors consists of processing an optical fiber, previously

damaged by the welding effect, to form an embedded microcavity FPI. There are opinions [5, 7, 8] that FPI sensors have significant potential in the design of a wide range of control devices.

Another use of optical sensors is the possibility of control using optical fibers with controlled birefringence, formed as a result of the introduction of liquid crystal material into the internal cavity of fiber optic fibers [8]. However, in the current developments of gait control devices, this is not considered.

In general, non-invasive measurement methods using optical fibers have significant advantages over electrogoniometers and control systems. Among the key advantages: resistance to electromagnetic interference, miniature size and flexibility of the design [5].

Analysis of scientific data [5, 7, 8] allows us to highlight the advantages of fiber-optic sensors compared to electronic counterparts. First of all, the use of dielectric materials in their design ensures insensitivity to electric and magnetic fields. In addition, they are resistant to most chemical reagents and ionizing radiation. Fiber-optic sensors can be adapted to measure various physical quantities, and they are relatively inexpensive to manufacture.

The list of advantages of optical sensors also includes:

– miniaturization: allows them to be integrated into compact devices without loss of efficiency, ensuring user convenience;

– high density of data transmission over long distances without distortion;

– insensitivity to electromagnetic and radiation fields;

– manufacturability: the possibility of using integrated technologies in manufacturing.

Additional advantages of optical sensors are their portability, low cost and ease of integration into microsystems, on the order of micrometers, structures. Important characteristics are also biocompatibility and the possibility of multiplexing into a single network [2].

Conclusions

Based on the results of studying existing developments in the use of optical sensors in the analysis of gait parameters of people with disabilities, the following key provisions can be formulated.

The use of optical sensors in electronic devices fundamentally changes the approach to monitoring the gait parameters of people with disabilities. The transition from periodic procedures to continuous, intelligent and personalized support allows to significantly increase the objectivity and impartiality of diagnostics and to minimize the influence of the human factor.

Modern gait assessment is moving from general methods to individualized strategies based on accurate data. This allows to create targeted rehabilitation plans, where objective control of the studied parameters plays a key role.

It has been studied that optical systems for monitoring gait parameters are divided into two main categories: marker and markerless. Marker systems are determined with ultra-high accuracy (error<1 *mm*), but are limited to laboratory conditions due to high cost, complexity of calibration and sensitivity to light. The main advantage of markerless systems is the possibility of analysis in natural conditions without discomfort for the control subject, although the question of their absolute accuracy remains open

The following are highlighted in the list of technological advantages of fiber-optic sensors. The use of fiber optics, in particular sensors based on Bragg gratings and Fabry-Perot interferometers, in control systems is one of the most

promising areas due to the complete absence of physical contact, insensitivity to electromagnetic and radiation fields, which allows them to be used in complex environments. In addition, they can be embedded in clothing, knee pads, shoes for simultaneous control of foot pressure and joint flexion angles.

In general, the use of optical sensors in control devices and systems provides: permanent control without limiting motor activity and wireless data transmission. Miniaturization of devices makes them portable and convenient for long-term wear. High accuracy of measurements of kinematic and kinetic parameters, which is critical for diagnosing disorders and making decisions about further rehabilitation.

Prospects for further research include studying the use of new materials, such as liquid crystal light guides in optical sensors to create even more effective systems for monitoring rehabilitation effects.

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