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EVALUATION OF BIOLOGICAL STABILITY OF PATIENT MOTION COORDINATES IN MULTIPLE SCLEROSIS AND PARKINSON'S DISEASE

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Early detection of neuropathologies is critically important for preserving a patient's quality of life and improving the effectiveness of medical care. Many neurological disorders, including Multiple Sclerosis and Parkinson's Disease, develop gradually and often begin with subtle or nonspecific symptoms. At these early stages, clinical manifestations may be barely noticeable, yet this is precisely the period when medical intervention can be most effective.

Timely diagnosis enables the initiation of treatment before irreversible changes occur in the central nervous system. This helps slow disease progression, reduce symptom severity, and delay disability. Moreover, early detection supports the development of personalized treatment strategies, including appropriate pharmacological therapy and rehabilitation programs, while also allowing continuous monitoring of their effectiveness over time.

The work examines approaches to assessing the biological stability of movement coordinates in patients with multiple sclerosis and Parkinson's disease as an important indicator of the functional state of the central nervous system. The relevance of quantitative methods for analyzing motor activity is substantiated for early diagnosis, monitoring disease progression, and evaluating treatment effectiveness. A methodology for analyzing time series of movement coordinates is proposed, incorporating statistical, spectral, and nonlinear indicators that enable detection of subtle changes in motor dynamics.

Special attention is paid to determining parameters of stability, variability, and regularity of movement, which reflect the level of neuromotor control.

The results confirm the feasibility of using the proposed approach as an objective tool for assessing biological stability of movement in a patient with neuropathologies. The method can be integrated into telemedicine systems and rehabilitation platforms for personalized patient management. Future research prospects include expanding the sample size, improving analytical algorithms, and applying machine learning techniques to enhance diagnostic accuracy.

Keywords: *multiple sclerosis, Parkinson's disease, motion coordinates, biological stability, patients, mathematical modeling, evaluation of disease progression, neuromotor control.*

Introduction

Motor function disorders associated with neurodegenerative and demyelinating diseases of the central nervous system represent a complex multifactorial process accompanied by changes in the biomechanical characteristics of movement, impairment of spatiotemporal coordination, and reduction in postural stability. Among the most common pathologies characterized by such alterations are multiple sclerosis and Parkinson's disease [1, 2]. Despite the different pathogenesis of these diseases, their clinical manifestations are often associated with impaired motor control, which is reflected in changes in movement coordinate parameters, increased trajectory variability, loss of rhythmicity, and reduced stability of the dynamic characteristics of the motor system.

Multiple sclerosis is a chronic autoimmune demyelinating disease of the central nervous system, in which damage to nerve fibers disrupts the conduction of impulses between different functional structures of the brain and spinal cord.

This leads to the development of movement discoordination, ataxia, gait instability, and impaired sensorimotor control [3]. Parkinson's disease [4], in turn, belongs to progressive neurodegenerative disorders characterized by impaired extrapyramidal regulation of movement, manifested by tremor, bradykinesia, rigidity, and postural instability [5]. In both cases, changes in the functional state of the motor system can be quantitatively described through the analysis of movement coordinates, their temporal evolution, and statistical characteristics.

Review of existing approaches

Modern methods for clinical assessment of motor impairments are mainly based on standardized rating scales, which allow determining the severity of neurological deficits; however, they have limited resolution for detecting early or subtle functional changes [4, 5, 6]. In this regard, the application of

instrumental assessment methods based on movement coordinate registration using stabilometric platforms, inertial sensors, accelerometric systems, video tracking, and optical sensors [7, 8] is becoming increasingly relevant. The obtained coordinate time series can be considered biomedical signals containing information about the dynamics of sensorimotor system functioning and the level of its biological stability.

Biological stability of movement coordinates can be defined as the ability of the motor system to maintain relatively stable spatiotemporal trajectory characteristics under conditions of physiological fluctuations and external perturbations [9].

From the perspective of dynamical systems theory, such stability can be assessed through the analysis of coordinate variance, spectral signal characteristics, correlation properties, entropy-based indices, phase trajectories, and nonlinear dynamic parameters [10]. Stability impairment manifests itself as an increase in oscillation amplitude, the appearance of additional frequency components, changes in the autocorrelation structure of the signal, and an increased level of stochasticity in the coordinate process.

Of particular interest is the analysis of movement coordinates as time series, which makes it possible to apply digital signal processing methods for extracting informative features of pathological processes. In particular, spectral analysis enables the assessment of energy redistribution among frequency components of the movement signal, which is characteristic of tremor in Parkinson's disease or ataxic oscillations in multiple sclerosis. The use of statistical stability criteria, correlation analysis, evaluation of fractal properties, and entropy-based characteristics makes it possible to identify hidden patterns in the structure of the movement process that are not always detectable during conventional clinical examination [11].

From a technical perspective, the problem of assessing the biological stability of movement coordinates is a task of analyzing multidimensional non-stationary signals whose parameters change due to disturbances in neuromotor control mechanisms. Solving this problem requires the development of an adequate mathematical model of the coordinate process, identification of informative stability criteria, and design of algorithms for experimental data processing. The application of such approaches creates prerequisites for the automation of diagnostic procedures, improvement of pathological change detection accuracy, and development of decision-support systems in neurological practice.

Thus, the assessment of biological stability of movement coordinates in patients with multiple sclerosis and Parkinson's disease is actual scientific and technical problem that combines methods of biomechanics, digital processing of biomedical signals, mathematical modeling, and intelligent data analysis. The development of quantitative criteria for evaluating the stability of coordinate parameters makes it possible to improve the objectivity of diagnostics, provide monitoring of disease progression, and create the basis for individualized rehabilitation technologies.

The purpose of this research is to develop and investigate methods for assessing the biological stability of movement coordinates in patients with multiple sclerosis and Parkinson's disease based on the determination and analysis of coordinates informative parameters characterizing the degree of sensorimotor control impairment.

Based on the foundations of the TONTOR theory, this study proposes an analysis of the correspondence of the imaginary and real informative parameters of the spaces of the technological phantom and the real space of objects, which provides the actual state of the object being controlled.

Materials and research methods

The main task of determining the stability of the coordinates of an object with possible movement disorders due to diseases of the nervous system is to control the ability to maintain a constant coordinate under the action of appropriate force loads. n order to have such an opportunity, the object must be able to solve a number of complex motion problems.

Let us consider the case of linear motion, when an object sets itself the task of moving from one point to another along known coordinates. In this case, the trajectory of motion is described by a conventional linear equation in the form

$$y = kx + b\,. \tag{1}$$

In this equation, for its fulfillment, the quantities and must be absolutely stable, otherwise the problem loses its meaning.

The problem of transformation from an imaginary function to an effective force can be solved using affine transformations

$$\begin{aligned} x &= A_2' x' + B_2' y' + C_2' \\ y &= A_1' x' + B_1' y' + C_1' \end{aligned}. \tag{2}$$

Substitution (7.1) into equation (7.2) where there is a relationship between the coefficients

$$\left.\begin{aligned} x' &= A_1 x + B_1 y \\ y' &= C_1 x + D_1 y \\ x &= A_2' x' + B_2' y' \\ y &= C_2' x' + D_2' y' \end{aligned}\right\} \tag{3}$$

gives us the equation of the segment , i.e.

$$\left(A_1' - aA_2'\right)x' + \left(B_1' - aB_2'\right)y' + \left(C_1' - aC_2'\right) = b\,. \tag{4}$$

Let us make the transition from imaginary to real coordinates.

To do this, we rewrite (2) in the form of a transition from imaginary to real coordinates

$$\begin{aligned} x_R &= Ax_u + By_u + C \\ y_R &= Dx_u + Ey_u + F \end{aligned}. \quad (5)$$

where x_R, y_R - coordinates of the real system, x_u, y_u - coordinates of the imaginary system, *A, B, C, D, E, F* - coefficients of linear transformation.

The unknown transformation coefficients can be found through a system of three points.

Further, we transform the equation equation (5) into matrices for n points, i.e.

$$\begin{bmatrix} x_1, x_2, x_3 ... x_n \\ y_1, y_2, y_3 ... y_n \end{bmatrix}_R = \\ = \begin{bmatrix} A & B & C \\ D & E & F \end{bmatrix} \times \begin{bmatrix} x_1, x_2, x_3 ... x_n \\ y_1, y_2, y_3 ... y_n \\ I, I, I ... I \end{bmatrix}_U \quad (6)$$

or

$$\mathbf{M}_R = k \times \mathbf{M}_u,$$

where $\mathbf{M}_u$ is the imaginary coordinate matrix supplemented by a unit row vector.

System (6) is solved using the least squares method and multiplication of the left and right sides by the transformation matrix. We have a model of affine transformations in the following form

$$\begin{bmatrix} x_R \\ y_R \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \cdot \begin{bmatrix} \eta_x & 0 \\ 0 & \eta_y \end{bmatrix} \times \\ \times \begin{bmatrix} 1 & -\sin\theta \\ 0 & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} x_U \\ y_U \end{bmatrix} + \begin{bmatrix} \lambda_x \\ \lambda_y \end{bmatrix} = \\ = \begin{bmatrix} \eta_x \cos\alpha & -\eta_y \sin(\alpha+\theta) \\ \eta_x \sin\alpha & -\eta_y \cos(\alpha+\theta) \end{bmatrix} \cdot \begin{bmatrix} x_U \\ y_U \end{bmatrix} + \\ + \begin{bmatrix} \lambda_x \\ \lambda_y \end{bmatrix} = \begin{bmatrix} A & B \\ D & E \end{bmatrix} \cdot \begin{bmatrix} x_U \\ y_U \end{bmatrix} + \begin{bmatrix} C \\ F \end{bmatrix} \quad (7.7)$$

Then

$$\mathbf{M}_R = \Omega \cdot \mathbf{H} \cdot \Psi \mathbf{M}_U + \Lambda = \mathbf{M}_T \cdot \mathbf{M}_U + \Lambda, \quad (8)$$

$\Omega = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}$ - rotation matrix around the center of coordinates,

$\mathbf{H} = \begin{bmatrix} \eta_x & 0 \\ 0 & \eta_y \end{bmatrix}$ - coordinate scale matrix,

$\Lambda = \begin{bmatrix} C \\ F \end{bmatrix}$ - displacement vector,

$\Psi = \begin{bmatrix} 1 & -\sin\theta \\ 0 & \cos\theta \end{bmatrix}$ - orthogonality deviation matrix.

In this case, the presence of the Ψ matrix violates the orthogonality of the transformation by additional rotation relative to the horizontal axis.

Therefore, since we know the solution in the form of the transformation matrix $\mathbf{M}_T$, we have the opportunity to determine the coefficients in equation (8).

Such coefficients include, firstly, η_1 and η_2 as the values of linear deformation, α_1 and α_2 - the angles of rotation of the coordinate system and θ - the angle of non-orthogonality.

All these quantities can be determined as follows

$$\begin{aligned} \eta_1 &= \sqrt{\lambda_{11}^2 + \lambda_{21}^2} = \sqrt{A^2 + D^2} \\ \eta_2 &= \sqrt{\lambda_{12}^2 + \lambda_{22}^2} = \sqrt{B^2 + E^2} \\ \alpha_1 &= arctg\left(\frac{\lambda_{21}}{\lambda_{11}}\right) = arctg\left(\frac{D}{A}\right) \\ \alpha_2 &= \alpha_1 + \theta = arctg\left(\frac{-\lambda_{12}}{\lambda_{22}}\right) = arctg\left(\frac{-B}{E}\right) \\ \theta &= \lambda_2 - \lambda_1 \end{aligned} \quad (9)$$

The given model of transition from imaginary to real provides a variant of description of transformation of the phantom of the second kind TF II into the third TF III and the third into the fourth TF IV. In this form it is the basic model of transformations [1, 12]. Let us consider a number of remarks concerning this model.

Firstly, the technological phantom of the third kind (TF III) coincides with the object in its parameters. The only noticeable difference is observed between the masses, i.e. purely coordinate transformations in (7.6) can be considered as

$$k = \begin{bmatrix} 1+\mathbf{[S]} & 1+\mathbf{[S]} & 1+\mathbf{[S]} \\ 1+\mathbf{[S]} & 1+\mathbf{[S]} & 1+\mathbf{[S]} \end{bmatrix} \approx 1 \quad (7.10)$$

Results and their discussion

In fact, this matrix (7.10) describes the parameters of the motion and geometry of the bioobject during the execution of the line in real coordinates. In this case, in the ideal case, the value **[S]** acts similarly to the value in equation

$$\delta \mathbf{r}_i = \frac{\delta \mathbf{r}_i}{\partial x_i} \delta x_i + \frac{\delta \mathbf{r}_i}{\partial y_i} \delta y_i + \frac{\partial \mathbf{r}_i}{\partial z_i} \delta z_i.$$

That is, this is the difference between the spaces of the technological phantom and real space.

Secondly, in addition, in the process of implementation in real space, the phenomenon of duality arises and therefore expressions (7), (8) and (9) take the following form

$$\begin{bmatrix} x_R + \mathbf{D} \\ y_R + \mathbf{D} \end{bmatrix} = \begin{bmatrix} (\eta_x + \mathbf{[S]})\cos(\alpha + \mathbf{[S]}) & -(\eta_y + \mathbf{[S]})\sin(\alpha + \mathbf{[S]}) \\ (\eta_y + \mathbf{[S]})\sin(\alpha + \mathbf{[S]}) & -(\eta_y + \mathbf{[S]})\cos(\alpha + \mathbf{[S]}) \end{bmatrix} \times \\ \times \begin{bmatrix} x_u + \mathbf{[S]} \\ y_u + \mathbf{[S]} \end{bmatrix} + \begin{bmatrix} \lambda_x + \mathbf{[S]} \\ \lambda_y + \mathbf{[S]} \end{bmatrix} \quad (11)$$

or

$$\mathbf{M}_{R\mathbf{D}} = \Omega_{\mathbf{D}}\mathbf{H}_{\mathbf{D}}\Psi_{\mathbf{D}}\mathbf{M}_{U[\mathbf{S}]} + \Lambda_{\mathbf{D}} = \mathbf{M}_{TD}\mathbf{M}_{U[\mathbf{S}]} + \Lambda_D \quad (12)$$

where

$\Omega_D = \begin{bmatrix} \cos(\alpha + \mathbf{[S]}) & -\sin(\alpha + \mathbf{[S]}) \\ \sin(\alpha + \mathbf{[S]}) & \cos(\alpha + \mathbf{[S]}) \end{bmatrix}$ - the rotation matrix about the coordinate origin considering actual measurement errors;

$\mathbf{H}_D = \begin{bmatrix} \eta_x + \mathbf{[S]} & \mathbf{[S]} \\ \mathbf{[S]} & \eta_y + \mathbf{[S]} \end{bmatrix}$ - coordinate scaling matrix considering object motion measurement errors;

$\Lambda_D = \begin{bmatrix} C & \mathbf{[S]} \\ F & \mathbf{[S]} \end{bmatrix}$ - the displacement vector always exists, even when C=F=0,

$\Psi_D = \begin{bmatrix} I & -\sin\mathbf{[S]} \\ \mathbf{[S]} & \cos\mathbf{[S]} \end{bmatrix}$ - the orthogonality error matrix is applied when the coordinate axes deviate from orthogonalit $\Theta > [\mathbf{S}]$ or $\delta\mathbf{s}_i > [\mathbf{S}]$.

It can be clearly seen that the degree of scaling and angular distortions is entirely determined by the relationship between the coefficients *A, B, C,* and *D*.

At the same time, from equation (9), there is a dependence of the rotation angles on the same set of coefficients. Thus, all distortions arise due to the displacement (misalignment) of coordinate systems relative to each other, while the coefficients merely characterize the magnitude of these distortions, which are a consequence of the properties of the real space.

The following parameters, according to equation (9), can never have an error smaller than **[S]**.

At present, the scale η and angle α functions can be interpreted in terms of the curvature of real space, i.e., as $\eta = \eta(r)$ and $\alpha = \alpha(r)$.

In our case, the spatial curvature depends on the displacement vectors $\boldsymbol{\lambda}_x$ and $\boldsymbol{\lambda}_y$, the combined effect of which can be described by the matrix Λ and the radius vector originating from the coordinate origin.

In this case, we obtain functional dependencies in the form of gradients of scale and angle variations:

$$grad\,\eta(r) = \frac{\partial\eta(r)}{\partial x}\mathbf{i} + \frac{\partial\eta(r)}{\partial y}\mathbf{j}$$

and (13)

$$grad\,\alpha(r) = \frac{\partial\alpha(r)}{\partial x}\mathbf{i} + \frac{\partial\alpha(r)}{\partial y}\mathbf{j}\ .$$

In vector form, the following result is obtained

$$\frac{\partial\eta(\mathbf{r})}{\partial\boldsymbol{\lambda}} = \boldsymbol{\lambda} grad\,\eta(\mathbf{r})$$

and (14)

$$\frac{\partial\eta(\mathbf{r})}{\partial\boldsymbol{\lambda}} = \boldsymbol{\lambda} grad\,\eta(\mathbf{r})\ .$$

If a level grid with an interval deviation **[S]** is constructed on our plane, it becomes possible to graphically determine both the magnitude and direction of the gradient.

In this case, the direction of the gradient is defined by the normal to the level curve at the measurement point. The value **[S]** is known, while the distance between the points can be measured.

The directional derivative of the gradient equals its magnitude. Therefore, we obtain:

$$\left|grad\,\eta(\mathbf{r})\right| = \frac{[\mathbf{S}]_\eta}{\lambda}$$

and (15)

$$\left|grad\,\alpha(\mathbf{r})\right| = \frac{[\mathbf{S}]_\alpha}{\lambda}\ .$$

In essence, the previous consideration of a virtual function in real space corresponds to the transformation of a virtual acceleration function into an effective force according to Newton's law.

Thus, when analyzing this case, we conclude that any force arises as a consequence of the appearance of acceleration of the object's center of mass, i.e., when the resultant acceleration exceeds the magnitude **[S]**. The exceedance of acceleration beyond the threshold **[S]** cannot occur due to unknown reasons. This phenomenon always has a physical basis, which leads to the emergence of specific physical forces, as previously discussed in the context of affine transformations.

Thus, based on the conducted analysis of the object's motion coordinate space using the TONTOR theory, it can be stated that the most relevant tasks in determining stability parameters are the measures of variability and regularity of movements, which reflect the level of neuromotor control of motor activity and its characteristics. This enables the development of algorithms for the analysis and early diagnosis of disturbances in the motion coordinate space in the presence of nervous system disorders.

Висновки

In this study, based on the approaches of the TONTOR theory, the main characteristic parameters of the object's motion trajectory in space associated with deformations and displacements were analyzed. These parameters reflect the assessment of the biological stability of motion coordinates in patients with multiple sclerosis and Parkinson's disease as an important indicator of the functional state of the central nervous system.

In this context, it is reasonable to propose a methodology for analyzing time series of motion coordinates, which includes statistical, spectral, and nonlinear metrics that enable the detection of subtle changes in motor dynamics. These methods, operating in conjunction with the proposed TONTOR theory approaches for identifying and analyzing technological phantoms of objects and the dynamics of their motion in space, will contribute to a more precise assessment of system state and to the early diagnosis

of nervous system disorders. These constitute promising avenues for further research.

The method can be integrated into telemedicine systems and rehabilitation platforms for personalized patient management. Future research perspectives also include expanding study sample sizes, developing and refining analytical algorithms, and applying machine learning methods to improve diagnostic accuracy through automated methods and systems.

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ОЦІНЮВАННЯ БІОЛОГІЧНОЇ СТАБІЛЬНОСТІ КООРДИНАТ РУХУ ПАЦІЄНТА ПРИ РОЗСІЯНОМУ СКЛЕРОЗІ ТА ХВОРОБІ ПАРКІНСОНА

Раннє виявлення нейропатологій є критично важливим для збереження якості життя пацієнта та підвищення ефективності медичної допомоги. Багато неврологічних розладів, включаючи розсіяний склероз та хворобу Паркінсона, розвиваються поступово та часто починаються з ледь помітних або неспецифічних симптомів. На цих ранніх стадіях клінічні прояви можуть бути ледь помітними, проте саме в цей період медичне втручання може бути найефективнішим.

Своєчасна діагностика дозволяє розпочати лікування до того, як відбудуться незворотні зміни в центральній нервовій системі. Це допомагає уповільнити прогресування захворювання, зменшити тяжкість симптомів та відтермінувати інвалідність. Крім того, раннє виявлення сприяє розробці персоналізованих стратегій лікування, включаючи відповідну фармакологічну терапію та програми реабілітації, а також дозволяє постійно контролювати їх ефективність з часом.

У роботі розглядаються підходи до оцінки біологічної стабільності координат руху у пацієнтів з розсіяним склерозом та хворобою Паркінсона як важливого показника функціонального стану центральної нервової системи. Обґрунтовано актуальність кількісних методів аналізу рухової активності для ранньої діагностики, моніторингу прогресування захворювання та оцінки ефективності лікування. Запропоновано методологію аналізу часових рядів координат руху, що включає статистичні, спектральні та нелінійні показники, які дозволяють виявляти ледь помітні зміни в руховій динаміці.

Особлива увага приділяється визначенню параметрів стабільності, варіабельності та регулярності рухів, які відображають рівень нейромоторного контролю.
Результати підтверджують доцільність використання запропонованого підходу як об'єктивного інструменту для оцінки біологічної стабільності рухів у пацієнта з нейропатологіями. Метод може бути інтегрований у системи телемедицини та реабілітаційні платформи для персоналізованого ведення пацієнтів. Перспективи майбутніх досліджень включають розширення вибірки, вдосконалення аналітичних алгоритмів та застосування методів машинного навчання для підвищення точності діагностики.
Ключові слова: розсіяний склероз, хвороба Паркінсона, координати руху, біологічна стабільність, пацієнт, математичне моделювання, оцінка прогресування хвороби, нейромоторний контроль.

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