Digital Evaluation of Human Gait in Diagnostic Physical Exercises based on Virtual Reality

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***Abstract*—Digitalized evaluation of human gait becomes a topical problem for mobile healthcare (mHealth) and well-being. We focus on the evaluation for a person performing diagnostic physical exercises. We introduce our algorithm for constructing a digital model of human gait when the person is performing a given exercise. The presented demo application observes human gait based on sensed data from Virtual Reality (VR) trackers attached to human body. Sensed data are collected in the database and processed to construct a 3D model of human motion based on a mathematical model for estimating the human gait parameters (metrics). The VR technology is used for visualization both when a person executes the given exercise and when constructing the resultant 3D model to analyze. Our experimental setup ensures the interconnection of the equipment to perform exercises in virtual space and organize the collection and processing of sensed data. VR trackers operates in real time. Based on the collected data, numerical motion metrics are estimated to form a digital model of human gait. The 3D model is then used by a doctor to analyze gait disorders or by the person him/herself.**

I. INTRODUCTION

The gait disturbance plays a significant role in a person's life, exerting a substantial influence on their quality of life. Gait disturbance can be initiated by the development of a pathological process in the body, as well as a decrease in a person's physical activity. To enhance motivation for increased physical activity in everyday life, solutions for real-time monitoring are proposed to construct an individual profile of daily activity [1].

Currently, there are numerous methods for assessing human gait. Many of them are based on performing standard medical tests, the results of which are evaluated by clinicians visually. Advancing information technologies have enabled the numerical assessment of gait parameters using various sensors [2][3][4] and technologies (e.g., analysis of video with smartphones using the OpenPose BODY25 pose estimation model [5]). Studies have shown that evaluating gait variability parameters provides clinically relevant digital biomarkers of gait impairments [1], and by assessing mobility performance indicators, individuals' concerns regarding falls can be remotely monitored [6]. The integration of medical and information technologies, as well as the development of solutions for remote disease diagnosis and rehabilitation at home, may help reduce the impact of medical resource deficits, improve diagnostic accuracy, predict disease progression, and track the course of rehabilitation [4].

This paper discusses virtual reality (VR) technology for studying human gait. VR can be defined as a three-dimensional computer simulated environment that attempts to reproduce real world or imagined environments and interactions, thereby supporting work, education, recreation, and health” [7]. The developed VR-based solutions are widely used in medical institutions for training both future medical workers and patients [8], psychotherapy, rehabilitation, exercise, and entertainment.

Given the relevance of studying human gait parameters, the following scientific tasks were identified: to develop a method for analyzing human motion based on virtual reality technology and a method for evaluating human gait parameters. The method for analyzing human motion is built on the use of virtual reality equipment, additional body-worn sensors, and the development of software that allows for the performance of simple exercises without the need for specialized equipment. The method for evaluating human gait parameters involves collecting position coordinates and angular rotations of key body points and further processing them to align with existing clinically gait parameters.

The stated scientific tasks can be addressed as follows: developing a mathematical model of human motion for the digital representation of exercises performed in virtual reality space, an algorithm and software module for tracking human motion using VR trackers, digital models of motion and exercise performance, and a method, algorithm, and software module for recognizing deviations in human motion.

The rest of the paper has the following structure. Section II introduces the problem of human gait analysis based on advances in mobile trackers and VR technology. Section III describes our experimental setup to evaluate human gait when the person performs diagnostic physical exercises. Section IV presents our mathematical model to evaluate human gait parameters. Section V shows our demo application and provides early experiments to test the feasibility. Section VI summarizes the key findings of the presented work-in-progress study.

II. PROBLEM DEFINITION

To describe the research issue, systematic reviews on the application of virtual reality (VR) technology for upper and lower extremity rehabilitation, balance, and movement speed were utilized. Articles with systematic reviews were selected from the PubMed database. The search was conducted using the keywords "virtual reality rehabilitation". A total of 6 articles with systematic reviews were included in the analysis, describing the effectiveness of VR technology in the rehabilitation of patients who have had a stroke or have a history of Parkinson's disease or multiple sclerosis.

The studies showed that rehabilitation using VR can improve motor function of the upper extremities with an increase in range of motion, as well as provide slight improvements in upper limb muscle strength [9]. VR rehabilitation demonstrates a positive effect on balance, gait, and activities of daily living in individuals who have experienced a stroke [10]. VR rehabilitation also shows positive effects on balance, fatigue, and quality of life in individuals with multiple sclerosis [11], as well as on balance, quality of life, and daily activity in individuals with Parkinson's disease [12]. Overall, VR rehabilitation is noted to have a positive impact on the physiological, psychological, and rehabilitative aspects of a person's life [13].

The combination of VR rehabilitation with mHealth technologies was also considered. It was noted that this combination has a positive influence on postural balance, suggesting that such integration of technologies in home rehabilitation is a continuation of traditional therapy [14].

Thus, it is proposed to develop software based on VR technology that would allow individuals to perform physical exercises in home settings, observe the exercise process from an outside perspective, analyze changes in numerical parameters of gait, and export a video recording of the exercise process (referred to as the Digital Assistant).

III. THE EXPERIMENTAL SETUP

To perform this task, an experimental setup was developed, on which a digital assistant operates (Figure 1).

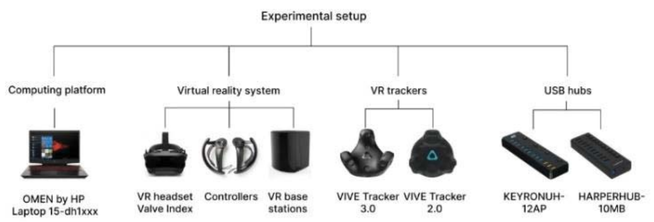


Fig. 1. Experimental setup

The experimental setup is divided into 4 groups.

Group 1. Main computing platform. It includes an OMEN by HP Laptop 15-dh1xxx, which serves as a temporary local server and the main machine running the digital assistant.

Group 2. Virtual reality system. This system includes a Valve Index virtual reality headset, 2 base stations, and 2 controllers. The headset displays instructions for performing exercises and creates a virtual environment, while the base stations provide user position tracking in the virtual space.

Group 3. VR trackers. This includes 2 VIVE trackers of version 2.0 and 7 VIVE trackers of version 3.0, which capture the X, Y, Z coordinates, rotation angles around the X, Y, Z axes, and the time elapsed since the start of exercise execution. This ensures accurate tracking of user movements. The collected data are used for gait analysis and its subsequent reproduction.

Group 4. USB hubs. This includes the KEYRONUH-12AP and HARPERHUB-10MB hubs, which allow for efficient communication between the virtual reality system, VR trackers, and the laptop, ensuring stable data transmission and interaction between devices.

IV. EVALUATING HUMAN GAIT PARAMETERS

To evaluate the gait of a person, it is necessary to assess its individual parameters, which include: step width, total distance, step length, average walking speed, cruising walking speed, knee lift height, deviation from the trajectory of movement, number of successful and unsuccessful step overs obstacles, number of steps taken to make a turn, variation in acceleration amplitude, rhythmicity, frequency of walking cycles per unit of time, gait variability. These parameters allow for a comprehensive and accurate assessment of the quality of a person's gait, enabling an evaluation of the presence or absence of deviations.

To implement the possibility of evaluating gait parameters, a software for collecting data on the position of a person's body in virtual space has been developed using virtual reality headsets, controllers, and VR trackers. The collected data used for gait parameter evaluation includes the coordinates of equipment placement X, Y, Z, and the rotation angles of the equipment around the X, Y, Z axes.

Virtual reality equipment is placed on the person's body to capture key points that can provide insights about the gait. Figure 2 illustrates the scheme of attaching virtual reality equipment to the human body.

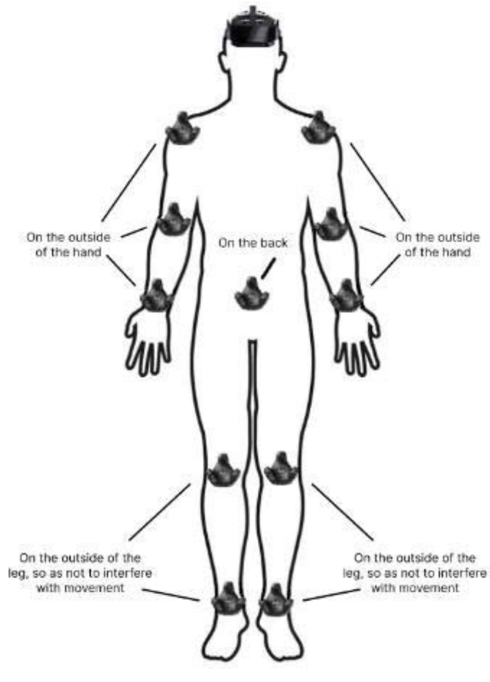


Fig. 2. Attaching Valve Index and VR trackers to the human body

The method for evaluating the presence or absence of gait deviations is based on comparing the results of numerical assessment of individual parameters with the reference values. For example, during movement over 10 m, the normal cruising walking speed for a healthy person range from 1.1 to 1.4 m/s, with a rhythm of 100 steps per minute. The metrics described in Table 1 were used to evaluate the human gait parameters.

TABLE I. HUMAN GAIT METRICS

Metric	Metric description	Calculation method
Cadence (C)	Number of steps per unit of time (minute, hour, etc.).	$C = \frac{Steps}{min}$ (1) Steps – Number of steps, min - time in minutes.
Cycle frequency (CF)	Number of walking cycles per unit of time (minute, hour, etc.).	It is calculated using the fast Fourier transform algorithm. $CF = \frac{CN}{min}$ (2) CN – number of gait cycles, min - time in minutes.
Step length (SL)	Average length of a person's step.	$SL = \frac{Distance}{Steps}$ (3) *Distance* – distance traveled in meters, *Steps* – number of steps.
Average Speed (AS)	The distance traveled during the experiment is calculated and divided by the duration of the experiment. The time between starting the timer and the start of the subject's movement is subtracted from the total duration of the experiment.	$AS = \frac{Distance}{Time}$ (4) *Distance* – distance traveled in meters, *Time* – time in seconds.
Total distance	Calculated using the Pythagorean theorem (the distance traveled is determined at each step by taking the square root of the sum of the squares of the distances traveled in the x and y directions).	$\sum_{t=1}^{T} \sqrt{\Delta x_t \times \Delta x_t + \Delta y_t \times \Delta y_t}$ (5) where Δx_t – distance traveled (in meters) along the x coordinate at time t, Δy_t – distance traveled (in meters) along the y coordinate at time t, T – the number of measurements during the experiment.
Knee lift height	The knee coordinate is considered at the lower and upper points. The knee lift is calculated as the difference in coordinates between the upper and lower points.	$max\ z_t - min\ z_t,\ t = 1..T$ (6) where $max\ z_t$ - maximum knee height (from the surface), $min\ z_t$ - minimum knee height (from the surface).
Deviation from the trajectory of movement	The strong deviation from the movement trajectory is taken into account when a person goes beyond the limits of the step base + double the width of the ankle (to account for the position of the trackers) to the right and left of the trajectory.	$max\ y_t - min\ y_t,\ t = 1..T$ (7) where $max\ y_t$ - maximum value of ankle latitude coordinate, $min\ y_t$ - minimum value of ankle latitude coordinate.
Number of unsuccessful step overs obstacles	The number of times a person hit an obstacle is counted. This is done by checking for entry into a forbidden zone. If the subject was in the coordinates of the obstacle, it means they hit or collided with the obstacle.	$\begin{cases} 1, & x_1 < x_t < x_2,\ y_1 < y_t < y_2,\ t = 1..T \\ 0 & \end{cases}$ (8) where x_1, x_2, y_1, y_2 - boundaries of the forbidden area.
Number of successful step overs obstacles	The number of times a person successfully stepped over an obstacle is counted. If the subject was not in the coordinates of the obstacle, it means they did not hit or collide with the obstacle.	$\begin{cases} 0, & x_1 < x_t < x_2,\ y_1 < y_t < y_2,\ t = 1..T \\ 1 & \end{cases}$ (9) where x_1, x_2, y_1, y_2 - boundaries of the forbidden area.
Number of steps taken to make a turn	The number of steps taken by the subject to change orientation to the opposite direction (a 180-degree turn) is counted.	$Steps_{tn}$ (10) consecutive number of steps performed at an angular velocity $gyro_y > 10°$

The proposed metrics provide estimation of individual parameters of person's gait. The metric can be compared with the norm (a healthy person).

V. Demo Application

The developed software solution includes a virtual space with training tracks on which the user performs exercises, as well as several software modules that implement the following functions:

- Tracking user movement with fixation of coordinates and rotation angles along the X, Y, Z axes of key points of their body, where VR trackers are attached;
- Assessing user's motion parameters, including rhythm, cycle frequency, step length in meters, average speed of movement, total distance traveled, knee lift height, deviation from the movement trajectory, number of unsuccessful obstacle crossings, number of successful obstacle crossings, number of steps taken to make a 180-degree turn;
- Recognizing deviations in user's movement based on the evaluation of gait parameters according to the proposed metrics (1-10) and comparison with a given reference value;
- Visualizing user' movement in virtual reality space;
- Displaying the history of completed exercises.

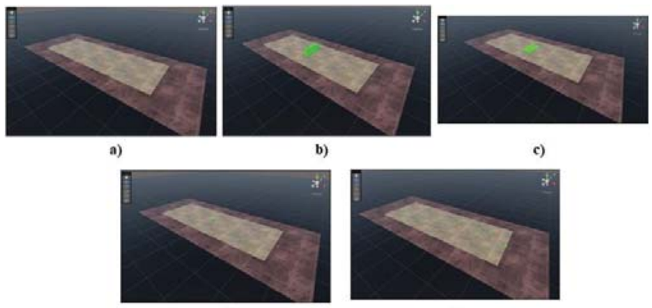
Before starting an exercise, the user is required to follow a basic scenario, which includes the following steps: assembling the experimental setup, powering on the Valve Index, powering on the VR trackers, attaching the VR trackers to the body using special fixing straps according to the scheme presented in Figure 3, launching the digital assistant software, selecting an exercise, performing the exercise, observing the exercise process with the digital avatar, closing the digital assistant software, removing the Valve Index and VR trackers.

The exercises are performed on training tracks in the virtual space. The developed training tracks allow for the execution of the following exercise groups: forward-backward walking with turning, stepping over obstacles of non-zero height (referred to as "Box"), stepping over obstacles of zero height and non-zero width (referred to as "Puddle"), stepping over a moving obstacle, accelerated walking, and trajectory movement.

During the exercise execution process, data is collected from the headset, controllers, and VR trackers. The obtained data is then processed, and the parameters of the user's gait are evaluated. The developed virtual environment with training tracks is presented in Figure 3.

Training tracks consist of a light brown platform that restricts the area of movement, a beige track that restricts the area of exercise execution, and a green obstacle that the user needs to step over.

The virtual space for implementing forward-backward walking with a turn consists of two parts: the platform and the track (Figure 2a). The exercise execution scenario includes 6 steps: 1 - start moving, 2 - walk to the end point of the training track, 3 - turn 180º, 4 - walk to the starting point of the exercise, 5 - turn 180º, 6 - stop. The exercise is performed at a comfortable speed for the user.



a) b) c) d) e)

Fig. 3. Virtual space for implementing a) walking forward-backward with turning, b) walking with stepping over boxes of varying heights, c) walking with stepping over puddles of varying widths, d) walking with stepping over moving obstacles, e) walking along a specified trajectory.

The virtual space for implementing walking with stepping over a box, a puddle, and a moving obstacle consists of three parts: the platform, the track, and the obstacle (Figure 2b-d). The exercise execution scenario includes 9 steps: 1 - start moving, 2 - reach the obstacle, 3 - step over the obstacle without reducing the speed of movement, 4 - walk to the end point of the training track, 5 - turn 180º, 6 - repeat steps 3-4, 7 - walk to the starting point of the training track, 8 - turn 180º, 9 - stop.

The virtual space for implementing walking with acceleration consists of two parts: the platform and the track (Figure 2a). The exercise execution scenario includes 8 steps: 1 - start moving with a comfortable slow speed, 2 - walk to the end point of the training track, 3 - turn 180º, 4 - walk to the starting point of the exercise, 5 - turn 180º, 6 - repeat steps 1-5 at a normal speed, 7 - repeat steps 1-5 at the maximum accelerated pace, 8 - stop.

The virtual space for implementing walking along a specified trajectory consists of three parts: the platform, the track, and the path of movement (Figure 2e). The exercise execution scenario includes 3 steps: 1 - start moving, 2 - walk along the specified trajectory, 3 - stop.

When immersed in VR, the described virtual spaces allow individuals to choose an exercise to perform, familiarize themselves with the instructions, and start performing it.

Simultaneously with the execution of the exercise scenario, information about the person's movement is collected and the parameters of their gait are evaluated based on previously gathered data according to the metrics described in Table 1.

VI. Conclusion

The following results were obtained during the development: an experimental setup was designed, providing minimal detailed information about human gait, which allows for a detailed assessment of motion parameters; a method for assessing parameters of human gait was developed, providing detailed information about gait compared to healthy norms, enabling the evaluation of rehabilitation measures or early diagnosis of emerging motor disorders. The obtained results are useful for a comprehensive assessment of human motor function by collecting statistical information about gait, enabling home-based rehabilitation and retrospective analysis with accumulated exercise history.

As part of further research, it is planned to expand the set of exercises, collect datasets of motion parameters from both healthy individuals and those with motor disorders, across different age groups with similar body types, and calibrate reference values against which gait parameters will be compared.

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