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Virtual Reality as Assessment Tool of the Risk of Falls in the Elderly

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Abstract: We present an assessment tool, based on virtual reality technology, for predicting motor control, attentional or cognitive factors of risk of falls in the elderly. Falls are the leading cause of accidents among the elderly. Each year, it affects 1 in 4 people over the age of 65. In order to better understand and predict this risk of falling, we developed an immersion solution that can collect and identify various indicators of the risk of falling. This easy-to-use solution automates the experimental protocol and the data collection of indicators, and immerses the patient in realistic everyday situations. Our virtual reality device, uses a total of 6 sensors worn by the patient to capture a kinematic of the complete body and generate a virtual avatar in real time to the patient. These kinematic data, replayable for the health practitioner, train a digital process. The scientific experiment, patient-centered, is based on 6 tests of motor or attentional disturbances, requiring global functional abilities. The results obtained showed that for high-risk fall patients, the longer completion times and the number of steps for the different tests compared to low-risk fall patients. Specifically, the introduction of manual and cognitive tasks affects high-risk fall patients more significantly.

Keywords: Fall, Motor Control, Aging, Immersive Virtual Reality

1. Introduction

Falls are the leading cause of accidents among people over 65: in France, around a quarter of people aged 65 to 85 report falling each year. These accidents become more frequent with age; one out of two people over the age of 80 will fall within the year [1]. Falls are the consequence of a complex interaction between risk factors such as age, comorbidities, gender or level of education [2, 3]. Fall is associated with several negative consequences such as fractures, hospitalizations and increased dependency, even institutionalization.

About a fifth of 55 to 85 year old's say they have limited their movements for fear of falling [4].

To meet these challenges, many clinical tests have been developed to assess the motor skills of patients. We propose a technological tool, based on virtual reality and tests inspired by the literature, allowing to evaluate the motor capacities, cognitive or attentional of the patients, in immersion in a realistic environment.

2. Fall Risk Assessment

Falls risk assessment can be performed by clinicians using a variety of standardized tests. The *Timed "Up & Go"* (TUG) test is frequently used to assess motor skills and fall risk in elderly [5]. The patient performs a chair lift, followed by a round trip of 3 meters before coming back to sit down. This

test is timed with the objectives to quantify the patient's motor skills and to predict a risk of falling when the patient exceeds an empirically time threshold [6, 7].

The Tinetti test [8] is based on a variety of qualitative indicators of motor skills and balance like the TUG test: getting up from a chair, sitting down, walking or balancing despite a disturbance. The patient's ability is scored by the clinician on an ordinal scale with a range of 0 to 2 for around twenty criteria. The individual scores of each criterion is then combined, providing a numerical indicator of the patient's motor skills.

These tests are simple to implement in a clinical context, in order to discriminate between falling and non-falling patients but they have several limitations. First, the administration of these tests is done in a clinical and non-ecological environment, which can influence the behavior of the patient. The administration of such tests in virtual reality would make it possible, on the one hand, to standardize the conditions of administration between the different patients, and on the other hand, to carry out the tests in an ecologically valid environment. That implies these tests have to reproduce as closely as possible the context in which the patient mobilizes his motor control, cognitive and attentional abilities on a daily basis [9, 10]. Then, the quality and quantity of indicators can be improved: for example, indicators collected in the Tinetti test, such as the height of steps, can be measured, thus adding more precise information for the diagnostic of the health practitioner.

The use of motion sensors, especially those included in virtual reality kit, allow precise collection of kinematic indicators, with high reproducibility.

The risk of falling can be the consequence of many factors resulting from the patient's interaction with the environment. In particular, an attentional, cognitive or motor failure, combined with disturbances or distractions from the environment, can disrupt the patient's motor control, as illustrated in Figure 1. In order to better consider the multifactorial risk of falling, some protocols assess the patient's motor skills in ecological situations involving the patient's manual or cognitive abilities [11, 12]. The predictive power of a TUG test is improved by adding an additional manual or cognitive task.

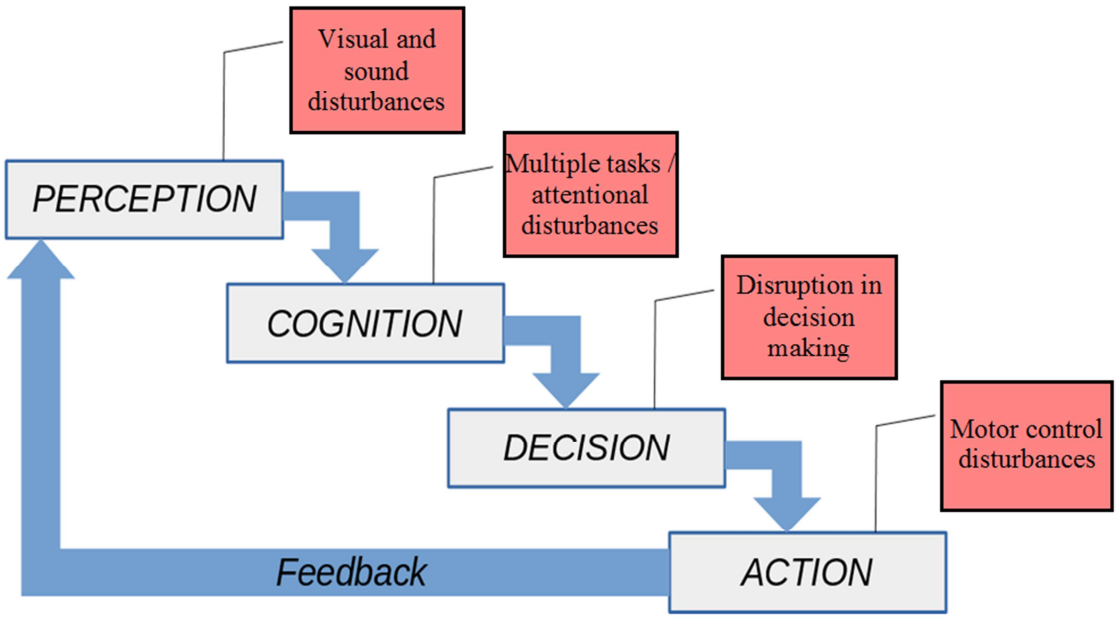

Figure 1. *Motor control loop and disturbances.*

Extrinsic factors related to a poor interior layout of the dwelling must also be considered: for example, tripping over an obstacle is a major cause of falls [13]. The behaviors on getting around or overcome obstacles differ between young or old participants [14-17]: for example, the height of the foot when overcoming an obstacle is a predictive of the risk of falling [18]. Unlike the TUG test, this ecological test is more difficult to perform in a clinical setting, since it generally requires a motion capture system and a post-processing of kinematic data.

In order to better identify the risk of falling, we designed an experimental protocol inspired by existing clinical practices and research protocols, allowing to better understand and evaluate the multiple factors of this risk of falling. This solution based on virtual reality technologies, is easy to use, and fully-automates the experimental protocol and the collection of biomarkers, ensuring the reproducibility of experimental conditions, and immerses the patient in a realistic environment and real-life situations.

3. Material and Methods

Our assessment tool offers a protocol for testing motor, cognitive and attention capabilities, using virtual reality technologies to engage the patient in a realistic environment, reproducing as much as possible the ecological conditions for administering the tests.

3.1. Virtual Reality

3.1.1. Material

Our assessment tool uses a virtual reality device that allows, on one hand, the immersion of the patient in different test situations, and on the other hand, the acquisition of kinematic data and performance indicators in the different tasks. The application is developed on the Unity engine, making it compatible with OpenVR virtual reality systems with:

1) virtual reality headset (HMD) with a system for wirelessly transmitting data and video stream between the headset and the computer;
2) hand-controllers, equipped with a button allowing the user to interact with objects in the virtual environment;
3) trackers equipped with a mounting system suitable for attaching to the patient's feet and back. If necessary, for example when the patient requires walking aid, one of the handheld controllers can be replaced with a fourth tracker attached to the wrist.

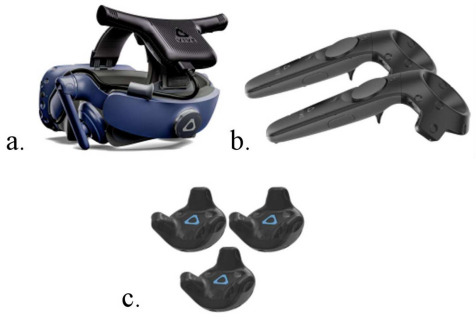

Figure 2. *Patient equipment: a. HTC VIVE Pro wireless virtual reality HDM; b. HTC VIVE hand-controllers; c. Additional HTC VIVE trackers.*

Each of these pieces of equipment has sensors to locate their position and rotation in a space of at least 5 meters by 2 meters. In this case, we use an HTC VIVE HMD with wireless adapter, 2 standard hand-controllers, and from 3 to 4 HTC VIVE trackers, represented Figure 2.

3.1.2. Virtual Environment

The application accurately reproduces the interior of a house, as illustrated in Figure 3, with two rooms used during tests. The first represents a kitchen with a U-shaped furniture that defines a space of approximately 5 meters in length and 2 meters in width, in which the patient can move. Most of the tests in the protocol take place in this part of the virtual environment. The second part represents an office, with displayed drawings and paintings, which is used for tests that involve cognitive and attentional tasks.

The set of sensors worn by the patient allows the total immersion in the environment. The position and orientation sensors of the HMD ensure the synchronization of the visual field with the patient's movements in the virtual environment. Since the patient's movements in the real environment are reproduced to scale in the virtual environment, there is no dissociation between visual perception of movement and proprioception, limiting the risk of motion sickness [19].

Figure 3. *Virtual reality environment: kitchen (top), office (bottom) used for cognitive tasks.*

3.1.3. Virtual Avatar

Figure 4. *Male/female avatars in the "I-pose" calibration position.*

To enhance patient immersion, the posture and the movements, captured by sensors, are rendered in real-time as a virtual avatar, from a selection of 6 avatars. The use of an avatar to represent the patient in the virtual environment is essential to reduce biases related to the use of virtual reality, reducing the user's mental workload, and increasing the accuracy of interactions with the virtual environment [20-22]. The avatar is calibrated for the patient before the tests: once equipped with all the sensors, the patient is asked to stand in I-pose - standing, with a straight back, feet parallel, and arms at the side of the body (see Figure 4) - during the calibration process (less than one second).

This calibration links each of the sensors to the corresponding part of the avatar's body: the virtual reality headset serves as a reference point to determine the patient's

orientation. This information, combined with the position of each sensor, allows for the distinction of left hand/right hand and left back/left foot/right foot. The orientation measured by each of these sensors during calibration is then corrected: the orientation of each sensor is considered relative to its initial orientation.

$r_{measured}$ the measured orientation of a sensor at a given time, $r_{calibration}$ its measured orientation at calibration, the corrected $r_{corrected}$ is given by the following equation (1):

$$r_{corrected} = r_{measured} \times (r_{calibration})^{-1} \quad (1)$$

where $r_{measured}$, $r_{calibration}$ and $r_{corrected}$ are rotations expressed in the form of quaternions. The equation ensures that, for all patients, the corrected orientation of each sensor during the I-pose calibration corresponds to the identity rotation (i.e., zero rotation). This correction standardizes the kinematic data collected between different runs, as the sensor positioning is not repeatable identically from one experiment to another. Only the orientation of the HMD is not corrected, its position being considered fixed from one patient to another, the raw measured orientation is sufficient to determine the orientation of the patient's head.

Using these corrected orientations, an avatar can be animated by a humanoid inverse kinematics algorithm [23]. Using the back sensor as the root of the avatar, the algorithm calculates the orientation of the different body joints of the avatar so as to position each of the avatar's extremities (hands, feet, head) in the positions and orientations measured by the corresponding sensors.

3.2. Test Conditions

The experimental protocol is divided into 7 short tests in which the patient is asked to perform one or more motor, manual, or cognitive tasks. Each of these tests involves back and forth between two lines marked on the floor in the virtual environment, spaced 3 meters apart, this path can be accompanied by one or more tasks or disturbances. This back and forth of 3 meters is automatically timed and separately for the go, turn-around and return phases, allowing a step-by-step and a locomotion time comparison between the different test conditions.

In each of the test conditions, the kinematic data provided by the different sensors is also recorded. These data correspond, for each sensor at a given time, to the corrected position and orientation of this sensor. The position of a sensor is expressed in 3 dimensions relative to the lines marked on the ground.

Before the start of each test, pre-recorded audio instructions are given to the patient. The clinician can then start the test, after making sure that the patient understands the instructions, or starting a rereading of the instructions. The patient is informed of the start of each test by a sound signal, from which it is timed. The test ends automatically when the application detects that the patient has fulfilled the objectives of each test (return behind the starting line, completion of manual or cognitive tasks, etc.).

At the end of the protocol, two questionnaires are proposed via the application in order to evaluate the patient's fear of falling, and the subjective quality of the patient's performance of the protocol. The first questionnaire concerning the fear of falling is the short FES-I questionnaire [24, 25], translated into French [26]. The second questionnaire is only intended to evaluate the realism of the virtual environment and the comfort of the patient during the experimentation, in order to allow us if necessary to improve our experimental protocol and our application.

After validation of the questionnaires, all the data collected during the protocol can be reviewed by the clinician and the patient. In particular, it is possible to visualize a replay of the performance of each of the tests, reconstructed from the kinematic data collected, or to visualize the different indicators collected in each of the test conditions.

3.2.1. Reference Test

This first test aims to evaluate the patient's motor abilities in the absence of any stimuli or additional task. The patient subject is asked to walk back and forth over 3 meters, crossing lines visible on the ground in the virtual reality environment.

The indicators collected during this test are:

1) Time (go, turn-around, return, total);
2) Length, height, average and maximum duration of steps, separately for the right and left foot.

To quantify the effects of habituation to the virtual environment but also the fatigue of the patient during the execution of the protocol, the reference test is repeated a second time after all other test conditions have been completed.

3.2.2. Test with Manual Task

This test aims to evaluate the patient's ability to perform a manual task simultaneously with a motor task, and specifically to quantify the degradation of the motor task in a multi-task situation.

The manual task proposed is inspired by the experiments described in [11, 12], which adds a task to the TUG of carrying a glass of water that should not be spilled. In our protocol, the patient begins by grabbing a cup from a shelf behind him. Once the cup is grabbed, he walks 3 meters to reach a coffee machine and places the cup, which is automatically filled (see Figure 5). The patient then turns around and walks 3 meters back to his starting point with the filled cup.

Figure 5. *Performance of the manual task: on the left, picking up a cup from a height before going; on the right: filling the cup after the return trip.*

The indicators collected during this test are:

1) Indicators of the reference test;
2) Average and maximum tilt of the cup on the way, on the turn around and on the way back;
3) Maximum, linear, and angular acceleration of the cup;
4) Time spent looking at the cup on the way, turning around, and on the way back.

3.2.3. Test with Obstacle Clearance

This test is identical to the reference condition, except for 3 static obstacles placed on the ground, which the patient will have to step over or go around. This test allows observing both the approach phase of the obstacle and the crossing, including how the patient's walk is affected when approaching an obstacle and the margin with which they are able to cross the obstacle.

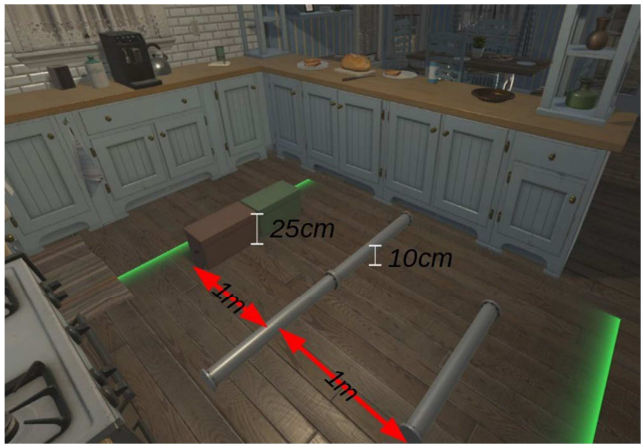

Figure 6. *Obstacle on the path.*

The experience described in [27] highlights differences, both in the approach and crossing phase, between Parkinson's disease patients with reduced mobility and a control group. In particular, patients with reduced mobility have a slower gait during the approach to an obstacle compared to the subjects in the control group, compared to a walking speed in an obstacle-free environment.

The 3 obstacles are static and placed on the ground, spaced one meter apart as shown in Figure 6. The first obstacle measures 10cm in height and depth with a width of one meter. The second obstacle has the same height and depth and a width of 2 meters, requiring the patient to step over it. The third measures 25cm in height and depth with a width of one meter. Having noted that this obstacle size could pose great difficulties for patients, we have not included an obstacle of 25cm that can't be circumvented.

The indicators collected during this test are:

1) Indicators of the reference test;
2) Average and maximum tilt of the cup on the way, on the turn around and on the way back;
3) Obstacle clearance height, at the highest and lowest point above the obstacle (*hmax* and *hmin* respectively, in Figure 7), for each foot crossing the obstacle;
4) Distance from the foot on the ground to the obstacle, before and after crossing (*d1* and *d2* respectively, in Figure 7), for each foot crossing the obstacle.

Time spent looking at each obstacle on the way, turning around, and on the way back.

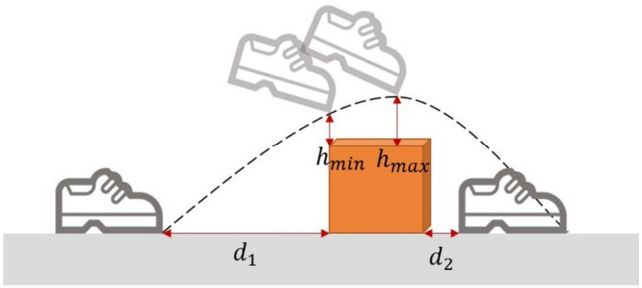

Figure 7. *Diagram of the indicators collected for the obstacle clearance by a foot.*

3.2.4. Test with Cognitive and Attentional Task

This test takes place in a office environment, where 5 copies of 2 types of paintings (see Figure 8) are placed in the environment at predetermined positions (see Figure 9). Before the start of the test, the 2 types of paintings that will be present in the room are shown to the patient. There are 5 paintings in the room. The patient is asked, while walking at a normal pace as possible, to determine which of the two types of painting is represented the most times in the room. On the way back, the patient indicates the painting they counted the most of, without being asked to give the exact number of these paintings.

Figure 8. *Two different types of paintings in the cognitive and attentional task.*

The indicators collected during this test are:

1) Indicators of the reference test;
2) Time spent looking at each painting;
3) Response to cognitive task (correct or not).

Figure 9. *Placement of paintings in the room.*

3.2.5. Tests with Multiple Conditions

Everyday situations may involve different tasks and disturbances simultaneously. For example, older people may be in environments with obstacles while being distracted by stimuli in the environment or while performing a task.

A first test with multiple conditions combines the manual task with the presence of obstacles. The second test combines the cognitive task with the presence of obstacles. In these two tests, the indicators of the reference test are collected, as well as the indicators related to each of the conditions (indicators of the test with obstacles and indicators of the test with manual task or cognitive task).

4. Results

A preliminary study on elderly patients and young participants allowed us to evaluate the suitability of the tool for real-world use. Both young and elderly subjects showed no reluctance to use virtual reality, and did not experience any symptoms of motion sickness. This may be due to good synchronization between real movement and perspective in the virtual environment, as well as the short duration of the experiment, which was less than 15 minutes. Subjects generally reported good immersion in the environment, which seemed realistic enough to them.

Expected results for high-risk fall patients are longer completion times for the different tests compared to low-risk fall patients. Specifically, in line with results presented in [11, 12], the introduction of manual and cognitive tasks should affect high-risk fall patients more significantly.

Comparing different indicators, such as those qualifying walking (step height, length, and speed), can also highlight a patient's difficulty with a given test condition [27].

Capturing visual attention indicators (such as obstacles, performing manual tasks, or cognitive tasks with paintings) could evaluate the patient's perception and ability to target and gather information in the environment while performing one or more tasks. These indicators can be compared to the indicators qualifying task completion (such as the angle of the cup in manual tasks or the margin of overcoming obstacles, etc.) to possibly detect a motor or attentional failure.

A questionnaire on the fear of falling allows a self-evaluation by the patient of his or her confidence in his or her abilities, allowing to add a psychological dimension to the collected indicators.

5. Conclusion

We propose a virtual reality tool to assess the patient's abilities through a series of immersive, interactive, and playful tests, as part of a multi-factor analysis of their fall risk. The different test conditions allow a contextualized evaluation of the patient's motor, attentional, and cognitive abilities in an environment and situations of everyday life. The exploitation of indicators by supervised learning algorithms and their interpretations will allow adapted physical activity professionals to propose exercises that take into account the specific needs of patients.

The tool is user-friendly and compatible with consumer virtual reality systems, making it suitable for use in a clinical setting.

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