Liftacube: A prototype for pervasive rehabilitation in a residential setting

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ABSTRACT
Persons with neurological disorders or spinal cord injuries, such as Cerebrovascular Accident (CVA) or Paraplegia patients, experience significantly reduced physical abilities during their activities of daily living. By frequent and intense physical therapy, these patients can sustain or even enhance their functional performance. However, physical therapy, whether or not it is supported by technology, can currently only be followed in a rehabilitation centre under supervision of a therapist. To provide technology-supported physical therapy for independent use by the patient in the home situation, our current research explores pervasive technologies for rehabilitation systems. In this paper, we describe our pervasive prototype 'Liftacube' for training of upper extremities. An initial evaluation with patients with a neurological disorder or spinal cord injury (CVA and paraplegia patients) and their therapists reveals a great appreciation for this motivating pervasive gaming prototype. Reflections on the technical set-up (such as size, form factor, and materials) and interaction preferences (such as feedback, games, and movements for interaction) for pervasive rehabilitation systems in a residential environment are elaborated upon.

Categories and Subject Descriptors
C.3 [**Special-purpose and application-based systems**]: Real-time and embedded systems; H.5.2 [**Information Interfaces and presentation**]: Pototyping & User-centered Design; J.3 [**Life And Medical Sciences**]: Health

General Terms
Design, Experimentation, Human Factors

Keywords
Motor training, neurorehabilitation, physical therapy, pervasive healthcare, residential environment, upper extremity

1. INTRODUCTION
Technology-supported physical therapies for neurological disorders are gradually finding their way in rehabilitation centres. It has been shown that patients benefit greatly from a personalized and intensive physical training [5, 6], which can be intensified using these technology-supported approaches. However, most current rehabilitation systems deal with lower limb rehabilitation, and are only available in rehabilitation centres due to the cost of the devices. As the upper limbs are used in different movements in many activities, upper limb dysfunctions which are common for neurological disorders, have a significant negative influence on the patient's functional and physical abilities in their social life and activities of daily living. Therefore, our research has a focus on upper limb rehabilitation, preferably using affordable technology to bring the training to the patient's home. Neurological disorders and spinal cord injuries strongly influence the patient's functional and physical abilities in a negative way. An example of common neurological disorder is a Cerebrovascular Accident (CVA) or stroke. Depending on the part of the brain affected by the stroke, the patient is left with specific deficits which affect the movements of upper and lower limbs, visual processing, muscle strength and several cognitive abilities. Paraplegia is a common spinal cord injury, due to which the patient can suffer from deficits in the lower limbs and upper limbs (loss of feeling, loss of muscle strength, limited range of motion or even complete paralysis). Besides CVA and paraplegia, there are several other neurological disorders (e.g. Multiple Sclerosis, trauma injuries, Cerebral Palsy) which cause dysfunctions in the upper limbs of the patient.

Performing training exercises (physical therapy) on different types of upper limb movements (e.g. lifting, reaching, transporting or rotations of the arm) in the first months of the disorder or injury is a key success factor of neurorehabilitation. As daily training at a high intensity is recommended, it would be beneficial for patients to train in their home environment. To be able to train in a residential environment without supervision of a therapist, patients would need a supportive training system which can provide them a personalized and independent training. Using low-cost pervasive technologies in rehabilitation systems, the price and complexity of the training systems could be lowered making these training systems available for home therapy. There-

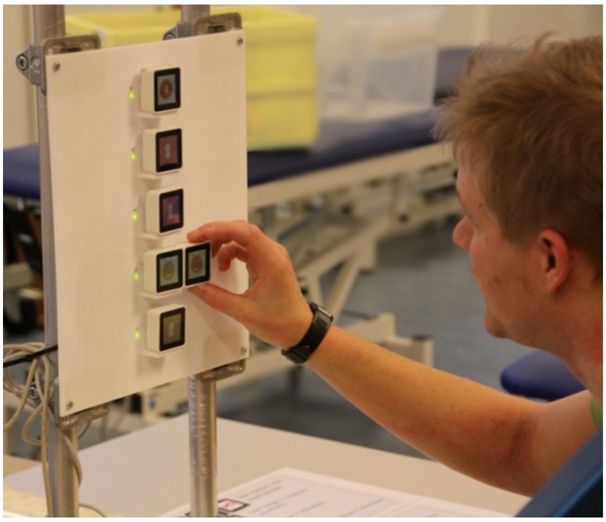


Figure 1: CVA patient playing with the Liftacube prototype

Figure 2: Liftacube rehabilitation game in action

fore, we realized and evaluated a prototype of a pervasive training system focusing on one particular arm movement, namely lifting.

In this paper, we report on our research contribution being a pervasive prototype 'Liftacube' for training of upper extremities, as well as its initial evaluation. Reflections for future pervasive rehabilitation systems in a residential context are formulated. Next to the general overview (section 2) of our prototype 'Liftacube' (figure 1), we illustrate our technical set-up using sensors and a pervasive technology (section 2.3) for training patients on the skill component of lifting an object (section 2.1). To motivate patients to perform the lifting movement at the needed intense pace, Liftacube consists of a simple game (section 2.2) to motivate patients to keep on training. Furthermore, we describe the evaluation (section 3) of our prototype (system set-up and preferences) with patients and their therapists. To conclude this paper, we discuss our prototype and formulate reflections for pervasive rehabilitation systems for home therapy (section 4).

2. LIFTACUBE - EXPLORING PERVASIVE REHABILITATION SYSTEMS

The Liftacube prototype offers a training game for upper limb lifting and stabilizing an object on a predefined height, intended for patients with a neurological disorder or spinal cord injury. A custom-made sensor board is used in combination with commercially available 'Sifteo cubes'. These Sifteo cubes provide a simple and accessible pervasive technology and function as physical objects to be lifted by the patient according to the game rules. In this section we elaborate on the Liftacube concept, whereas the next section describes the initial evaluation done with patients and therapists to explore possible system properties and preferences for pervasive technologies in rehabilitation systems for physical therapy in a residential environment.

2.1 Training on skill components - lifting and stabilizing an object

Rehabilitation for upper extremities focus on regaining or sustaining the functional abilities necessary to perform activities of daily living (e.g. eating a meal, drinking, washing the body, combing the hair, cleaning). These abilities are often limited or lost by the neurological disorder or spinal cord injury. Physical or occupation therapy involves the patient in personalized training exercises with real objects under supervision of a therapist [13]. For a successful rehabilitation, these training exercises focus on repeating a set of specific meaningful movements of the arms or hands (e.g. lifting, transporting, reaching or rotations) at an intense pace. These movements are the basic skill components (activity of daily life skills or ADL skills) in which an activity of daily living can be divided [11]. Usually, the therapy progresses from training separate skill components to training combinations of skill components, depending on how well the patient masters the different skills.

Given this typical therapy flow, Liftacube is situated in the beginning of the therapy session, when patients are focusing on training one movement. Liftacube provides an exercise on lifting and stabilizing an object on a predefined height as separate skill components. It is not a coincidence that lifting was selected as the skill component to be supported by our pervasive technology. Lifting is a skill component which is used in many daily activities (e.g. eating, drinking, washing, cleaning) and therefore essential in a therapy. To lift an object, a tight grip is required to bring an object to a specific height without support of the arm/hand or dropping the object, especially for small or thin objects. Furthermore, after lifting an object, a patient needs to stabilize this object and perform other skill components in order to complete his activity. So mastering lifting and stabilizing is crucial before training other skill components and activities of daily living.

2.2 A motivating rehabilitation game

The sensor board and Sifteo cubes are the technological components used in Liftacube to train the lifting skill component, but it is the gaming concept that offers the training exercises and motivates the patient. This gaming concept, presented figure 2, has been inspired by an activity of daily living in which lifting is one of the key skill components, namely inserting a key in a door lock to unlock it. The game supported by Liftacube (figure 2), derives the patient's mind from the serious training and motivates him or her to complete the required repetitions of the lifting movement. The game consists of four locks, one key and one score each presented on a different Sifteo cube. The key and locks are presented in five colors (green, blue, pink, brown and orange) which are randomly assigned during the game while the score presents the number of points gathered by the training patient.

At the start of the game, the different cubes (four locks and score cube) are attached to the five slots on the sensor board, positioned at different heights as can be seen in figure 3a. Depending on the patients' abilities, the lock cubes can be placed in the lower or the higher slots of the sensor board, making the lifting and stabilization less or more intense. The game starts only after all cubes are attached to the slots of the sensor board. If one of these cubes is detached from the board during the game, the game will automatically pause and show the patient a warning that the detached cube(s) needs to be placed back on the board to continue the game.

The objective of the game is to collect 30 points by opening locks with a correct key or collecting extra points from additional game events. A lock can be opened by matching the freely moveable key cube with a lock cube on the sensor board (figure 2). When a key is matched with a lock, the game will check that the key and lock have the same color, and that the key is placed at the correct side of the lock. For a correct match it is required that the blade of the key points towards the lock. Similar to opening a lock in real life, a patient needs to lift and stabilize the key cube at the level of the lock cube for three seconds before the lock is opened. Of course, this takes over the general idea of opening a lock, not the complete real life actions. As additional motivational factors, we added two game events which can randomly appear on the cubes and can influence the game performance. These game events are only available for six seconds and need to be handled quickly. The first game event is a bonus event represented by a 'star' on the lock cubes. The 'star' event allows patients to collect two points in a single lift movement when completed before the time runs out. The second game event is a 'bomb' event that lowers the score with two points if not given attention within six seconds.

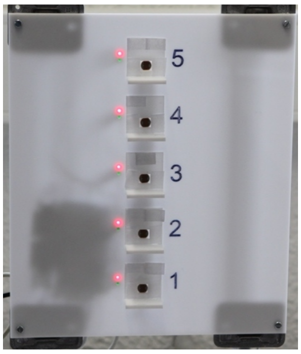
Besides lifting the cubes, four actions on the cubes are used in the game; 'pressing the screen', 'flipping a cube', 'shaking a cube' and 'neighboring two cubes'. First, 'pressing the screen' is used to handle a star event and get additional points as mentioned above. Secondly, 'Neighboring two cubes' is used to match the key cube lifted by the patient, with one of the four lock cubes, which are attached to the different slots on the sensor board. Thirdly, 'Shaking the key cube' is used in two situations; changing the key color or handling a bomb event. As the colors of the locks and key are randomly assigned, it is possible that the key can have a different color than all locks. In that case, the patient can change the color of the key to continue the game by shaking the key cube. In the other case, a bomb can appear on the key cube when changing the key. A patient can handle the bomb event by shaking the cube. Finally, 'flipping a cube' will pause the game when playing or restarting after the game finished.

After each event, feedback informs the patient on the correct handling of game events such as matching or mismatching key and lock, and handling a star or a bomb event. Event-specific audio feedback allows to distinguish between the events like a match, a mismatch, a bomb appearing, a star appearing, good feedback and bad feedback. Audio feedback also announces the appearance of a game event such as a star or bomb. If the key is correctly or wrongly matched, audio and visual feedback (smiling face for a match and a sad face for a mismatch) inform the patient about the correctness of the match. A smiling face for correctly handling the event and a sad face for not handling the event in time is the feedback for game events. After the feedback, the lock or star will be reset automatically to a random lock or new star after three seconds. The bomb or key can be reset to a random key or bomb by lowering and placing the lifting cube on slot 0 of the sensor board, which is a separate board resting on the table (figure 3c).

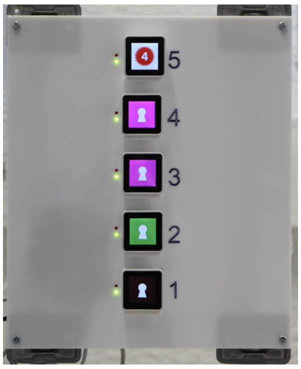
2.3 Pervasive technologies and sensors in the Liftacube prototype

In this section we give a more elaborate description of how we incorporated the Sifteo cubes and the custom-made sensor board in our Liftacube prototype. After a general overview of how the components of the set-up collaborate to realize the lifting game concept, we provide more details on the Sifteo cubes on the one hand and the sensor board on the other hand. The Sifteo cubes provide physical objects to handle in the game focusing on the key skill component. Our custom sensor board is a supportive component, extended with sensors and LEDs, for detecting the height on which the Sifteo cubes are attached. The lifting height is indeed a determining parameter for the quality of the patient's lift movement. A separate board resting on the table with one additional slot is used to detect if a patient lowered his arm after lifting a cube. By combining the sensor board and the Sifteo cubes, Liftacube is able to detect the lifting of the patient's arm as well as fine locomotion interactions of the hands.

The Sifteo cubes provide physical objects to handle in a motivating game Liftacube, focusing on the key skill component lifting, and at the same time they provide fine locomotion interactions for the hands. Sifteo is a commercially available pervasive game technology, which provides a rich gaming experience by actively engaging their players through hands-on interactions. Sifteo cubes originate from a research project 'siftables' [8] of David Merrill and Jeevan Kalanithi of the MIT Media lab and were later commercialized as Sifteo cubes. Sifteo cubes (as far as concerns the version we used in the prototype) connect to and exchange their data with a computer. The computer monitors and controls the cubes and deals with the game logic. Audio is played by the siftrunner manager software, through a wireless communication, on this same computer. Thanks to the wireless communication between the cubes and computer, our rehabilitation game does not need to deal with limited



(a) Adjustable sensor board with empty five slots



(b) Adjustable sensor board with five Sifteo cubes

(c) Slot 0 of the sensor board resting on the table to detect the lowering of the arm after lifting a cube

Figure 3: Technical set-up of the lift sensing board

memory, extra storage for images or audio files, a slow processor or low-level processing of the sensor data. These Sifteo cubes can be classified as tangible objects which embed a large set of electronic components and sensors in a small cubic container (4.5cm x 4.5 cm x 1.8cm). This size and form of the cubes allows us to investigate the required physical properties for pervasive technologies in this kind of movement training, in order to come up with a set-up that patients can manipulate while being confronted with a reasonable challenge during the training. The LCD screen on the cubes allows us to directly present the game's visual components and feedback without having to switch to the computer screen. The visual enhancements together with the direct and tangible interactions make the cubes attractive and engaging for playing the rehabilitation game. As for the interactions, Sifteo cubes are able to detect shaking, flipping, tilting in two directions, pressing the screen and neighbouring with another cube. When mapping the game actions to the interactions of the Sifteo cubes, we decided to leave the tilting event out as this movement is less relevant in the current lifting game concept and also for the training of the targeted skill component as such. As all events of the cubes are very sensitive and precise, Sifteo cubes are a plausible pervasive technology for rehabilitation of upper extremities and for fine locomotion of the hands in a residential environment.

The sensor board (figure 3) is used to detect the height of the sifteo cubes during the game using two boards with embedded light sensors and LEDs. The boards are separated from each other to detect the lifting and lowering of the patient's arm during the game. On five different heights, the sensor board is equipped with a slot with a little shelf below to support the cube being positioned by the user (figure 3). Each slot is extended with a green and red LED, and a light sensor which is used to detect if a cube is placed in the slot. When the light sensor is covered, the green LED lights up to inform the patient that the Sifteo cube was placed correctly in the slot. The red LED will light up when no cube is placed in the slot or when the cube is placed wrongly in the slot. The LEDs and light sensors are connected to an arduino MEGA microcontroller, which reads the light sensor status, transmits changes in the status to the game and sets the LEDs according to the light sensor's status. The first board (figure 3c) contains only one slot for a Sifteo cube (slot 0) and is located resting on the table. This slot is used to detect if the patient lowers his arm after handling the game events or matching a key with a lock. When a patient matches a lock and key or handles a game event, the cubes provide feedback on the performed actions. The lifting cube can only be reset by placing it on the slot 0, which obligates the patients to lower the arm back to the level of the table before continuing the game. slot 0 is not extended with a shelf or Velcro tape because the lifting cube does not need to be attached. Also, the board is resting on the table with the light sensor facing upwards which prevents the cube of falling off the slot.

Our second board (figure 3a) is attached to a steel support construction which gives the board stability and allows to adjust the height of the board to fit the patient's arm limitations. The five slots for the Sifteo cubes are extended with a small Velcro strip and a narrow, small shelf to support the attached cubes during the game. The slots are positioned at different heights and they are vertically aligned. A label with a number from one to five is attached to the slots to identify these at the start of the game, when placing the cubes in the appropriate slot. In summary, the role of this sensor board is to have a collector for the score and lock cubes at different heights. Furthermore, the sensor board supports the detection of the lifting movement by the patient when placing the key cube side-by-side with one of these lock cubes. Obviously correct positioning of the Sifteo cubes in the sensor board allows the patient to gather points.

3. EVALUATION OF LIFTACUBE WITH PATIENTS AND THEIR THERAPISTS

Patient-centric design is a methodological approach for developing rehabilitation systems where patients (and therapists) are the primary target users. The goal of patient-centric design is to adapt the design of the training system to optimally fit the needs of the patients and therapists by involving them in the development of the rehabilitation system. As such, this approach adheres strongly to the user-centered design approach in which possible end-users of a computer system or application are closely involved in the design and development process. Iterative evaluation of prototypes is a crucial aspect of any user-centered methodology. In this section we elaborate on the way we involved patients with a neurological disorder or spinal cord injury and their therapists actively in the design and development process of our Liftacube prototype, as well as the results of the prototype's evaluation.

3.1 Design

While our overall research goal is to investigate the benefit of pervasive technologies in (mainly neurological) rehabilitation systems for a residential environment, our Liftacube prototype explored possibilities and preferences for pervasive interaction styles with patients with a neurological disorder or spinal cord injury and their therapists. All four patients and the four involved therapists participated voluntary. They were asked to play one session with our Liftacube prototype and afterwards they were interviewed about their experience.

3.2 Procedure

The evaluation of Liftacube started by welcoming the patients and their therapists. A short general explanation on the research domain and the prototype was given, followed by an introduction on the game concept and the interaction using Sifteo cubes. A document presenting an overview of the game and interactions was available during the test. By providing an introduction of the game, the patients could directly start playing and focused more on interacting with the prototype than on finding out game rules. Patients evaluated the Liftacube game by completing the lifting exercise which corresponds to gathering 30 points in the game. Therapist were asked to test the game after their patient. After their interaction with the Liftacube game, we interviewed the patients and therapists about their experiences. The inquiry focused on the game concept, the feedback and interactions in the game, the size and form factor of the Sifteo cubes and their vision on pervasive technologies in physical therapy. Finally, the patients and therapists were thanked for their participation.

3.3 Participants

Because Liftacube aims for pervasive rehabilitation for lifting of the arms, eligible patients for Liftacube have difficulties with grasping and lifting an object. Patients should be able to perform the exercise without support of external tools as these are not always available in the patient's home or another residential environment. Four patients with a neurological disorder or spinal cord injury and four therapists participated in our evaluation of Liftacube. Two patients were paraplegia patients (one male and one female) and the other two patients were CVA patients (both male). The paraplegia patients were wheelchair-bounded and had severe dysfunctions in both arms and hands. The CVA patients were severely disabled in one of their arms and the corresponding hand. None of the patients had cognitive dysfunctions therefore all of them should be able to understand and play our rehabilitation game.

Besides the patients, four therapists from Adelante tested and evaluated the Liftacube prototype. One therapist for paraplegia patients (female), one therapist for children with a neurological disorder (female) and one therapist for CVA patients (female) tested the prototype and participated in the interview revealing their thoughts based on their expertise and their point of view on applicability of this kind of therapy for other patients with the same neurological disorder or spinal cord injury. The fourth therapist (male) worked with CVA patients and only observed the prototype during the tests. He explained his vision on pervasive technologies in therapy for CVA patients. All therapists gave additional feedback on future directions for pervasive technologies in physical therapy.

3.4 Results

Overall, the results of the evaluation reveal a great appreciation of all patients and therapists for the pervasive technologies and the game concept present in our Liftacube prototype. Patients' and therapists' insights and feedback elaborate on possible future system properties, user preferences for pervasive technologies and interactions, and gaming concepts in rehabilitation systems in a residential setting.

The off-the-shelf Sifteo cubes are essential in the Liftacube prototype, so their evaluation will strongly influence the overall user appreciation of the prototype. Patients and therapists liked the form factor and size of the cubes even if some critical remarks were given. Several patients had difficulties with grasping and holding the Sifteo cubes, but they liked the challenge and were willing to persist training the lifting skill component during the game. Thinking aloud about possible improvements of this prototype and future game extensions, therapists suggested a ball as being easier for patients to grasp and hold, while a cylinder could be better for training exercises involving rotations. As for the size of the cubes, the therapists (in contrast with the patients) warned that the current size might be too small to be precisely manipulated by most patients. In line with the expectations of the research team, the therapists proposed using physical objects in different sizes as a way to personalize the training.

Our sensor board was found to be very stable and its adjustability was appreciated by all test persons, though clearly the number of possible positions and the available exercises need to be extended to be used effectively in real therapy settings. Several patients were having difficulties with forwards tilting of the free cube to correctly match the lock cube on the sensor board. Tilting the board slightly backwards is likely to solve the patients' problems when attempting to place the key next to the lock cubes.

Besides commenting on the technical set-up of the prototype, patients and therapists also provided feedback on the game concept. In general, the participants found the game very understandable and pleasant to accomplish as complementary training. However, therapists emphasized that a good introduction would be necessary for patients with cognitive dysfunctions. This is not surprising, because also the involved test persons initially had a hard time to decipher the game elements and possible interactions (movements with the cubes). Both the visual and audio feedback during the game were very well received by patients and therapists. Additional feedback about the patient's gaming performance would be welcomed in particular at the end of the game, thus motivating the patients to continue their training. The therapists expressed their appreciation for the 'counting down' feedback that was used to encourage patients during stabilization to perform the exercise correctly. Patients and therapists are already looking forward to additional games and training exercises building on the Liftacube concept to extend it for use in long-term physical therapy.

The Liftacube prototype allows the patients to interact with the Sifteo cubes in different ways, as part of an intense training consisting of repetitive movements. Where possible, the movements to be trained are directly mapped on the interactions to be done with the cubes. Patients liked the fact that they were challenged to grasp harder not to lose the cube while lifting, and to lift higher to reach a certain position on the board. The tests have revealed that shaking the cubes is very difficult for patients. Tilting or flipping a cube was mentioned by different participants as a potential additional skill component for training. All participants liked to change between their good and bad hand/ arm during the game, which is supported by the system and allowed in this particular game concept. Therapists stated that detecting the hand being used would be beneficial for other skill components (e.g. rotation).

When providing their vision and feedback on Liftacube, patients and therapists agreed on most examples. As was expected when considering training needs for specific patients, CVA and paraplegia therapists raised different issues regarding the form factor of the pervasive objects (ball or cylinder grip for CVA patients vs. motor grip for paraplegia patients), the key skill components to be trained (lifting/transportation/reaching/rotation vs. fine motor skills), the complexity of the rehabilitation game (simple and cognitive load restricted vs. cognitive challenging), and usage of audio feedback (continuous classic music vs. short attractive sounds).

4. DISCUSSION

The evaluation of our Liftacube prototype revealed potential future directions for research and development of pervasive rehabilitation systems. Very important is continuing evaluation with a focus on the clinical effect of Liftacube and similar pervasive rehabilitation setups at home. Therefore, future work includes long-term evaluation of the patient's progress, using e.g. kinetic performance data collected by the system. In collaboration with therapists, standard clinical assessment scales (e.g. the Fugl-Meyer, ARAT or Wolf motor test metrics for stroke patients) are used to estimate the patient's progress.

Several technical improvements and functional extensions of the pervasive training prototype are envisioned. Liftacube was designed to train only one skill component, more specific lifting in combination with stabilization of an object at a certain height. The promising results of the initial evaluation are encouraging to design and evaluate additional game concepts for other skill components, in order to strive for a motivating set of games based on pervasive technology. This approach to technology-supported physical therapy will help the patients to continue frequent and repetitive training.

Another possible extension for the technical set-up of the Liftacube system is to extend the number of positions on which the Sifteo cubes can be detected. By extending the board to detect more positions for the Sifteo cubes, the sensor board and Sifteo cubes can be reused for different training exercises combining different skill components without the need for additional technologies or objects. Currently, our system was set up to detect the lifting movement of the patient's arms. When extending the Liftacube concept to train other skill components (e.g. reaching, transporting and rotation of the arms), the set-up of the board needs to be changed by placing the sensor board and slot 0 in a different formation. For example, for transportation exercises, the sensor board could be placed left or right from slot 0, on an acceptable distance depending on the training hand and capabilities of the patient. However, to allow training for more than one skill component, the detectable positions on the sensor board need to be extended.

Related to extending the rehabilitation game, a therapist needs to be able to personalize the training exercises to the capabilities of their patients. When different training exercises and difficulty levels are available in the rehabilitation game, the system needs to provide an interface to program the training by setting the correct training levels, order of the training exercises and preferences for the games. A solution similar to the visual programming environment we used in the therapist interface of I-TRAVLE [9] can be integrated. Based on previous research [10], we target an adaptive system that will be able to automatically adjust the training exercises to capabilities of patient by logging and analyzing the movements of the patient.

On the longer term, integrating the pervasive system with movement measurement system is beneficial for the patient. Especially when the therapist is not around during training, it is of utmost importance to detect movement quality to avoid wrong movements and overtraining. The logged movement data are not only useful in the context of adaptation, but can also be delivered to the (remote) therapist to evaluate the patient's progress and personalize the therapy.

5. RELATED WORK

Liftacube explores the use of pervasive technologies in rehabilitation for the upper limbs. As research on pervasive technologies for physical therapy is only recently upcoming, most related work includes research on haptics, exoskeletons and robotics in rehabilitation therapy for the upper limbs for patients with a neurological disorder or spinal cord injury.

A first category of rehabilitation systems for patients with a neurological disorder are the robotic systems which are very common in neurorehabilitation research. The Armeo Spring tool of Biometrics [4], is an example of an exoskeleton rehabilitation system which helps MS patients to train on performing daily activities. The focus of Armeo is to improve upper limb muscle strength and functional capacity. This exoskeleton is capable of providing physical support (like force feedback and gravity support) to allow a patient to train on difficult or limited tasks with a virtual realistic environment. Results of an effectiveness study showed that patients improved their functional capabilities during an intense training scheme (eight weeks training with three sessions in a week for 30 min) with the Armeo system. However, robotic systems and exoskeleton are expensive, large and complex systems. Therefore, these systems are not available for patients to train in their residential environment. This problem motivated us to explore possibilities for using low-cost pervasive technologies to be used in rehabilitation system, making them available for a residential environment.

An second example of a robotic rehabilitation system which can be used in a residential environment is the Robotic skate arm of Wong, et al. [14]. The robotic arm skate is an exercising device for patients with upper limb dysfunction to assist and train their arms on different skill components on a table top surface. The software of the robotic arm skate provides the patient with some localization training exercises (catching butterflies or fish) and monitors the pose and movements of the patient to adjust the level of the assistance provided by the arm skate. Using the arm skate, patients can train on reaching and transportation movements of their arms. Though the interactive training system contains dedicated exercises for the upper limbs, the set-up is still too complex to be used in a home environment.

A second category of rehabilitation systems are haptic rehabilitation systems. Haptic systems provide force feedback and support for the patients during the training. A haptic-based rehabilitation system focusing on training patients with an neurological disorder (CVA patients) is the Gentle/s system [7] of Loureiro, et al. Gentle/s provides haptic robot, the MOOG HapticMaster, and an custom-made ADL gimbal with overhead frame to support the hand and elbow during the training. Software provides three different virtual training environments for functional skills which are set by the therapist at the start of the training by selecting or creating the appropriate exercises with a personalized exercise path and setting the parameters for the system support. To inform the patients on their performance during the training, Gentle/s implements four types of feedback; visual, audio, haptics and performance cues create Active feedback on the patient's performance. Similar to the Liftacube approach, Gentle/s structures the training exercises and games based on skill components.

The Individualized, Technology-supported and Robot-Assisted Virtual Learning Environments (I-TRAVLE) rehabilitation system [9, 3] supports physical therapy for MS and CVA patients through personalized training exercises on different skill components for the upper limbs. The I-TRAVLE system consists of the MOOG HapticMaster extended with the custom-made ADL gimbal to support mild to severe disabled patients to perform training exercises for the upper limbs on activities of daily life. The software allows to personalize the training exercises in several manners; e.g. setting the parameters for training exercises by the therapist, measuring the active workspace and automatic adaptation of the difficulty level by measuring the performance of the patient [10]. I-TRAVLE provides training exercises on one skill components and motivating rehabilitation games which combine different skill components in one training session [3]. Particular attention has been given to an appropriate 2,5D visualization of the training exercises and games, after a formal experiment regarding the capabilities of the patients [12]. Our former experience in our I-TRAVLE research line provides us with information on the skill components to be trained and the value of serious games for neurorehabilitation. This has been inspiring for the design of Liftacube.

Tangible objects are often used in traditional rehabilitation therapy and research systems. Beursgens, et al. [1] created a table top game with tangible objects for upper limb training and compensation avoidance. Their training exercise focusses on using a fork and knife on a table top with an engaging and attractive game. In their game, a patient uses a fork and knife to move vegetables on the table top around to catch a moving bug. The patient wears a sensing jacket to measure the compensation which he makes during the training. At the beginning of the training, a therapist can set a threshold for the amount of compensation a patient can make during the training. Whenever the patient surpasses this threshold, the sensing jacket will give haptic feedback to inform the patient that he is compensating too much. The use of real-world objects and tangible interaction inspired us to explore the sifteo cubes as pervasive technology in our Liftacube prototype.

Recently, the kinect received more attention in research rehabilitation systems for patients with a neurological disorder or spinal cord injury. An example of such a research rehabilitation system is the kinerehab system of Chang et al. [2]. Kinerehab explored the use of the kinect sensor for physical therapy of young patients with a motor deficit in a school environment. The objective of kinerehab was to determine if a patient is performing their skill components correctly and reaches his rehabilitation goals. The system processed the images of the depth camera to detect the patient's movements and to determine the quality of these movements. To motivate the patient to complete his training exercise, the kinerehab system provided audio and visual feedback on the patient's performance during the training. Kinerehab was evaluated by two young patients with motor deficits during a training of a month. Results of this evaluation revealed great appreciation for the kinerehab system and showed an improvement in the exercise performance and motivation. In our Liftacube prototype, we chose to use motion sensors (e.g. accelerometers) for detecting the lifting movements made by the patient. Video and camera systems and motion sensors both are widely used as low-cost motion input components for computer systems, so we investigate the benefits of both technologies in neurorehabilitation.

6. CONCLUSIONS

In the evaluation of our Liftacube prototype, we gathered initial knowledge on using pervasive technologies in upper extremities rehabilitation for patients with a neurological disorder or spinal cord injury in a residential environment. Our pervasive rehabilitation prototype 'Liftacube' with motivating rehabilitation game uses a pervasive technology and sensors to train patients on the skill component of lifting and stabilizing an object on a specific height (section 2). Our prototype was evaluated by four patients (two CVA and two paraplegia patients) and their therapists in a qualitative study with a short interview on their experiences with our prototype (section 3). Results of our evaluation revealed great appreciation for our prototype Liftacube. Patients stated that they would use our rehabilitation prototype at home if training with Liftacube was proven to help them to perform their activities of daily living more efficiently.

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