Movement estimation methods based on the motion capture system

Viktoriya Smirnova
Kazan Federal University
Kazan, Russia
ORCID: 0000-0002-1107-2152

Elena Yaikova
Neurosurgical Department, Central City Clinical Hospital
Ulyanovsk, Russia
yaikovavictoriya@mail.ru

Maxim Baltin
Kazan Federal University
Kazan, Russia
ORCID: 0000-0001-5005-1699

Nikita Kharin
Kazan Federal University
Kazan, Russia
ORCID: 0000-0003-4850-143X

Tatyana Baltina
Kazan Federal University
Kazan, Russia
ORCID: 0000-0003-3798-7665

Oscar Sachenkov
Kazan Federal University
Kazan, Russia
ORCID: 0000-0002-8554-2938

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***Abstract*—The purpose of this work is to develop and describe methods for assessing the movement of the subject. The article presents a mathematical formulation of the definition of kinematic parameters, which makes it possible to speed up the diagnosis of the disease and individualize the treatment. The presented methods are maximally general, and it allows to use them for different experimental schemes. And the presented methods are easy to automate. An example of use is also provided. Calculated parameters such as step length, maximum foot lift, and foot swing give a clear indication about the subject moving. Also, the construction of angulograms is informative, the average values of the change in the angles of the hip and knee in steps and the standard deviation are calculated. Angulograms can be used to determine gait in normal and pathological conditions, as well as before and after treatment. Motion is recorded with six Vicon MX cameras (Vicon Motion Systems, Oxford, UK). The data obtained from the cameras are used to calculate the investigated kinematic parameters.**

Keywords— motion capture system, movement analysis, gait, biomechanics

I. Introduction

Comparison of the parameters of movement of healthy subjects and subjects with injuries is an urgent task [1-4]. The kinematic characteristics of the movement make it possible to describe the spatial displacements of the body and its individual relations with environment. Moreover, using kinematics data it is possible to solve the inverse dynamic problem to find forces that initiate the displacements. The kinematic characteristics of movement contain information about the speed, time, and magnitude (amplitude) of movement over a distance [5]. Nowadays it is popular to use kinematics data for diagnostics and treatment tactics decisions in clinics. E.g., using kinematics analyses of motion it is possible to improve the quality of lower limbs prosthetics.

So, in the work of Hiroaki Khabara et al. [6], the walking of a person with a prosthesis on the stairs was investigated. Kinematic parameters were calculated, such as the angle at the hip and knee, the average bending speed during the swing, the index of absolute symmetry of the stance and the duration of the step, which allowed us to assess the quality of movement. These parameters made it possible to compare prosthetic and healthy limbs. The subsequent assessment was carried out using the angulogramms of the joint and the average rate of flexion of the joint. The general analysis of the angulogramms is based on the detection of local maxima and is performed manually. Gawłowska et al. [5] similarly investigated the movement of a person on the stairs using various sets of prostheses. The average speed of movement and the average vertical reaction force of the support were also calculated. Changes in articular angles in the step phases were analyzed to assess the quality of movement. The study made it possible to illustrate the influence of the choice of a prosthesis on the gait of a disabled person.

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Motion analysis is used in experimental animal models along with other biological parameters. For example, in the work of Michael Bettger et al. [7], high-resolution video was used to analyze the range of motion in experimental knee arthritis in rats. To calculate the range of motion, the difference between the maximum flexion and extension movements in the joint was taken. This is a widely accepted approach, but it is uninformative for an accurate assessment of movement.

In M.E. Baltin et al [8] Vicon motion capture system was used in the analysis of kinematics in the case of spinal cord injury in rats. The positive effect of therapy based on the functional restoration of the kinematic parameters of the movement of rats is shown. The article used an analysis of the volume of movement calculated as described above [7].

So, despite the widespread use of the motion capture method, the analysis of kinematics is still subjective and based on the comparison of angulograms. This means that the development of a method that would automate data processing and the determination of unique quantitative parameters of the quality of movement remains an urgent task. Such a solution would reduce the time for the diagnosis of diseases, as well as facilitate the adjustment of the therapy used depending on the current condition of the patient. The article presents general approaches to the quantitative assessment of motion kinematics, which expands the scope of the methods and allows for a qualitative assessment of motion processes.

II. Methods

The input data can be presented in the following structure:

$$Data_N = \{t_i, \vec{m}_i^1(x_i^1, y_i^1, z_i^1), \dots, \vec{m}_i^N(x_i^N, y_i^N, z_i^N)\} i = \overline{(1, M)} \quad (1)$$

where t_i - time data, m_i - marker data and x_i, y_i, z_i - coordinates of marker m_i, M - number of frames and n - number of markers.

The X and Y axes were placed in the horizontal plane, the Z axis was normal to the plane. The data were used to assess the articular angles [9].

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Using data set $Data_N$ the skeleton can be visualized. The next step is to divide the entire record into steps performed by the subject. The criterion for completing a step is the contact of the toe with the support surface. For this purpose local minima along the Z axis of the corresponding marker should be found in the data. The found indices of the local minimum allow divide initial data. Thus, we get a new dataset:

$$D_j = \{i_j^{start}, i_j^{end}, Data_K\},\ K \in i = \overline{(1, M)},\ j\overline{(1, N_{step})} \quad (2)$$

where i^{start}, i^{end}, - indices of the beginning and end of the step, $Data_K$ - the data corresponding to the step, N_{step} - number of whole steps.

A. Overall quality of movement

For the analysis of the subject's step, such values as the step length, the maximum lifting height, and swing are calculated. Let's interpret swing as a deviation in a plane perpendicular to the direction of movement of the subject. The mentioned parameters can be calculated for a specific marker. Let us denote index of the specific marker by the X, and the marker as mX. Introduce the direction of movement in a step:

$$\vec{L}_j = \left(\vec{m}^X_{i_j^{end}} - \vec{m}^X_{i_j^{start}}\right)\Big|_{z=0} \quad (3)$$

So, the length of each step can be calculated by the equation:

$$L_j = \|\vec{L}_j\| = \left\|\left(\vec{m}^X_{i_j^{end}} - \vec{m}^X_{i_j^{start}}\right)\Big|_{z=0}\right\| \quad (4)$$

The maximum lifting height H is the difference between the maximum and minimum values of the data set reflecting the change in applicate for one step at each time point. Let's describe maximum lifting height by the equation:

$$H = max(\vec{m}_i^X \cdot \vec{k}_i) - min(\vec{m}_i^X \cdot \vec{k}_i) \quad (5)$$

To estimate the swing, movement in the plane perpendicular to movement should be quantified. Let the difference between the maximum and minimum values of the data set reflecting the change in the ordinate for one step at each time point. Then swing can be described by the equation:

$$D = max\left\|\vec{m}_i^X - \vec{L}_i\right\|\Big|_{z=0} - min\left\|\vec{m}_i^X - \vec{L}_i\right\|\Big|_{z=0} \quad (6)$$

A triangle was constructed to determine the range of motion of the limb. Let's describe the construction of the triangle. The tops of the triangle are the coordinates of the sacrum at the moment of initiation of the movement, the coordinates of the foot at the moment of initiation of the movement, the coordinate of the foot at the moment of being at the highest point of the ascent. Fig. 1 shows the example of positions of a limb during a step phase, with a highlighted range of motion triangle. To quantify the range of motion of the limb the triangle area was used. The area of a triangle can be calculated as half of the vector product:

$$S = \frac{1}{2}\left\|\left(max(\vec{m}_i^X \cdot \vec{k}_i) - \vec{m}^X_{i_j^{start}}\right)\left(\vec{m}^X_{i_j^{start}} - \vec{m}^Y_{i_j^{start}}\right)\right\| \quad (7)$$

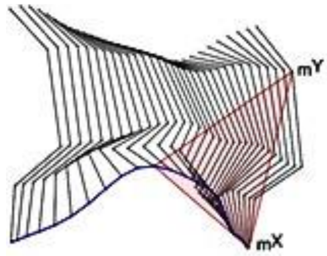

Fig. 1. Image of the position of the hind limb of rats during the step phase

Lateral deviation of the foot is the next indicator of gait assessment. This value shows the deviation of the foot from the direction of movement to the side. To calculate the deviation, you should build a plane passing through the point of the hip, knee and ankle. So, the plane can be defined by the normal vector (Fig. 2).

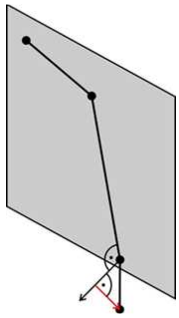

Fig. 2. Illustration for the algorithm for calculating the lateral deviation

Let's introduce a vector connecting the hip and knee, and a vector connecting the knee and ankle (Fig.3), then normalize them:

$$\overrightarrow{BC} = \frac{\vec{C} - \vec{B}}{\|\vec{C} - \vec{B}\|} \quad (8)$$

$$\overrightarrow{CD} = \frac{\vec{D} - \vec{C}}{\|\vec{D} - \vec{C}\|} \quad (9)$$

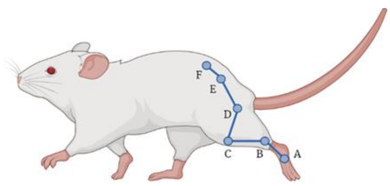

Fig. 3. Schematic arrangement of markers on the hind limb of a rat

Then the lateral deviation can be calculated by the following equation:

$$T_j = (\overrightarrow{BC_j} \times \overrightarrow{CD_j}) \cdot \vec{L_j} \quad (10)$$

B. Angle estimation

Consider a method for determining the angles in the hip and knee joints of the subject. In fig. 3 shows a schematic arrangement of markers on the hind limb [9-12].

At this stage, a set of indices has been obtained, dividing the entire data array into whole steps. To determine the femoral and knee angles, it is necessary to construct the vectors that form these angles:

$$\begin{cases} \overline{BC} = \bar{C} - \bar{B} \\ \overline{CD} = \bar{D} - \bar{C} \\ \overline{DE} = \bar{E} - \bar{D} \\ \overline{EF} = \bar{F} - \bar{E} \end{cases} \quad (11)$$

The vectors found are used to determine the angles in the hip and knee joints. The method of goniometry is used - this is a study of the motor function of the joints of the limbs by measuring the amplitude of movement in them by calculating the angle. Operation for calculating the angles in the hip and knee joint according to the equations (11) at each moment of time [13-16]:

$$\begin{cases} \angle BCD = \arccos\left(\frac{\overline{BC}\cdot\overline{CD}}{|\overline{BC}|\cdot|\overline{CD}|}\right) \\ \angle DEF = \arccos\left(\frac{\overline{DE}\cdot\overline{EF}}{|\overline{DE}|\cdot|\overline{EF}|}\right) \end{cases} \quad (12)$$

The construction of angulograms involves the calculation of the average values of the change in the hip and knee angles in steps and the standard deviation. According to angulograms, it is possible to determine the gait in normal and pathological conditions, as well as before and after treatment, e.g., when applying positive treatment (rehabilitation), angulography begins to approach the norm [17, 18].

To analyze angle changes results were averaged for all steps. To estimate deviation in movement standard deviation was calculated for all steps. In this case, the resulting distribution can be presented as follows:

$$\bar{\varphi}_{\pm}(\tau) = mean(\varphi(\tau), N_{step}) \pm std(\varphi(\tau), N_{step}) \quad (13)$$

where $\varphi(\tau)$ – angle function, mean $(\cdot, k)$ and std $(\cdot, k)$ – mean and standard deviation of function according to steps, N_{step} – number of steps.

$$std(\varphi(\tau), N_{step}) = \sqrt{\frac{1}{N_{step}} \sum_{i=1}^{N} (x_i - \bar{x})^2} \quad (14)$$

To quantify the volume of motion degree, the following equation was used to calculate range of motion:

$$\bar{\varphi}^m = \max_{\tau}(\bar{\varphi}_+(\tau)) - \min_{\tau}(\bar{\varphi}_-(\tau)) \quad (15)$$

The function $\varphi_{\pm}(\tau)$ and the volume of motion degree marked in Fig. 4.

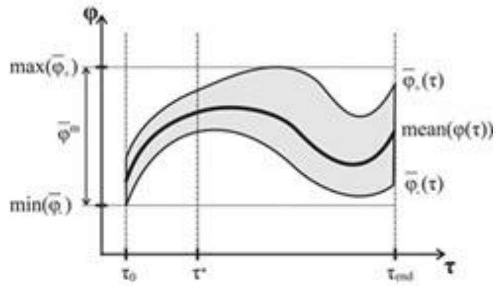

Fig. 4. Main features calculated from angulogram

Large range of function $\varphi_{\pm}(\tau)$ mean that angles change a lot in steps, that can be explained by unevenness of step (interval $[\tau^*, \tau_{end}]$ in Fig. 4). Small range of function $\varphi_{\pm}(\tau)$ mean is consequence of uniform steps (interval $[\tau_0, \tau^*]$ in Fig. 4).

III. Results and Discussions

Three-dimensional data were obtained using six Vicon MX cameras (Vicon Motion Systems, Oxford, UK) placed on special mounts in a semicircle. An active and calibration marker was used to calibrate and synchronize the cameras (Vicon Motion Systems, Oxford, UK). Further, according to the above algorithm, the data was divided into phases of the step cycle.

To analyze the data obtained, the described method was implemented in the MATLAB software package. All of the above operations were performed for each record. Consider an example of the results obtained for one test rat. The calculation of step length, maximum limb lift and swing proceed using marker A (Fig. 3), which is located on the toe of the rat.

In Fig.5 knee angle results are presented, here the thick line – mean values of angle, grey field – deviation (function $\varphi_{\pm}(\tau)$) of an angle. The hip and knee angles were averaged for the study recording over three steps.

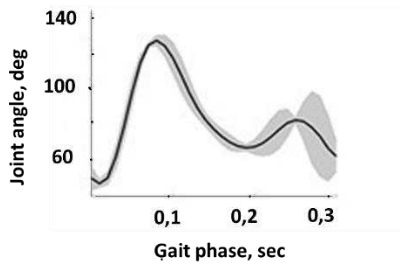

Fig. 5. Angulograms of the knee angle: the thick line – mean values of angle, grey field – standard deviation of an angle

In intact rats, in the first third of the step-by-step cycle, the knee flexion angle changed from 43±2° to 123±5°, in the second third of the step-by-step cycle, the angle was 67±2°, in the last third of the step it returned to its original value (Fig. 5). The maximum lift of the rat's foot during the movements of the hind limbs were determined using the described methods. In the control group, the foot lift was 18±4 mm.

Fig.6 shows an image of the projection of the motion of the test rat in the horizontal plane.

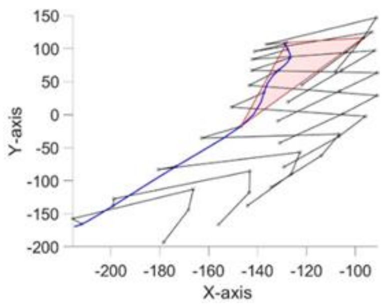

Fig. 6. The image of the range of movement of a test rat in the horizontal plane

The image shows the deviation of the foot from the main direction of movement - it is an illustration of lateral deflection. Test rats had the ability to confidently lean on the surface of the foot and support their weight. The lateral deviation was 1 ± 1 mm. The range of motion is 2009 ± 7 mm^2 ($p<0.05$).

The above technique is applicable not only to rats but also to humans. There is a need for a technique that allows quick assessment changes in the movement for patients undergoing rehabilitation. Fig. 7 shows an angulogram of the change in the angle of flexion in the knee joint over time. At the beginning, the angle value decreases as the knee flexes, and the swing phase begins. Further, the value of the angle increases, the knee is extended and the foot is moved forward, followed by lowering to a horizontal surface. There was a change in the knee flexion angle from 130±4° to 175±5°.

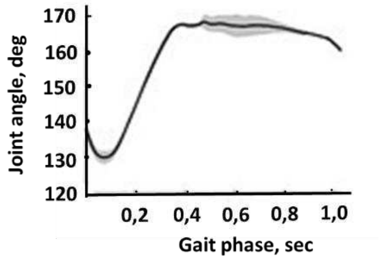

Fig. 7. Angulograms of the knee angle of human: the thick line – mean values of angle, grey field – standard deviation of an angle

Fig. 8A shows an image of the position of a person's leg at each moment of time within one step in the sagittal plane.

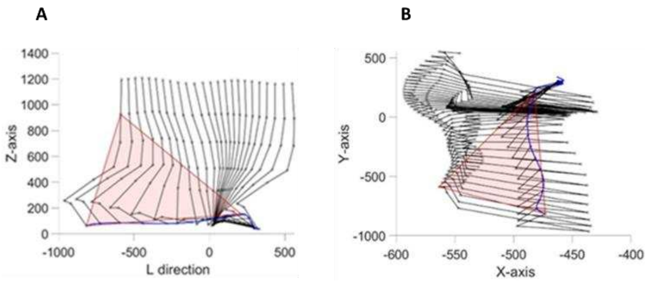

Fig. 8. A. The image of the range of movement of a human in the sagittal; B. The image of the range of movement of a human in the horizontal plane

The maximum height of the foot was 113±2 mm. The analysis of the obtained results was carried out according to a similar algorithm. The range of motion of the hind limb was 440475.75 = 20 mm2 ($p<0.05$). Fig. 8B shows an image of the position of a person's foot at each moment of time within one step in the horizontal plane. The lateral deviation was 23±3mm.

Thus, with the systematic application of this technique, it becomes possible to track the dynamics of the quality of the object's movement.

IV. Conclusion

The developed technique helps to accelerate the diagnosis of the subject's disease and personalize the treatment. The calculated parameters are indicative and give a clear picture of the nature of the subject's movement. This technique will be useful for tracking the dynamics of the subject's state. The proposed methodology is based on simple optimal algorithms and is easy to be automized.

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