Measuring systems for monitoring the human state: human digital twins based on a kinematic portrait

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Abstract. The report is concerned with the analysis of the functional and physical structures of human characteristics for the formation of reference digital models and individual portraits of a human which are his digital twins. A database structure has been developed for describing the human state, based on a variety of models, measured physical quantities, and results obtained from a mobile information and measurement system. The paper outlines an approach to the study and design of mobile information and measurement system designed for the construction of individual kinematic portraits of a human. A variant of a part of the inference system is shown on the example of studying the trend of changes in one of the time characteristics of the movement technique.

1. Introduction
The authors proceed from the fact that it is impossible to create a universal human model. Therefore, to create human digital twins (HDT), it is necessary, first of all, to determine the goals that each assigned task is aimed at, to determine the biophysical parameters that are informative for these purposes, and the methods of measuring these parameters (physical quantities).

The papers of a number of authors [1-5] are dedicated to the creation of information and measurement systems (IMS) for the study of movement parameters in the field of medical diagnostics, rehabilitation measures, and training processes. To date, special attention is paid to the development of mobile information and measurement systems. However, it is worth noting that there is a need to create databases of digital twins that reflect kinematic portraits of a human for different fields of activity. Such databases will allow to diagnose and predict the development of the current state of a human, which will provide support of decision-making by the attending physician.

2. Materials and methods
It follows from medical practice experience that the same biophysical characteristics of a human can indicate different effects of his state for different genders, age groups, as well as weight and size parameters.

Therefore, when designing the database (knowledge base) of the HDT, first of all it is necessary to determine the functional and physical structure of human characteristics.
To define groups of people, we select the following characteristics: "gender" - {m, w}, "age" - {20, 40, 60, 80}, "weight" - {20, 40, 60, 80, 100}.

Each group member:

- Can be in a normal state: the reference state of the human (RSH) of the group without deviations.
- Have deviations from the normal RSH: "sport" - {sport disciplines}, "profession" - {professional types}, "disease" - {disease types} - (SPD).
- Can be in a certain psychophysical state (PPS) [6]: OSP - the state of morning awakening (background state); "joy"; "mental fatigue", "physical fatigue"; "intoxication" - {O, J, M, P, I}.

Each group can be described by generalized characteristics that represent the reference digital model - the group digital twin. As each human in the group can have a deviation and can be in a certain state, it is necessary to reflect this fact as a subset of digital models - the base of deviations reference model and the base of states reference model. The formed bases of reference models are the ground for creating a working digital model that defines the field of medical and biophysical measurements aimed at monitoring and analyzing the current state of a human. On the basis of the working digital model, which defines the list of possible monitored quantities, an individual human portrait (HDT) is formed on the basis of a priori information, which includes a list of numerical and qualitative characteristics that must be monitored, as well as ranges of their measurement and analysis algorithms to obtain current assessments of the human state and make recommendations. The structure of databases describing the human state belonging to one of the groups is shown in figure 1.

![Diagram](image)

**Figure 1.** The structure of databases describing the human state belonging to one of the groups.

An individual human portrait (IHP) describes the characteristics of a human, taking into account his/her location in a certain group, defines a list of informative parameters that need to be measured to obtain assessments of his/her state. The mobile IMS must ensure the required accuracy and reliability of the measurement results. The analysis and inference system is a set of interrelated algorithms and methods of analysis that provide reliable diagnostic conclusions, which are the basis for making
recommendations. Since any human state is a complex biotechnical and psychophysical process, the most important stage in the formation of the technical specification for the creation of an IMS is the definition of informative parameters, methods of their measurement, as well as analysis algorithms. Note that the described approach requires the accumulation of a lot of experience and close interaction of specialists, and this is not always easy to implement. The result can be positive if all the necessary informative parameters can be measured with the required characteristics.

Another approach is possible. There are measuring instruments: sensors, measuring channels or measuring systems that provide reliable measurement of biophysical quantities. It is necessary to determine for which diagnostic tasks these instruments will provide the measurement of informative parameters. In this formulation of the problem, the creation of the IHP is performed on the basis of the capabilities of the measuring instruments. In this case, the vector of the measured biophysical quantities determines the diagnostic field. This approach allows to study the possibilities of the IMS with increasing complexity. First, by solving simple diagnostic tasks. Then, to complicate the system, expanding the scope of its application, complicating the field of diagnostics. An example of this approach is the papers [6], which studies the possibilities of diagnosing the human state based on the "DiaSled" hardware and software suite. The authors use this approach to analyze the capabilities of an IMS built on the basis of micromechanical sensors that measure the kinematic characteristics of various points on the human body. At the same time, a number of individual kinematic portraits of a human (IKPH) are formed.

A variant of the analysis system presented below is implemented for a personalized information and measurement system being developed to assess the degree of recovery of walking skill, containing two measurement modules located in the heel area of the right and left legs, respectively. The measuring module is based on a micromechanical sensor with a three-axis accelerometer and a gyroscope; the measurement information is transmitted by wireless communication channel. The measurement module includes 6 measurement channels, so the following information is transmitted to the server: measurement time, angular velocities along the three axes of the gyroscope, linear accelerations along the three axes of the accelerometer. The algorithm for determining the time coordinates for determining the boundaries of the step phases is performed using linear accelerations along the three axes of the accelerometer, but the values of the angular velocities are necessary to adjust the accelerometer readings relative to the global (world) coordinate system.

3. Results and discussion

In the implemented personalized system for assessing the degree of recovery skill walk of patient, transition rules were obtained for the time parameters (pace and rhythm) which providing for the transition from the quantitative values of the measurement results to the qualitative values of the inference system scale in order to further combine and process the set of qualitative assessments along the spatial and time characteristics of the walking technique [7, 8]. The development of such transition rules was based on the processing of a large number of experimental data (N>50). The characteristics of interest were established by doctors and specialists in the field of physical rehabilitation. Below is a part of the inference system for the time characteristic of the Rhythm walking technique.

Rhythm of movements (time rhythm) is a time measure of ratio of the movement parts, which determined by the ratio of the duration of the movement parts [9]. Thus, the Rh rhythm assessment is calculated as follows:

$$R_h_{ij} = \frac{\sum_{i=0}^{N} \theta_{5ij} - \theta_{1ij}}{N}$$

where $T_r, T_l$ is the duration of the steps of right and left legs, respectively; $N$ is the number of steps; $\theta_{1ij}$ is the moment of the beginning of the phase where the foot leaves the surface; $\theta_{5ij}$ is the moment of the beginning when the foot reaches the support; $i$ is the number of the right leg step; $j$ is the number
of left footstep. The step phases are determined at the previous step of the algorithm for obtaining informative parameters [10, 11].

The rule of transition from a quantitative value to a qualitative one for the Rhythm time characteristic obeys the following expression:

\[
QS(Rh) = -7.1 Rh^3 + 4.5 Rh^2 + 12.8 Rh - 0.29,
\]

where \( QS(Rh) \) is the value of the qualitative scale that characterizes the rhythm, \( Rh \) is the quantitative value of the rhythm assessment result.

Diagnosis of the current state of the studied parameter and, as a result, the state of the patient should be performed on the basis of the accumulated measurement information: either a reference individual kinematic portrait of the patient himself (taken at the initial stage of treatment), or relative to the general norm of the kinematic portrait of the corresponding group of people. Thus, during the entire period of treatment or rehabilitation, it is necessary to monitor the trend of the development of the current state of the studied parameter.

When assessing the time characteristics of walking technique, experiments were conducted to monitor the trend of changes in time characteristics for a neurosurgical patient who underwent removal of a neoplasm at the thoracic spine level (age group of 40-50 years). Figure 2-4 shows the qualitative values of the results of rhythm monitoring at different time intervals: 3 days after surgery, 5 days after surgery, 8 days after surgery.

The graphs show that the patient improved his motor skills during the rehabilitation period. This trend can be traced based on the results of the assessment of the time characteristics of walking technique.

Figure 5 shows the result of predicting the effect of rehabilitation measures on the time characteristics of walking technique (the rhythm in present case). The prediction is performed using the least squares method when iterating through the embedded functions. The best calculated polynomial for this situation is a 2nd degree polynomial with the following coefficients:
The confidence factor of the approximation (shows the proximity of the trend line value to the actual data) is \( R^2 = 1 \).

(3)

The prediction result for the characteristic of the Rhythm movement technique was confirmed in the course of further experimental studies (figure 6).

Figure 5. Predicting rehabilitation results.

The results of prediction for 15 people were also confirmed. The main difficulty in monitoring the trend of the current situation is the short period of the stay of patient in the hospital (from 3 to 10 days), since a significant part of the subjects leave the hospital after 6 days of rehabilitation measures.

4. Conclusion
The paper considers a variant of the system for displaying the time characteristic of the Rhythm walking technique. The results of the study of the trend of changes in this time characteristic during the rehabilitation of a neurosurgical patient who underwent removal of a neoplasm at the thoracic spine level are presented.

It is planned to obtain the rules for the transition from the quantitative values of the measurement results to the qualitative values of the normalized scales for the spatial characteristics of walking technique for a generalized analysis of the human state during the recovery of motor activity.

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