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A Serious Game for Upper Limb Stroke Rehabilitation Using Biofeedback and Mirror-Neurons Based Training

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Abstract

Upper limb stroke rehabilitation requires early, intensive and repetitive practice to be effective. Consequently, it is often difficult to keep patients committed to their rehabilitation regimen. In addition to direct measures of rehabilitation achievable through targeted assessments, other factors can indirectly lead to rehabilitation. Current levels of integration between commodity graphics software, hardware, and body-tracking devices have provided a reliable tool to build what are referred to as serious games, focusing on the rehabilitation paradigm. More specifically, serious games can captivate and engage players for a specific purpose such as developing new knowledge or skills. This paper discusses a serious game application with a focus on upper limb rehabilitation in patients with hemiplegia or hemiparesis. The game makes use of biofeedback and mirror-neurons to enhance the patient's engagement. Results from the application of a quantitative self-report instrument to assess in-game engagement suggest that the serious game is a viable instructional approach rather than an entertaining novelty and, furthermore, demonstrates the future potential for dual action therapy-focused games.

Keywords:

Computer Games; Patient Engagement; Rehabilitation; Stroke.

Introduction

Cerebrovascular diseases have a great impact on an individual's health. These diseases are one of the leading cause of hospitalizations, mortality and disability in the world population, surpassing heart disease and cancer, the two leading causes of death in industrialized countries. A stroke is defined as a sudden neurological impairment due to vascular injury, including lesions caused by hemodynamic disturbances. The severity of the condition and the functional impairment varies according to the affected area and to the vascular structures, and may cause cognitive, sensory and or functional deficit.

The advancement of technology has allowed the development of procedures enabling exploration of brain activity during rehabilitation therapies, where brain activity is a vital factor in motor rehabilitation. Recently, in order to determine the most effective and efficient techniques, a branch of study has focused on trying different methodologies relating biofeedback and mirror-neurons.

The treatment of neuromuscular disorders including hemiplegia and hemiparesis requires training of the remaining functional capacity. Thus, the motor training is based primarily on a rehabilitation process, in which the feedback is an essential component. Biofeedback goals in rehabilitation include the optimization of muscle contraction and elimination of mass movements and synkinesis. Therefore, patients can improve the symmetry and synchronization between the affected side and the healthy one, seeking functionality and spontaneity of movement. Mirror neurons are activated both when performing an action and during the observation of the same action performed by another person. As they seem to integrate observation and action, mirror neurons have been the focus of studies on how humans understand others and to what extent they are able to share experiences. Such integration includes an internal representation involving the same neural structures related in the execution of the observed action. It also has been considered as a key for rehabilitation purposes.

A Natural User Interface (NUI) represents a current concept that deals with the interaction between human beings and electronic devices. Through the identification of gestures, voice commands, expressions, body movements or detection of human body parts such as face, hand or joints, new games have been built, incorporating this technology.

The entertainment factor aside, serious games are designed to solve problems in several areas. Considering the health application, one can highlight the important contribution of these games to physical therapy and the rehabilitation of patients with motor disabilities secondary to neurological diseases. These patients require physical therapy programs appropriate to their problems in order to improve their quality of life, as much as possible. However, traditional physiotherapy is often boring and repetitive and can discourage patients, causing them to abandon their rehabilitation programs before they have finished.

This paper presents a serious game application for upper limb stroke rehabilitation based on biofeedback and mirror-neurons-based training, focusing on patients with mild or moderate stroke incapacity. The game helps the therapist by assessing the quality and efficiency of the patient's treatment. The patient participates by playing a game that uses quantitative measures to assess in-game engagement while incorporating existing interfaces for human-computer interaction.

The paper sections are laid out in the following order: Related Work, Hemiplegia and Rehabilitation, Game Framework and Design Elements, In-Game Engagement Assessment, Results, Discussion, and Conclusions and Further Work. The Related Work section displays some relevant information on the approaches and technologies concerning the rehabilitation process and the application of serious games within the field of rehabilitation. The section titled Hemiplegia and Rehabilitation briefly illustrates the causes, symptoms, and treatment of hemiplegia. The Game Framework and Design Elements section discusses the necessary components for serious game development, primarily focusing on rehabilitation. The following section reports initial upper extremity assessment based on a valid control group of physical therapists. The Results, Discussion, and Conclusion and Further Work sections present a general discussion on game design, engagement, and use in upper limb rehabilitation, including therapist perspectives.

Related Work

Current research indicates that in the target audience, visibility and feedback may be considered for the development of serious games for rehabilitation, since they are important human factors [1]. The principles of game design that have particular relevance to rehabilitation are meaningful play and challenge. The former is the relationship between player's interactions and system reaction, while the latter aims at maintaining an optimal difficulty in order to engage the player [2][3]. Some important criteria for the design and evaluation of serious games in the rehabilitation area have been identified as game interaction and interface, number of players, genre, adaptability, performance feedback, game monitoring and portability [4]. It was also observed in [5] that serious games must ensure that patients are correctly performing the exercises as well as provide a motivating atmosphere for therapy, so as to yield maximum impact on the rehabilitation process.

Several technologies are used in serious games for physical therapy and rehabilitation, namely virtual reality and sensor networks. Games for physical therapy with severe injuries in the upper limb are proposed in [6]. The neurogame therapy, used for the rehabilitation of patients with severely compromised movements after stroke, is depicted in [7]. To improve the communication between physical therapists and patients with disabilities, a set of requirements for an authoring tool to enable therapists to create exercise animations for home viewing is presented in [8].

The benefit of almost all of these technologies is that they are inexpensive and can be implemented in any clinical environment. Perhaps their greatest benefit is that they provide real time feedback to the player and if designed effectively, they are more enjoyable than traditional exercises, and may therefore increase adherence.

Hemiplegia and Rehabilitation

Cerebral Vascular Accident

Stroke is the second major cause of death worldwide and is one of the greatest causes of overall disease burden. Each year more than 5.5 million deaths are attributed to cerebral vascular accidents. Despite this, less than one-third of countries take minor measures against it such as mortality reporting [9]. In 2010, 31% of stroke victims were children (aged <20 years old) and adults between 20 and 64 years old, with a higher overall proportion of strokes noted in the elderly [10]. In addition, [16] presents a complete statistical study on stroke by country income which reveals that fatality and incapacity rates are higher in low and middle-income countries. The high death rates among older people (aged > 75) indicates that younger adults suffer most from disability-adjusted life-years (DALYs).

Hemiplegia and Hemiparesis

Hemiplegia is a condition of full or partial paralysis of one side of the body that can occur secondary to a brain tumor, vascular accident, stroke, childhood head trauma, or congenital or perinatal injury. Unilateral impairment of hand and arm function are the most disabling symptoms of hemiplegia. Motor and sensory impairments in people with hemiplegia may compromise movement efficiency [11]. Hemiplegia is similar to hemiparesis, but it is far more serious. Hemiparesis is usually characterized by one side of the body being affected not by paralysis, but a less severe state of weakness.

Serious games are one possible clinical intervention for people living with the effects of stroke. In a serious game, a computer generates an engaging environment in which the patient must perform goal-oriented tasks that they find difficult. In this instance a serious game experience is similar to a regular video game experience, the key difference being the main goal: serious games aim to elicit physical movements. This treatment can be effective as the brain is a resilient organ that produces new neural connections in response to external stimuli and activity to compensate for damage.

Rehabilitation of Individuals with Disabilities

Physical therapy is the leading therapy in the treatment of individuals with disabilities. Therapy goals can include enabling people to reach and maintain optimal physical, sensory, psychological, social, and intellectual levels. Rehabilitation provides disabled people with the necessary tools to achieve independence and self-determination. To achieve these goals, physical therapists may apply various techniques to improve physical and mental capacity of the impaired patient.

In addition to sensory or motor deficit, people with disabilities can develop secondary pathological conditions such as shoulder pain, which affects 34% to 85% of those involved in the treatment. [12]. Rehabilitation and recovery constitutes a great challenge for both the complexity of the functions lost and the high incidence of shoulder pain, resulting in a negative impact on the overall rehabilitation process.

Game Framework and Design Elements

Natural User Interfaces in Physical Therapy

Nowadays, NUI is highly used in rehabilitation, generating research and applications that contribute to patient performance and facilitating the assessment of patient progress. NUI-based physical therapy has a functional, concrete, and challenging context, bringing a direct benefit for both the people with disabilities and the physical therapist through the adaptability of these systems. Advanced technologies are used to produce simulated interactive and multidimensional environments. Visual devices and hardware devices for body tracking are important to immerse patients in a virtual environment and give them the ability to modify the environment based on the rehabilitation goals.

NUI can also be considered more fun and appealing than the traditional set of exercises. The use of new tools, which certainly increases the quality of service they provide, also allow greater coverage without increasing risks. By using a NUI console, patients are encouraged to play games and stay engaged, rather than becoming bored. The console offers a variety of opportunities to work on physical abilities, depending on which game is selected.

Biofeedback and Mirror-Neurons

Various rehabilitation techniques such as biofeedback training to stimulate motor functions, have been studied and introduced in regular therapeutic techniques. Biofeedback techniques allow the patient to have an immediate response to exercise in view of the effects caused by neuronal stimulation, demonstrated with the aid of devices and tests that give a noticeable response externally. Thus, patients can monitor their motor and cognitive improvement, even if not visible at first sight, which reinforces the continued treatment while stimulating other areas of the brain to recognize biofeedback response.

The biomechanical biofeedback involves measuring the movement, posture and control forces produced by the body [13]. Microsoft Kinect may represent a reasonable alternative for obtaining data that is relevant to the analysis due to its ability to map the body's joints of the patient participating in the game. The camera sensor helps physical therapists to examine movement quantitatively, which is beyond the game learning aspects, working as a learning speed-up tool so that the patient can quickly grasp the meaning. Based on these aspects, it is possible to use the Kinect to analyze the optimal position of upper limbs through the joints to make measurements of abduction and adduction as well as extension or flexion.

A small window in the game interface shows relevant information through a biofeedback character in stick figure (i.e. a digital goniometer), whereby patients as well as physical therapists can monitor real time movements. Based on this information, physical therapists can correct possible errors (i.e., movement or postural deviation errors) which can occur during the game. Physical therapists are allowed to monitor hardware and software setup, tailoring the game according to the levels of the treatment. The interface can be programmed to show several variables that may help rehabilitation and recovery.

A unique property of mirror-neurons is the ability to act both during the implementation of the action as well as in the observation of specific actions. This property allows humans to perceive the intentions of others through action observation. Therefore, observation is essential in imitation-based learning and empathy. While working with upper limb stroke rehabilitation, it has been observed that the mirror-neuron system in adults is still plastic and artificial activation of this system can provide the basis for cerebral post-stroke rehabilitation patients. The use of active observation as a form of rehabilitation is an asset in patients with severe paresis, for whom rehabilitation can be difficult [14]. Imitation-based learning requires a complex cognitive function that is constructed step by step, including motor observation. Therapies that activate mirror-neurons may be used along with the treatment, seeking a better post-stroke rehabiliation. The proposed serious game includes video recording of motor activities.

Playability and Usability

There are a number of aspects in the usability of digital games where the factor efficiency and effectiveness should be secondary to the satisfaction factor. Thus, game engagement must be addressed on a different perspective of the working software. The main point is to identify where the challenge must be and keep any other aspect out of this context according to the traditional recommendations of usability working software. Thus, the designer should create challenges that are part of the fun of achieving the goals of the game rather than undermine the patient's experience and effectiveness in tasks that should require some effort.

Serious Game into Play

After analyzing regular exercises with physical therapists in a rehabilitation ward, a decision was made in favor of shoulder abduction, as it was identified as the most common issue across various neurological diseases. Shoulder abduction is important for upper limb functions, as more distal functions depend on a stable shoulder.

Game prototyping is a high quality product development method in which a prototype is built, tested, and then reworked as necessary until an acceptable prototype is achieved. As a preliminary step in the prototype evolution, the target audience was defined. The proposed serious game is intended to be a complementary treatment to people with upper limb impairments after stroke in a mild or moderate condition.

The analysis of existing video games on the commercial market was important to support the concept and the choice for the game engine that integrates seamlessly with the Kinect. Later, it evolved to a concept that was more focused on patient engagement through a concept and argument that would provide an immersive environment necessary for their motivation. The biofeedback integration approach with mirror neurons served as support for the development of the serious game for physical therapy rehabilitation.

The game was implemented using Unity3D game engine and Kinect. Unity3D is a commercial engine, providing the developers with a large range of useful tools and scripts, as well as the underlying graphical tasks for game development. Even though such an engine is commonly used for entertainment games, a systematic move into serious game development has been recently detected. Given its integrated development environment with some set of game reusable components, Unity3D, in close cooperation with Kinect software development kit (SDK), reduces the workload needed to produce the game, allowing developers to concentrate on the higher levels modules of the game.

A screenshot of the serious game for upper limb stroke rehabilitation is shown in Figure 1. Control panels on the left and right side are intended for software setup. The goal of the game is to harvest as many fruits from the tree as possible and put them in the baskets within a certain time period. The winner will be the one who harvests more fruit. The angles shown in the interface are the measures of player abduction. Calculations are made based on the position of the joints. The shoulder angle is measured by the elbow, shoulder and pelvic tilt while the player is measured by the bowl and neck to the ground.

Figure 1 – Screenshot of the serious game for upper-limb stroke rehabilitation

The player collects the fruits by simply moving his/her hands until it touches the object on the screen. A Unity3D hand collider performs the detection so fruit coordinates become hand coordinates. Once the fruit is following the character's hand, the player must bring them to the basket where another collider transfers the coordinates to the fruit basket.

In-Game Biofeedback and Rapid Prototyping

After the game scenarios have been built, a feedback from the control group of therapists is needed as a particular step in the rapid game prototyping approach. The control group watches a therapy session of players and afterwards discusses it. This ensures that the scenarios are well adapted for the therapy and appealing to the audience. After this step, strategies, game design ideas and concerns are evaluated and considered for the next prototype.

The effective user-centered design (UCD) issues on prototyping recommend prevention of implementing the final solution directly. Therefore, the serious game proposed is developed in an iterative manner. After the first prototype, UCD continues in an iterative process of evaluation and redesign. Observations and recommendations on the serious game are made by the control group of therapists while performing typical tasks for the game experience both in the process of doing the exercises and their relevant opinions about the game.

In-Game Engagement Assessment

Recruitment

Participants were instructed to play several rounds of the serious game. During the prototype development based on user-centered design, the game metaphor was chosen because it can be easily used to evaluate selection and reaching performance. Thus, the serious game is mildly challenging, has a player motivating potential, is not gender-specific and can be played by people of all ages. Furthermore, the game is easy to learn and understand.

Forty-eight participants (36 female and 12 male) took part in the in-game engagement assessment. Two participants (1 female and 1 male) had to be excluded due to impaired vision and the not meeting eligibility criteria. The age of participants ranged from 20 to 43 years. Participants had no prior knowledge of the experiment. They were recruited via academic and technical staff from the neuro-rehabilitation ward, including physical therapy undergraduates and graduate students, physical therapists and lecturers from the physical therapy department. Participants in the control group were required to have normal or corrected to normal vision as well as no physical impairment, to be eligible.

Preliminary Procedures and System Setup

Experiments were conducted on weekdays from 10 AM until 6 PM. The average time for an experimental session was 20 minutes, including setup and cleanup. Upon arrival, participants were informed about the nature of the experiment, which was the usability evaluation rather than a therapeutic application. Participants were also informed of the rehabilitation goals of the game, anonymity and ethical approval and the experimental procedure.

After description of the procedure, each participant signed an image consent release form and an informed consent form. Shoulder, elbow, and wrist joints were tracked and mapped to the avatar in the application scenario for upper limb rehabilitation. Since hemiplegia is characterized by unilateral impairments, the game was developed in such a way that the player could use both sides of the body.

Participants were led to the center of the room for the setup and sensor calibration. After this step, participants played the game levels in accordance with the goals set by the physical therapist. Each game session was set to 15 min, but participants could finish early. After the experiment, participants filled out a digital short-form version of the Game Experience Questionnaire (GEQ) to assess in-game engagement. Participants did not receive any kind of reward for their valuable participation in the evaluation experiment.

Measuring Serious Game Experience

A short version of GEQ was used to assess in-game assessment. The questionnaire has been validated as an effective tool both for commercial and non-commercial games. In this paper, only the first fourteen items were considered as a general metric to evaluate game experience. The findings cannot be considered to evaluate technical details in the user-centered development process.

The questionnaire links several game-related measures and implemented focusing on group research, consisting of seven dimensions: sensory and imaginative immersion, flow, competence, tension, challenge, positive and negative affect. Each dimension was measured by two questionnaire items on a Likert scale (0: no agreement with the statement to 4: complete agreement with the statement). The questionnaire[1] was clinician-administered upon participants' completion of the experiment.

Results

Results obtained from GEQ categories are represented in Figure 2. Our serious game prototype for upper limb stroke rehabilitation performed very well, considering the control group of therapists, in the positive affect dimension (M 3.22, SD 0.60). Players had a lot of fun playing the game and felt happy. Significant feelings of competence (M 2.20 SD 0.34) and challenge (M 2.8 SD 0.53) were observed. Participants lost their sense of time quite early in the game, suggesting substantial flow (M 2.98 SD 0.62).

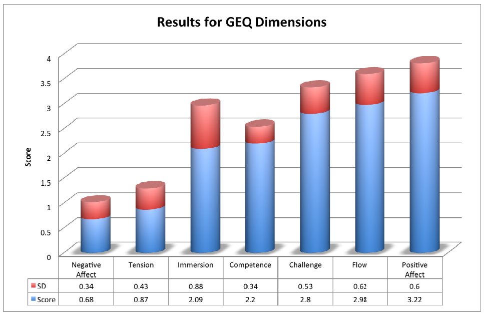

Figure 2 – Results of In-Game Engagement Assessment

The game performed reasonably well in the immersion dimension (M 2.09 SD 0.88). Almost all participants were visually delighted by the interface prototype (3.2) and were moderately impressed (2.04). The majority of players found that the game was neither tiresome nor boring (M 0.68 SD 0.34), suggesting that the prototype performed well in the negative affect dimension. A small amount of tension was observed (M 0.87 SD 0.43).

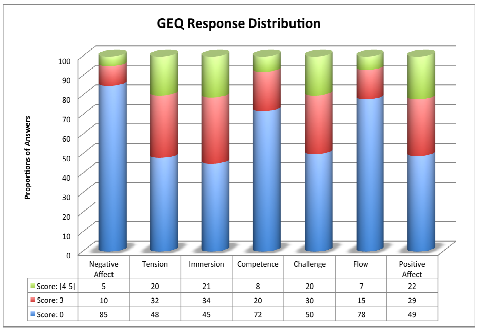

Figure 3 – GEQ Response Distribution

[1] The Game Experience Questionnaire captures game experience and playing experience based on a number of items. See more in http://www.allaboutux.org/game-experience-questionnaire-geq

Figure 3 presents the GEQ response distribution. T-tests were conducted to determine which response distributions differed significantly from the no agreement with the statement (score 0). A significant number of responses were either rather or exceptionally positive for items ($p < 0.05$) for dimensions competence $t_{14} = 2.92$, tension $t_{14} = 2.84$, positive affect $t_{14}= 2.41$, and sensory and imaginative immersion $t_{14}= 2.23$. Participants scored 0 exhaustively for negative affect, flow, and challenge dimensions.

Discussion

Results achieved during the in-game assessment suggest that the serious game prototype performed quite well in terms of usability and game experience. The serious game for upper limb stroke rehabilitation is rather new in the neurorehabilitation ward of the HUSM. Nevertheless, results gathered from the in-game assessment can be used as a standing point for new prototypes derived from the same game metaphor. Limitations include use of the short version of the GEQ scoring system and the need of functional evaluation using Capabilities of Upper Extremities Questionnaire (CUE-Q)[15].

Conclusion and Further Work

The main contribution of this work was the development of a serious game for upper limb stroke rehabilitation based on NUI, which allows the achievement of customized physical therapy sessions in real time. Measurements taken by the therapist allow the exercises to be kept within the limits of each individual, acting as an interface to the choice of how much and how long each movement should be performed based on competition and the entertainment stimuli provided by the game.

Besides assisting in the treatment of post-stroke rehabilitation, the serious game allows patients to enjoy the game and encourage movements that are generally repetitive. This extra motivation accelerates recovery and can be achieved by biofeedback and mirror-neurons through natural user interfaces. Results obtained during the in-game assessment were relevant to the evaluation of the prototype.

As future work, the interface may be enhanced using animation techniques to achieve a more engaging experience. A psychological and functional evaluation is planned in the near future to support therapist decisions over the course of treatment.

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