Algorithms Based on Computational Intelligence for Autonomous Physical Rehabilitation at Home

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Abstract. Exergames provide efficient and motivating training mechanisms to support physical rehabilitation at home. Nonetheless, current exergame examples lack some important aspects which cannot be disregarded in rehabilitation. Exergames should: (i) modify the game difficulty adapting to patient's gameplay performance, (ii) monitor if the exercise is correctly executed, and (iii) provide continuous motivation. In this study, we present a game engine which implements computer intelligence-based solutions to provide real-time adaptation, on-line monitoring and an engaging gameplay experience. The game engine applies real-time adaptation using the Quest Bayesian approach to modify the game difficulty according to the patient's performance. Besides, it employs a fuzzy system to monitor the execution of the exercises according to the parameters set by the therapists and provides on-line feedback to guide the patient during the execution of the exercise. Finally, a motivating game experience is provided using rewards and adding random enrichments during the game.

Keywords: Rehabilitation, Bayesian optimization, Gamification, Exergames, Fuzzy systems.

1 Introduction

Stroke is the leading cause of death in adults [1] and physical rehabilitation is needed to recover from its consequences [2]. With stroke figures increasing every year, rehabilitation is bound to have an even bigger impact on the expected costs of healthcare providers. On the other hand, healthcare providers strive to reduce those same costs, reducing personnel, discharging patients as soon as possible and reducing support. Rehabilitation is presently based on intensive exercising with an almost daily schedule that is carried out with a therapist; new solutions that can extend traditional rehabilitation, or even replace it, are needed.

Exergaming represents one promising solution to this problem. Exergames merge the therapeutic effects of exercises to the engaging factors of games. They guide

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patients to autonomously perform the exercises required by the rehabilitation therapists, thus requiring less supervision and opening to the possibility of self-rehabilitation at home, further reducing costs both for the healthcare provider and for the patient on one side, and supporting intensive rehabilitation on the other side. In addition, exergames add a layer of engagement to the traditionally boring repetitive exercising required by rehabilitation session, allowing the patient to exercise longer and have even fun while doing it [3]. Several instances of successful rehabilitation exergames have been reported [4], but there are still many open problems concerning how to properly structure exergames so that the therapeutic validity of the exercises is not sacrificed and no hazard occurs to the patient. For this reason, exergames are presently used mainly inside the rehabilitation centers or with remote supervision by the therapist (tele-rehabilitation).

Recent commercial video games require the player to move in order to play correctly. For instance, WiiFit is a collection of games produced for the Nintendo Wii, a gaming console that requires the player to use her body movements to play, has been successfully used for in-hospital rehabilitation [5]. However, video games such as Wii Fit have been designed with a different scope in mind than professional rehabilitation and they lack many of the needed features that would make such exergames usable without the presence of a therapist. For instance, commercial games usually impose fixed difficulty settings, making them impractical for impaired people; they do not track nor log the player's movements and do not provide any supervision. These practical considerations are of utmost importance if we want exergames to be useful in an at-home setting, and thus further reduce the costs of healthcare.

We propose here, as a solution to these issues, the application of intelligent algorithms inside a game engine to support the features needed for a correct therapy. Such features can be summarized as follows [6]: a) **Scheduling**, as the configuration of an exercises session must be carefully tailored to the patient's current state; b) **Adaptation**, as the same exergames should be played by patients with varying degrees of impairment and still provide a reasonable challenge. c) **On-line monitoring**, as the movements of the patient must be evaluated in real-time to avoid dangerous movements and maladaptation. d) **Assessment**, as the results of the exercises have to be reviewed by the therapist for tuning and evaluation. e) **Motivation**, as the gaming elements of the exergames must be carefully designed to maximize compliance both in the short and in the long term. Specific intelligence-based algorithms can be applied to all these different features, allowing exergames to be safely used at home. We delineate here how computational intelligence can be used to empower exergames, and we focus especially on the solutions we have introduced for adaptation and monitoring. We incorporated the design considerations we have presented into a game engine that we have fully realized and that is currently being tested by patients.

2 Methodology

In this section, our game engine and its computational intelligence based solutions that mainly address adaptation and monitoring, are presented in detail.

2.1 Intelligent Game Engine for Rehabilitation

The Intelligent Game Engine (IGER) [7] has been developed as part of Rewire platform1. The main objective of Rewire is to develop a low-cost game-based platform that assists patients, discharged from the hospital, to pursue their rehabilitation autonomously at home under remote supervision of the clinicians. The Rewire platform is constituted of three main components: a patient station (PS), a hospital station (HS), and a networking station (NS). The HS allows therapists to monitor remotely the ongoing rehabilitation at patient's home. It also provides features for the therapists to schedule rehabilitation exergames and assess the rehabilitation outcomes. The NS provides advanced data mining tools that analyze common features of rehabilitation treatment among hospitals and regions. The PS is installed at the patient's home and it is the core of the Rewire platform. It guides the patient through exercises prescribed by the HS by games.

The PS has four main modules. The hospital module is used by patients to interact with the therapists at the hospital through audio/video communication and to download their scheduled exergames. The lifestyle module collects data on the patient's daily activity through a body sensor network. The community module allows patients to interact with other patients online. Finally, the IGER module guides the actual rehabilitation using 3D exergames. IGER's structure (Figure 1) and its computational intelligence based features are the focus of the present work.

IGER has at its core a typical game engine, i.e. a software architecture designed to support video games. We have used Panda3D here, but any other game engine (e.g. Unity 3D) can be used. The Game engine has been expanded through scripting language to support a set of features tailored to rehabilitation, and especially post-stroke physical rehabilitation for balance and posture.

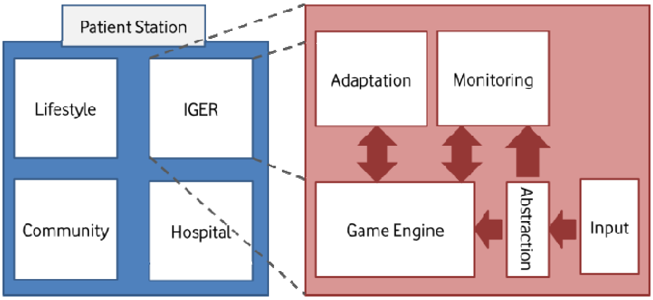


Fig. 1. The components of the PS and the IGER module

The IGER module embodies two components: the game engine and the game control unit. The former provides all the gaming functionalities: input data, animation, collision detection, rendering, scoring and game logic. The latter contains the game control unit that provides the features needed for rehabilitation-oriented exergames. IGER presents modules for therapist-driven scheduling and assessment.

[1] REWIRE project: `http://www.rewire-project.eu`

The exercises associated to each rehabilitation session are configured off-line at the hospital by the therapists and their parameters are configured for each patient. The therapists can select which exercises and consequently which games to include in each training session, the duration of each exercise, the number of repetitions, and the difficulty level. In addition, the therapists can also select the most suitable input device for each rehabilitation task. Finally, the therapist can access the detailed outcome of the rehabilitation session and assess the patient's performance and status.

2.2 Adaptation

In video-games field, the widely accepted flow theory [8] defines flow as a state of heightened focus during which he/she is completely immersed in the activity, time flies by, and external inputs are ignored; a person can enter the state of flow while performing an activity, on the condition that the difficulty of the activity matches the person's skills. This state is desirable because it is engaging, and many games strive to provide it by changing their difficulty in real-time, either through their intrinsic design or through specific Dynamic Difficulty Adaptation (DDA) algorithms.

To design a DDA algorithm, one or more parameters can be selected for adaptation, making sure to choose parameters that directly affect the difficulty of the task. A simple method uses heuristics to change dynamically the parameters according to a metric derived from the patient's input, such as the number of correct trials performed during a session of play.

An alternative is to resort to statistical methods to support adaptation. In our system, we perform adaptation through a Bayesian framework, based on the QUEST psychometric method [9], to update one parameter and adapt it to the patient's behavior. The parameter is changes on a trial or epoch basis, analyzing the success rate in the game tasks such that the overall rate approaches a desired score. The optimal parameter value according to the therapist plays the role of a-priori value. This method is based on three assumptions that are all satisfied in our case. First, the function that relates the parameter to the performance in the game must have the same shape under all conditions. This can be obtained by considering an adequate function (in our case, Weibull distribution). Second, the subject's threshold should not vary from trial to trial. Third, individual trials must be statistically independent. The last two assumptions are satisfied, since the adaptation scope is a single session of a game and thus patient's skill improvement can be safely disregarded.

2.3 On-line Monitoring

One of the most important roles of the physical rehabilitation therapist, if not the one of utmost importance, is real-time monitoring of the user's performance and movements. Video-games, in fact, try to challenge the user to move fast and this can become dangerous for patients with limited motion control and capabilities [10]. Monitoring is aimed to avoid mal-adaptation, i.e. it avoids making the patient perform movements that would be detrimental to the therapy while attempting to perform the exercises correctly.

In classical rehabilitation the exercises are performed in presence of the therapist who can correct the posture of the patient when she does not move correctly through verbal feedback or direct intervention. In an autonomous setting, such as at-home rehabilitation, the watching eye of the therapist must be replaced by a suitable software system. In fact, the focus of the exergames alone may be on the games instead of on the exercise (and this is all the more likely if a state of flow is reached), we see that correct and responsive monitoring becomes even more important. In addition, consider that the autonomous and nonintrusive system cannot directly intervene on the patient's movement as a therapist would do, hence why clear visual and audial feedback is needed. Note that correct monitoring cannot be achieved with commercial active games, as they provide feedback based on the game's results but fail to give useful feedback to the patient about her actual movements. This might be one of the causes the leads to a relatively high drop out in the first tests on using exergames for rehabilitation at home. Monitoring can greatly benefit from Computational Intelligence that can provide algorithms suitable to be used to analyze in real-time the movements of the patient and select what feedback to give to the patient as well as its frequency in time.

From a high-level perspective, we can see monitoring as being composed of three parts: the inputs given by the patient (i.e. her movements), the rules that dictate when the movements are correct and what is more important, as chosen by the therapist, and the generated feedback. A fuzzy system [11] has been developed for this purpose (Figure 2).

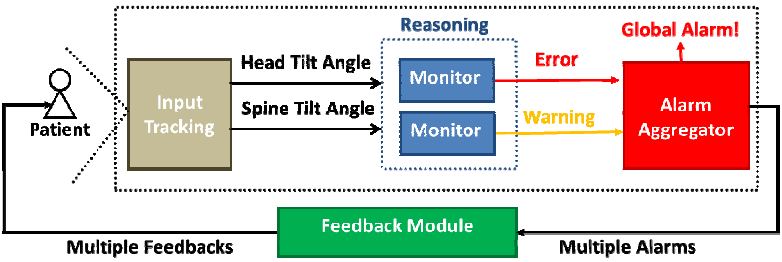


Fig. 2. The scheme of the monitoring mechanism in IGER

The rules on the movements are created by the therapist inside the hospital and incorporate the therapist's knowledge and requirements on the exercises. These rules map the input variables to the alarm level output, according to the monitor configurations; they are translated into fuzzy clauses that are associated with an alarm level. For instance: "If bend laterally_MEDIUM spine, raise alarm_MEDIUM". At run-time the monitoring system receives as input all the motion data and feeds them to a fuzzy inference engine that outputs an alarm level for each chosen monitor. Such alarm level is used by the feedback system to notify the patient of wrong movements. From the different alarm level a single global alarm level is raised through defuzzification. The alarm level is transformed into a color code that is applied to the avatar:

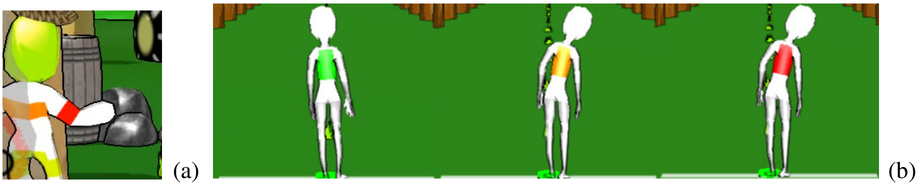


Fig. 3. Color-coded monitoring examples from games (a)Fruit Catcher (b)Animal Hurdler

white means no error and a color progressively going towards red indicates dangerous postures. The patient can therefore see immediately how she is performing (Figure 3). If the patient movement is beyond the maximum allowed range defined by the therapist, the game pauses and a virtual therapist appears and advice the patient on how to perform the exercise correctly. Afterwards, the game resumes.

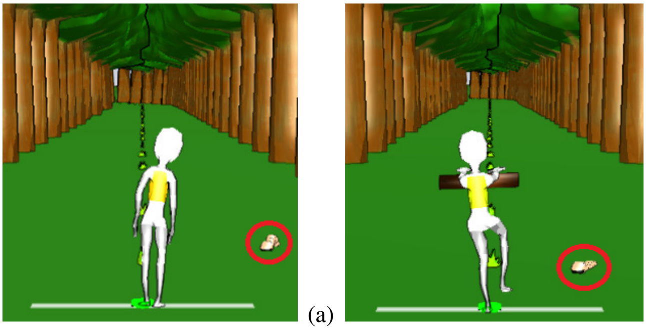
3 Results and Discussion

IGER offers efficient exergames for rehabilitation and provides computer-intelligence solutions to adaptation, monitoring and motivation mechanisms as described in the previous sections. These solutions allow us to tailor rehabilitation to the patient's performance, monitor the correctness of the exercise and motivate the patient by combining good game design principles with an engaging gaming environment. We have designed and implemented a total of 18 exergames that incorporate all these features and that are aimed to posture and balance and neglect rehabilitation. These games have been designed starting from the inputs provided by the therapists.

For instance, the Animal Hurdler exergame (Figure 4a) aims at training patients on balance, while providing an additional cognitive load (dual task). In the gameplay, the patient is guided to raise her leg such that the avatar can step over worms that approach it. To step over the creatures, the patient, alternatively, can move laterally (lateral step). Thus, the game supports several exercises: lateral stepping and leg-rising exercises. Leg rising exercise can be tracked through Kinect device and a balance board can also be used to have a direct and reliable estimate of the center of mass. When lateral stepping exercise is performed, motion is tracked only with the Kinect device.

An additional cognitive load can be added to the game, by asking the patient to keep his arm at ninety degrees, asking him to let her avatar to carry logs with its arms (Figure 4b).

The performance of the patient in each exergame is computed by considering how many worms have been caught in respect to how many have been missed on a set of trials. The adaptable parameter of Animal Hurdler is set as the number of approaching worms per minute. Therefore, when the patient performs well during the exergame, the number of animals is incremented so that the user has to perform the same exercise more times in the same time period. The animal size and the speed of the animal are also adaptable parameters. However, it was considered unsafe to ask the patient to perform higher or faster steps and therefore the height of the foot and the speed of the motion are not controlled or adapted.



(a) (b)

Fig. 4. (a) Animal Hurdler exergame (b) Animal Hurdler exergame with dual task

Monitoring is applied on the avatar's spine and neck, to make sure the patient does not bend them, and on the COP of the patient to make sure she does not move around the playing area. As described in Section 2.3, the therapist sets the optimal range for the monitoring exercises and visual and audial feedback is given to the patient depending on the alarm severity.

Another game example is Fruit Catcher (Figure 5), which is designed for weight-shift and lateral steps exercises. In Fruit Catcher, the player must catch fruits falling from the top of a tree. The player, represented in third view by an avatar, stands below the tree with a basket on her head and can either shift her body to the left and to the right, while keeping the feet still on the ground, or move the body laterally to catch the fruits in the basket; depending on the requisite of the exercise.

Fig. 5. Fruit Catcher exergame

The game can be played with different devices for different exercise goals, with a balance board (weight shift) or a Kinect (lateral steps). The performance of the patient is measured by the number of fruits caught by the patient with respect to the number of fruits missed. The adaptable parameter of Fruit Catcher is set as the frequency of the falling fruits. Monitoring is applied on the avatar's spine and neck, to make sure the patient does not bend them, and on the COP of the patient to make sure she does not move around the playing area or she does not exceed the defined limits. The bending of the knee can be also monitored, as well as the movement of the arms.

Motivation is yet another factor that must be taken into account for physical rehabilitation, as exercising is hard and can be painful. This has even more importance for autonomous rehabilitation, as in absence of a therapist that orders the execution of the exercises, intrinsic motivation of the patient (who is willing to improve) has to be supported with external motivation provided to the patient with different means.

Exergames possess an intrinsic motivational factor in their gaming nature which strives to make the exercises fun to execute, provided the game that is linked to the exercise is well designed. The game alone, however, comes short to provide motivation to the patient, especially due to the limits on the gameplay imposed by the exercise and due to prolonged exercising periods. As such, additional motivational factors can be added to the experience, such as enrichments and reward systems.

Using IGER, we have developed a set of eleven exergames for balance and posture rehabilitation, six of which have been thoroughly tested for usability with post-stroke patients [7]. IGER has also been used to create nine exergames for neglect rehabilitation, highlighting how the engine is flexible enough to be used for the rehabilitation of different pathologies. Two of the games can be used for both neglect and posture rehabilitation. A pilot test with patients in their own homes has started at the end of April 2014. Preliminary results are quite promising. Full results will be available at the end of 2014.

4 Conclusion

Different types of computer intelligence based solutions are implemented in IGER that offer real-time performance-based adaptation, on-line monitoring and a dynamic motivation mechanism. These features provide an ever-changing gameplay experience tailored to the patient's performance. Besides, during the gameplay, correct execution of the exercises is targeted by monitoring and guiding the patient based on the parameters defined by the therapists. These features can make rehabilitation at home an efficient, personalized, safe and engaging option.

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