Movin(g) Reality: Rehabilitation after a CVA with Augmented Reality

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ABSTRACT

Many Cerebral Vascular Accident (CVA) patients suffer from gait and balance problems, which have a large impact on daily functioning. During clinical rehabilitation, a multidisciplinary team uses advanced training facilities to help patients regain optimal function. After discharge, however, CVA patients have difficulty to continue training to improve or even maintain their perceived functioning level. One of the limitations of at home training is that patients do not receive any feedback on their performance and progress. Feedback on the execution is important in CVA patients because sensorimotor feedback is disturbed. Moreover, feedback on the progress of their functioning level keeps the patients motivated. Within our project “Movin(g) Reality” we are developing two patterns: TRAIN@HOME, and TRAIN2Go in addition to the already existing pattern TRAIN@THECLINIC.

CCS CONCEPTS

• **Human-centered computing** → *Interaction design theory, concepts and paradigms.*

KEYWORDS

Augmented Reality, Wearable sensors, Inertial Measurement Units, Cerebral, Vascular Accident, Gait Rehabilitation, Human-machine interaction

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1 INTRODUCTION

Training is very important for optimal rehabilitation after a Cerebral Vascular Accident (CVA) [9]. A CVA is a condition where poor blood flow to the brain results in cell death, which leads to loss of motor function in 80% of all CVA survivors [19]. Moreover, 35% of the patients with motor deficits of the lower limb do not fully recover [9]. Impaired gait and balance is a major risk factor for falls and capacity for independent living. Therefore, optimal lower limb function is an important rehabilitation goal for CVA patients. In this paper, we present three patterns in the Movin(g) Reality project: TRAIN@THECLINIC, TRAIN@HOME and TRAIN2Go to motivate the CVA patient to train lower limb function. The TRAIN@THECLINIC pattern is applicable when the patient is at the rehabilitation clinic and includes advanced training facilities that require trained medical staff. The second pattern is Train@Home, which uses an application on the patients smartphone to continue lower limb function training after discharge from the clinic. The third pattern, TRAIN2Go, provides feedback during Activities of Daily Life (ADL) that involve walking. In the remainder of this paper, the background for the patterns will be presented and the patterns itself will be discussed.

2 BACKGROUND

2.1 CVA and gait rehabilitation

According to the World Health Organization (WHO), 15 million people suffer from CVA worldwide each year. CVA is the second cause of death, with 5 million people dying each year [22]. A CVA can be caused by either a blood clot blocking an artery in the brain (an ischaemic stroke) or by an internal bleeding of a burst vessel (a haemorrhagic stroke), which results in poor blood flow to the

brain with cell death as a result. Damage to the motor cortex of the brain can cause hemiplegia with distal weakness causing patients to experience motor deficits. A common impairment is the inability to dorsiflex the foot (Figure 1) during the swing phase of the gait cycle (Figure 2). The amount of dorsiflexion can be expressed as reduction of the angle($^{\circ}$) between foot and tibia. The inability to actively dorsiflex the ankle is referred to as a “drop foot”. It often results in limited functional mobility, excessive hip and knee flexion, slowed gait velocity, asymmetrical gait pattern due to compensatory muscle activation, and increased risk of falling [2, 16].

Figure 1: Dorsiflexion of the foot by movement in the ankle joint, expressed in the angle($^{\circ}$) between foot and tibia.

Rehabilitation therapy starts as soon as possible after hospitalization or admission to a rehabilitation clinic. The most important objective for gait rehabilitation is independent walking with or without a walking aid. To monitor gait rehabilitation after CVA, spatiotemporal gait parameters such as step duration and stride length are often used and relatively easily obtained [3, 12]. Variability and asymmetry in these parameters can indicate the ability of a user to adapt their gait to environmental circumstances such as obstacle avoidance. Many of the altered spatiotemporal parameters and asymmetry between the legs is caused by the inability to dorsiflex the foot. Therefore, measuring the amount of dorsiflexion and providing feedback about dorsiflexion can help a CVA patient to improve their walking capacity. Feedback should be provided continuously in a way that patients can either see, hear or feel the feedback, while also being able to understand and process the provided feedback. It is important to note that many CVA patients also experience other symptoms such as reduced sensory function, neglect (visual input is neglected or distorted), and reduced cognitive function in addition to their affected motor function [14].

After discharge from the clinic, therapy continues at home with frequent visits to paramedics. However, 20% of the CVA patients experience a decline in functionality when they are discharged from the clinic [17]. An important cause of this decline is that they do not perform the exercises on a regular basis. Although there are many reasons for patients to not adhere to their exercises, main reasons are the loss of motivation, concern, loss of interest, and emotional response or reduced propulsion [21].

Figure 2: Phases in a gait cycle [7]

2.2 Inertial Measurement Unit (IMU) and gait cycle evaluation

Important for the patterns TRAIN@HOME and TRAIN2Go is that movements of body parts and gait cycle events can be obtained outside the laboratory environment. Inertial Measurement Units (IMUs) have been widely used for assessing gait parameters. Current IMUs measure the linear accelerations (m/s^2), angular velocities ($^{\circ}/s$), and the earth magnetic field in three axis. By combining this information, the orientation of an IMU can be calculated. By attaching an IMU to a body segment, the orientation and movement of this body segment can be measured. Attaching an IMU to the foot enables to estimate the amount of dorsiflexion (see Figure 1). Moreover, the angular velocity can be used to indicate the various phases in the gait cycle [3, 12]. Combining orientation of the foot with the various phases of the gait cycle can be used to give immediate feedback on the amount of dorsiflexion during the swing phase of the gait cycle. The patient can use this information to adjust the dorsiflexion in the next steps. In this case, feedback is provided when the foot is not lifted sufficiently: the system sends a signal indicating that the foot should be lifted more.

2.3 Involved parties

The development of the Movin(g) Reality patterns involve several parties. The most important ones being

- (1) **patients:** as the potential end users of the applications, and
- (2) **healthcare providers:** as they set up a training program that meets the training goals for the patient. They should also be able to interpret the data in order to adjust the training program or provide additional feedback.

Other parties that should be involved in the development of the Movin(g) Reality project: *software developers* and *industrial product designers* for designing the patterns, *researchers* to validate the patterns and evaluate their effectiveness, *healthcare institutions* for a smooth transition from rehabilitation clinic to paramedics, and *insurance companies* for costs of the pattern and reduced costs of gained and retained functionality.

2.4 Virtual Reality

In addition to the assessment of the movements of body parts and gait cycle events, patients have to receive feedback of their performance and have to interact with the environment. We have chosen for Virtual Reality (VR). There is more than one type of VR. Generally, VR refers to using computers to generate a new,

interactive environment. The following three types of VR could possibly be applied to train lower leg movements.

- (1) **Immersive Virtual Reality (IVR)** In IVR, the observer is immersed in a virtual world by using a headset that excludes the real world. A user cannot see, hear or feel anything of the real world. Therefore, it is often unsafe for CVA patients to walk around with an virtual immersive headset. In IVR, visual input of the environment is no longer available, which is unsafe for patients who suffer from imbalance or neglect. Moreover, patients, are not used to wear a headset in order to see a virtual world. Headsets have a certain weight that affects the movements of the patients head. This can limit smooth movements from the patient or decrease the velocity of the head movements due to the mass of the headset. Another reason why some headsets might be immersive is the high price.
- (2) **Augmented Reality (AR)** The user can see the real world around him while virtual objects are additionally presented to the real world. AR is already used to improve gait functionality [10]. For the proposed patterns, AR is the most feasible option because of safety and usability.
- (3) **Mixed Reality (MR)** The observer is immersed in a mix of real and virtual objects that interact with each other. Since MR not only adds certain virtual objects to the real world, but also filters visual information about real objects from the real world, MR might cause safety issues.

2.5 Game Design

Several factors are taken into account while designing the training application. First factors are based on regular games to keep users motivated [4, 15], whereas the other factors are more specific for the target population. It is important for effective gait rehabilitation training to keep motivation high in order to keep training intensity and repetition high. The following have to be taken into account:

Objective and specific rules for actions. Predetermine what a user can and cannot do in the game.

Rewards. For example successful interactions.

Rapid feedback cycles. Keep the user focused and allows for quick learning of skills.

Competitive elements. To increase motivation and social interaction.

Location. The required (laboratory) environment and need of certain trained staff.

Meaningful play and feedback. The game should incorporate exercises or ADL that are difficult to achieve in the real world for these patients.

Simplicity. CVA patients often experience reduced cognitive function in addition to their impaired motor function. Therefore, the game must be easy to play. Nevertheless, a minimum level of cognition and motor function is required. The minimum cognitive level for the patient is the ability to use a smartphone, meaning activating an application. The motor function required for the patient is the ability to make a few steps without stand-correcting walking aids. Walkers or walking sticks are allowed, as well as help to attach the IMUs.

Difficulty of challenges. Skills and challenge should find a balance between boredom and anxiety as illustrated in Figure 3 [5]. The continuous balance between more challenges and improved skills is called the *flow channel*. Modifying thresholds to implement the skill level so that the performance is more challenging in several ways. However, the challenges must be realistic in order to prevent frustration and anxiety. Adjustment to skill level should be easily made because the severity of impairment varies between CVA patients and over time.

Social interaction. Social interaction is proven to be a strong motivation for patients to continue training for rehabilitation [1]. Relevant social interactions between people are competition, cooperation, compare performances, and comfort. Although CVA patients suffer from a wide range of impairments, patients could interact at individual levels.

Figure 3: Flow is a channel between Boredom and Anxiety based on a balance between Skills and Challenges [5].

2.6 Hardware

The aim is to use ubiquitous hardware for the patterns that is achievable, affordable, easy to use and commercially available.

Smartphones (iOS, Android) are already in use by most patients. The patients are familiar with their device, and no additional costs need to be made.

Sensors are needed in order to measure the orientation (dorsiflexion) and movement of the foot as well as gait cycle events. The MetaMotionR IMUs from Mbitent Lab are 9DoF sensors, which include the accelerometer, gyroscope and magnetometer sensors [18]. The IMUs can both stream and log data. Streaming real time data is supported by Bluetooth light and limited to a maximum of 120Hz, which should be enough for gait cycle event detection [20]. Costs of these IMUs are less than €90 each.

3 PATTERNS

The pattern definitions we used in this paper originate from the pattern concept by architect Christopher Alexander to design cities and buildings. The patterns TRAIN@HOME (Section 3.2) and TRAIN2Go (Section 3.3) are so called “proto-patterns”. These patterns are not

proven as such in practice but they serve as a concept in a pattern form [13]. The patterns, however, are derived from recurrent observations in practice and re-ordered into new patterns.

3.1 Pattern: TRAIN@THECLINIC

3.1.1 Problem. This pattern is only applicable when the patient is in the clinic for rehabilitation. Since most recovery takes place in the first weeks after a CVA [14], clinical rehabilitation consists of *intensive training* for several hours per day of physiotherapy and occupational therapy amongst other therapies. Another requirement for clinical rehabilitation is the availability of a *team with qualified therapists*. Since patients are among people in similar situations, the *social aspect*, where patients train together and stimulate each other, is also facilitated at the clinic. Last but not least, a requirement that can only be satisfied at the clinic is the availability of *high-end and expensive training devices*. An advantage of these devices is that the performance of the patient can be observed quantitatively. Although change in performance can be “measured” by the trained eye of a therapist, small changes in performance are harder to detect while they could be important.

3.1.2 Forces. The following forces need to be considered:

Location bound. The training device requires certified operators and its use is therefore often restricted to a clinical environment. The patient stays at the clinic or goes to the clinic for training with the devices.

Task specific and intensive. Repetitive task-specific training has been found to achieve improved strength and functional gains [8]. Variety in the exercises must be provided in order to keep patients motivated and the training intensive.

Meaningful feedback. The physiotherapist gives immediate feedback to the patient on the performance and tips for improvement.

Simplicity. Exercises should be easy to understand.

Motivational rewards. Motivational rewards in forms of higher scores or extra challenges when the movements are performed correctly could also be beneficial.

Difficulty and challenges. It must be possible to keep a continuous balance between regained functionality (skills) and new challenges to motivate the patient. Even in the clinic the patient might get upset when exercises are too difficult [5, 6]. Therefore, the therapist should be able to select different training programs and settings to adapt the difficulty of the exercises to the actual functionality level.

Social interaction. Competing on the patient’s own level with other patients might be beneficial, but also playing together to achieve a certain goal might be a good motivation.

Safety. Patients might not have enough stability to stand for a longer time, or the patient might lose his balance when the exercises become more difficult [2]. Safety precautions need to be taken in order to prevent the patient from falling while training exercises on the edge of the patients skill level.

Measurements. Accurate measurements for monitoring and analysis of the performed movements can be very helpful in tracking the progress of the patient and used as a diagnostic tool.

3.1.3 Solution. When at the rehabilitation clinic, the patient has access to advanced training facilities, programs, methods and well

trained (para)medical personnel. Technological training devices are equipped with a safety harness to prevent patients from falling. This allows patients to perform challenging exercises including treadmill perturbations in VR environments while their performance is real-time processed. Hence, patients can be challenged with mechanical, visual and cognitive dual-tasks in a safe, controlled environment [11]. Trained staff is available to operate the systems, therapists can provide feedback, and a large variety of exercises, complexity and visuals to optimize the training program is available.

3.1.4 Consequences. The advanced training facilities are able to simulate challenging situations such as perturbations that are difficult to mimic at home but are important for safe walking outside. The training games offer feedback on performance: higher scores or levels when exercises are performed correctly.

3.1.5 Examples. The Gait Real-time Analysis Interactive Lab (GRAIL) and Computer Assisted Rehabilitation Environment (CAREN) are good examples of advanced training devices. They both include a treadmill with a dual belt, handrails, a large screen in front of the treadmill, and certain games can be played in order to perform exercises. The dual belt can be adapted to the speed the patient is able to walk, but can also simulate tripping by uneven speed for the left and right belt. The treadmill can also move in directions to fit with other real-life situation such as walking uphill or downhill. The large screen is accompanied by speakers to enliven the environment and the games, but can also give audio cues and audio feedback (see Figure 4 for the set up). The patient is wearing markers, which are tracked by 3D motion analysis systems, to detect the movements and behavior of the patient. With this data the patient can control the game, but the data can also be used by therapists and researchers for further analysis. These devices do have a certain entry level; the patient should for example be cognitive sufficient to understand instructions to perform the movements. Moreover, the patient should have a certain level of stability to stand and walk on the GRAIL. The safety harness should only be there to prevent the patient from falling when certain exercises are too difficult, but is not used as a body weight support to assist the patient in standing up. Furthermore, the graphics in the game are realistic to some extent, which can disturb patients who have difficulty in perception.

The TRAIN@THECLINIC pattern is extensively used at rehabilitation centers. It includes advanced training in order to train the patient to a certain level that discharge from the clinic is possible and the patient can return to the home situation in a safe way.

The Technology Readiness Level (TRL)¹ of the TRAIN@THECLINIC pattern is 9. The actual system is “flight proven” through successful mission operations.

3.2 Pattern: TRAIN@HOME

The second pattern is TRAIN@HOME. The pattern is applicable when the patient is discharged from the clinic and has to train at home. The therapists and advanced training devices from the clinic are not available at home.

¹https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

Figure 4: The GRAIL including therapist, patient and operator

3.2.1 Problem. The operation of systems such as the GRAIL is not achievable nor affordable for home use. However, rehabilitation training does not stop when the patient is discharged from the clinic. When doing exercises at home, the patient can feel uncomfortable and unsafe to train because there is no safety harness or therapist available and they have to train in limited space or at a slippery floor. Furthermore, home exercises are often perceived as boring and the amount of exercises to choose from is limited. Moreover, patients do not get real-time feedback on the performed exercises at home. Without assistance, patients easily forget how to execute the exercises correctly. In addition, the status and progress of the patient is unknown to the therapists up to the next visit. Training schedules based on the expected progress might not fit the actual progress of the patient, but cannot be adapted as long as this is unknown. When motivation drops or exercises are not performed in the correct way, regained functionality can drop substantially.

3.2.2 Forces. The following forces need to be taken into account for defining a solution:

Location. The solution can be performed at home and is not bound to a certain (laboratory) environment. It should also be able to use it without assistance of trained staff (GRAIL operators or therapists).

Variety. The solution should be fun to use in order to keep patients motivated to use the solution. This includes for example variety in visuals or levels.

Feedback. The solution should provide the user with real-time feedback on performance.

Simplicity. No extensive training should be needed to operate the solution. See also simplicity as described in Section 2.5.

Difficulty and challenges. It must be possible to keep a continuous balance between regained functionality (skills) and new challenges. The patient should not get bored by too simple exercises but it should also still be safe to do the exercises [5, 6].

Safe to use. No safety hazard should emerge due to use of the solution.

Review results. Therapist should be able to review the accomplished training in order to provide adapted training schedules and monitor the patient.

Available, accessible, acceptable and affordable. The solution must be commercially feasible.

Hardware. The solution should not be dependent on immersive headsets.

3.2.3 Solution. Conditions for this pattern are that patients could train safe at home, get continuous motivational feedback on exercises, and is independent from therapists. The training could include motivational aspects such as competition elements with scores and levels or a developing story in which the patient plays a role.

3.2.4 Consequences. The solution for training at home provides the opportunity for the patient to train at home in a safe way with a certain game aspect in the exercises. Therapist can provide in feedback in addition to the feedback the games offer by assessing the performance of the patient. The therapist can also monitor the patient and adapt certain training goals. Researchers can gain valuable insight in walking patterns and effectiveness of therapy by analyzing the gathered data.

3.2.5 Examples. The TRAIN@HOME pattern is designed for home situations. The TRL is 3 (proof of concept). The pattern includes an AR solution where a virtual ball is presented in a real-world situation. The patient can kick the ball while an application on his phone can measure the movement of the foot and the amount of dorsiflexion. Every time the virtual ball is kicked away, the virtual ball is ready for a new kick. For this solution, the patient is using a smartphone and IMUs to measure and analyze the movements and present the virtual ball. This situation describes the training (Figure 5). The main difference between the TRAIN@HOME and the TRAIN@THECLINIC pattern is that this pattern is specific for a certain exercise and has limited feedback (only the amount of dorsiflexion). Another important feature is the use of AR instead of VR. The patient is aware of the real-world and only a virtual ball is added. Although the monitoring is less verbose than in the clinic, it provides a good insight in training frequency, duration, and performance. A proof-of-concept has been shown. This AR application allows the users to kick a virtual ball on a smartphone by use of a previously described IMU. The performed training sessions

provide feedback on performance to both the patient and therapist. The patient receives feedback in a way that the virtual ball is either kicked or stays at the same place, depending on the performance of the kicking motion. The therapist receives feedback from the IMU data. The solution can safely be performed by the patient in a home situation and does not require the walking or space kicking an actual ball would require. Furthermore, the game aspect of the training is expected to increase the motivation of the patient to do the exercises.

Figure 5: Kicking a ball with TRAIN@HOME, including scores and levels.

3.3 Pattern: TRAIN2Go

The TRAIN2Go pattern is applicable when the patient is discharged from the rehabilitation clinic and wishes to apply the training in ADL. The main difference between the TRAIN2Go pattern and the TRAIN@THECLINIC and TRAIN@HOME patterns is that feedback continues in daily life activities and is not limited to a training session.

3.3.1 Problem. Patients do exercise for retaining and gaining functionality, but the transition from gained abilities in a training environment to ADL is not always self-evident. Feedback is key to improve performance but is only given in training sessions, while full attention is given to the performance of certain exercises. There are many situations in the ADL that require good performance of functional abilities, but also require attention to other aspects. For instance, when crossing the street or buying groceries, one also needs to focus on other things such as traffic lights and other people. Providing feedback in these ADL might increase the transition from gained functionality in training sessions to increased functionality in daily life.

3.3.2 Forces. The following forces should be taken into consideration:

Location. In order to provide feedback in ADL, the solution must be location independent and portable.

Variety. No variety is needed in sense of game visuals and levels as in the previous patterns, but the solution must be able to provide feedback in different situations and activities.

Feedback. Feedback on ADL might be very meaningful but the solution should be able to work continuously for a longer period of time. The *type of feedback* can be visual, auditory, or haptic.

For ADL, visual AR is expected to be too immersive to perform these activities, while due to reduced sensory perception in CVA patients, haptic feedback cannot be provided on the affected body part(s). On the other hand, providing haptic feedback on another body part than the body part that should perform differently, might cause confusion as well. Therefore, it is expected that the solution should use an audio cue. It is also important that the feedback is not intrusive to others since it can cause a feeling of shame in the patient that negatively influences the performance. Furthermore, *optimal timing* for providing feedback within the gait-cycle is of importance for the ability to either correct the ongoing step or the next step (Figure 2).

Simplicity. The solution should be easy and fast to set up and the feedback should be easy to understand. Furthermore, after use of the solution the data should be easily stored and send to the therapist so monitoring of transition of the gained functionalities from the training environment to the ADL is possible.

Motivational rewards. It would be beneficial if patients can receive motivational rewards during these activities as well. For example by providing the percentage of correctly executed steps while doing a certain activity.

Difficulty and challenges. The ADL in itself are of various difficulty to a patient. By monitoring the performance of the patient by a therapist, the therapist could set certain goals within ADL for the patient. This way, the challenge and skill balance for ADL can be influenced on several parameters.

Available, accessible, affordable and achievable. As well as the TRAIN@HOME pattern, this solution should also be available, accessible, affordable, and achievable [23].

3.3.3 Solution. The solution for this pattern requires a different approach. Instead of contextual feedback as in training sessions, the feedback should be very short and clear. Audio feedback would be preferred over haptic feedback, since CVA patients often also suffer from sensory deficits. IMUs can be used to measure the orientation of the foot in this solution as well, since they are not bound to a certain environment and easy to attach to a shoe. The solution could still be started from the patients own smartphone.

3.3.4 Consequences. Providing feedback on performance, in this case the amount of dorsiflexion, while the patient is performing ADL, should increase the transition of gained functions in the training environment to the ADL. This does however, require to take the environment of the patient more into account compared to the TRAIN@THECLINIC and TRAIN@HOME patterns. The solution also provides therapists and researchers insight in effectiveness of therapy and actual transference of the gained functions in training sessions to ADL.

3.3.5 Examples. The TRAIN2Go pattern is used in ADL at the TRL is 3 at the moment. A proof-of-concept is available and has been tested (see Figure 6). Within the TRAIN2Go pattern, the patient can select a difficulty level based on the amount of ankle dorsiflexion he wishes to achieve. While the patient is walking, the TRAIN2Go pattern uses audio feedback that is minimally intrusive for others. The system is providing a simple *beep* from the users' smartphone if the ankle dorsiflexion is not sufficient within three consecutive gait cycles.

Figure 6: Continuous feedback with TRAIN2Go during daily activities such as walking.

4 OUTLOOK

For TRAIN@HOME and TRAIN2Go patterns, it is important that the processing speed is fast enough in order to provide feedback in real-time. Processing speed is highly dependent on the hardware that is used to run the applications. Since the proposed solutions use the patient's own smartphone, the minimum required processor speed to run the applications should be available on the average smartphone of a CVA patient.

For the future, the type of hardware to provide feedback with visual AR should be further investigated for the TRAIN@HOME pattern. At the moment, the TRAIN@HOME pattern requires a processing power that is not available in the average smartphone. As consequence, movements of the real-world or augmented objects are disturbed or are very artificial without many details. Also, the patient needs to hold the smartphone in the hand limiting the ability to hold for example a walker.

Within the TRAIN2Go application it is important to further investigate the *type of feedback* that should be given. The type of feedback can be visual, auditory, or haptic. Although audio feedback seems to be the most appropriate type of feedback for this pattern, the preferred and most effective type of feedback has not yet been studied. Furthermore, *optimal timing* for providing feedback within the gait-cycle should be studied. The option of *feed forward* should also be explored, since this could prevent the patient from executing a step with a drop foot, instead of providing feedback that he just did perform a step with a drop foot. Finally, the actual effect of feedback on the gait pattern should be studied.

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