

# PhysiCube: providing tangible interaction in a pervasive upper-limb rehabilitation system

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## ABSTRACT

Persons with a neurological disorder are confronted with significantly reduced physical abilities during their daily activities. Physiotherapy, for these patients mainly provided in rehabilitation centres, utilizes tangible, real-world objects in training for the upper limbs. Only by intensely and frequently exercising, patients have a chance to sustain or enhance their functional performance. Our research explores pervasive technologies and tangible objects to provide motivating, technology-supported training systems in a residential environment for independent use by these patients. In this paper, we describe our pervasive training system 'PhysiCube', consisting of prototypes 'LiftACube' and 'ReachACube'. PhysiCube takes advantage of tangible interactions and games to provide motivating physical training for the upper limbs. An evaluation with therapists showed great appreciation for our prototypes. Reflections on the technical setup and use of tangible interaction for these pervasive rehabilitation systems in a residential setting are elaborated upon.

## Author Keywords

Motor training, neurorehabilitation, physical therapy, tangible interaction, pervasive healthcare, upper extremity.

## ACM Classification Keywords

C.3 Special-purpose and application-based systems: Real-time and embedded systems; H.5.2 Information Interfaces and presentation: Prototyping & User-centered Design; J.3 Life And Medical Sciences: Health.

## General Terms

Human Factors; Design; Experimentation.

## INTRODUCTION

Neurorehabilitation is the complex medical process that aids the recovery a person with a neurological disorder and minimizes the functional disabilities. Neurorehabilitation mostly requires patients to train intensively, usually a few times a week. For chronic patients suffering from e.g. MS (Multiple Sclerosis) the rehabilitation is a long term process

that has to be continued at a level of difficulty that is adapted to the patient's changing capabilities over time. For stroke patients, an intense training pace in the first months after the stroke event is necessary, followed by training sessions over a longer period. Typically, the patients we target are adults over forty. Without distinguishing between details for individual neurological disorders, the upper limb training focuses on regaining or sustaining the functional abilities necessary to perform activities of daily living (e.g. eating a full meal, washing their body). Physical or occupation therapy involves the patient in personalized training exercises, some of which involve the manipulation of real objects of daily life, under supervision of a therapist [13]. These settings demand for a tangible setup that requires the user to grasp, hold and move objects. As frequent intense training is recommended, these patients benefit from training in their residential setting after their stay in a rehab center or in combination with a treatment there. Most of the current rehabilitation exercises that a patient can do at home are rather static setups specifically targeted toward the development of individual and combined basic movements. Because of the repetitive nature, these exercises do not engage patients over longer time [14-16], which has an important impact given a patient should take initiative and remain motivated to intensively train at home.

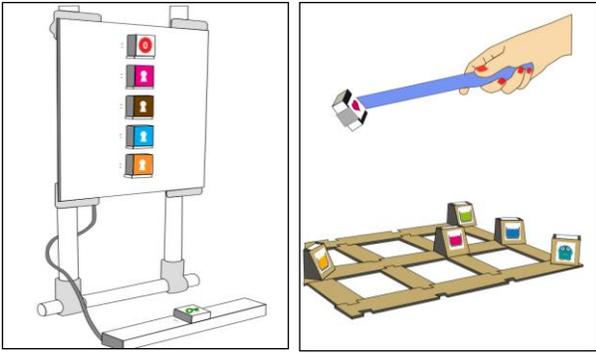
Skill components [6] are specific, low-level components of upper limb movements in which any daily activity can be subdivided. Examples of skill components are transport (left-right), lift (up-down) and reach (back-front). These skills are trained to learn how to perform daily activities. Usually, the therapy progresses from training separate skill components to training combinations of skill components, depending on how well a patient masters the skills.

The contribution of this paper is an engaging, low-cost interactive training setup for upper extremities in a residential setting. We combine low-cost materials with small interactive Sifteo Cubes in two tangible setups: one for horizontally oriented skills, 'ReachACube' and one for vertically oriented skills, 'LiftACube'. The Sifteo Cubes contain games that drive the physical interactions and steer the training efforts. Our setup allows configuring the system to accommodate for the patient's needs, and in addition games can be updated to keep a patient motivated.

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**Figure 1: Conceptual design of PhysiCube with two prototypes 'LiftACube' (left) and 'ReachACube' (right).**

## RELATED WORK

PhysiCube provides pervasive physical therapy for upper extremities in a residential setting for patients with a neurological disorder. As research on home-based training systems is gaining attention, most work on rehabilitation systems includes haptics, exoskeletons and robotics. While these are very common in neurorehabilitation, they are too expensive and impractical for residential training.

A first category of training systems covers the robotic systems and exoskeletons. The Armeo Spring tool of Biometrics [4], is an exoskeleton rehabilitation system for Multiple Sclerosis patients to train on performing daily activities in a virtual realistic environment. The focus of Armeo is to improve upper limb functional capacity and muscle strength and provide physical support (such as force feedback and gravity support) to allow a patient to train on difficult or limited tasks. 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 exoskeletons are expensive, large and complex systems. Therefore, these systems are not available for patients to train in a residential setting. This problem motivated us to explore possibilities for low-cost pervasive technologies to be used in training system, making them available for a residential setting.

The second category of rehabilitation systems are haptic systems, which provide force feedback and support for the patient during his training. An example of a haptic-based rehabilitation system for upper extremities of CVA patients is the Gentle/s system of Loureiro et al [5]. Their system includes a haptic robot, the MOOG HapticMaster, and a custom-made ADL gimbal with overhead frame to support the hand and elbow during the training. Their software provides three virtual training environments (empty, real and detail room) for functional skills. Each environment is personalized by the therapist by selecting or creating the appropriate exercises for a skill component and setting the parameters for the system support. The exercises are focused for performing gross motor movements with a personalized exercise path. To inform patients on their performance, Gentle/s implements four types of feedback;

visual, audio, haptics and performance cues. Their research results showed that virtual environments and exergames motivated patients to commit to their long-term training. Similar to the Gentle/s approach, we include exergames to make our system more motivating and structure them along the skill components.

Another example of a haptic rehabilitation system is the Individualized, Technology-supported and Robot-Assisted Virtual Learning Environments (I-TRAVLE) rehabilitation system [3,8]. I-TRAVLE supports physical personalized training exercises for MS and CVA patients on different skill components for the upper limbs. Similar to Gentle/s, I-TRAVLE includes a MOOG HapticMaster with a custom-made ADL gimbal to support mild to severe disabled patients to perform training exercises on activities of daily life. Before each training session, exercises and games can be selected by a therapist depending on the physical disabilities of their patient [8]. Furthermore, exercises can be personalized by setting the parameters before the training or by the system during the training; e.g. measuring the active workspace and automatic adaptation of the difficulty level by measuring the patients performance [9]. I-TRAVLE inspired us for exergames related to daily activities and to structure these games based on skill components for upper extremities. Also, this research provided us with information on the value of serious games in technology-supported training systems.

Recently, research is focusing on mobile, pervasive and tangible devices to provide physical therapy to persons with a neurological disorder. In contrast to the abovementioned systems that can easily cost over ten thousand euros, the low-cost systems aim solution cheaper than thousand five hundred euros. Papangelis et al [10] used off-the-shelf devices (such as an iPad, iPhone, iPod or MS Kinect with television) to present different physical exercises to children with Cerebral Palsy and to collect performance data in real time. Their system connected to a server to analyze the performance data and allowed therapists to make adaptations in training exercises. Dunne et al [12] researched a tangible training system for children with Cerebral Palsy. Their system used an accelerometer to measure compensations of the body, a touch table to present exergames and tangible objects (such as a pen or ball) to handle virtual objects. These research systems used low-cost pervasive technologies to provide physical therapy in the form of exergames for children with Cerebral Palsy. Their reflections on pervasive rehabilitation systems provided us with valuable information on and inspired us for the design and technical setup for our prototypes.

## PHYSICUBE - A TANGIBLE UPPER-LIMB TRAINING SYSTEM WITH PERSVASIVE TECHNOLOGIES

PhysiCube is our technology-supported training system for upper extremities for persons with functional disabilities due to a neurological disorder. PhysiCube explores the use of tangible objects and pervasive technologies to train these



**Figure 2: Five types of interactions detected by Sifteo Cubes.**

patients on gross motor and fine locomotion movements. Currently, two prototypes focusing on particular movement training have been realized according to the overall PhysiCube concept, namely LiftACube and ReachACube. In the following sections, we elaborate on these prototypes. Here, we describe the system setup built around the interactive mini-displays ‘Sifteo Cubes’, which we apply as a tangible, pervasive game technology.

The Sifteo Cubes evolved from a MIT research project “Siftables” by Merrill and Kalanithi [11] and were later commercialized. Sifteo cubes are an example of a pervasive low-cost game technology and can be classified as tangible objects. These cubes embed a large set of electronic components and sensors in a small cubic container (4.5 cm x 4.5 cm x 1.8 cm) and are capable of detecting fine motor movements of the hand (fig. 2). The cubes (as far as concerns the version we used) connect to and exchange their data with a computer that monitors and controls the cubes and deals with the game logic. The LCD screen on the cubes allows us to present visual output and feedback to the user. PhysiCube makes use of a combination of both direct and tangible interactions, which makes playing rehabilitation games more engaging. Using the sensors embedded in the cubes we indirectly measure the effect of gross and fine motor movements that patients perform.

### LIFTACUBE - LIFTING & STABILIZING

A first training concept in our PhysiCube training system is provided by the LiftACube game [7]. We explore tangible physical training with the pervasive Sifteo Cubes for one gross motor movement (lifting and stabilizing an object) and four fine motor movements (see figure 2; neighboring, pressing, shaking and flipping).

#### Goal

LiftACube (fig. 1 and 3) trains one particular movement: lifting. Lifting is a skill component which is used in many activities of daily living (e.g. eating, drinking, washing), and often it is only effective when the person is also capable to stabilize her hand on a certain height for a short while. A tight grip is required to bring an object to a specific height without dropping it. This is challenging for patients whose upper limbs are affected by a neurological disorder, especially for small or thin objects. There are often situations in daily living where a patient needs to stabilize this object and immediately perform other skill components in order to complete the desired activity, such as transporting a cup sideways to put it on a table. Therefore, LiftACube provides training to help a patient master the crucial skills lifting and stabilizing at first.



**Figure 3: LiftACube with self-made sensor board with 5 high positions for Sifteo Cubes and 1 position for the free cube.**

#### Technical setup

The technical setup for the LiftACube training game consists of six Sifteo Cubes and a custom-made sensor board. The displays of the Sifteo Cubes are used to visually present motivating game components and to provide feedback. Therefore, we created a sensor board with six positions to detect the locations where Sifteo Cubes are placed by a patient. As shown in figure 3, five positions are situated above the level of the table and one position is at the level of the table. Each position on the sensor board is extended with a light sensor to detect if a cube is placed in this position. LED’s besides each position notify if a cube is placed correctly on the board. As not every patient has the same range of motion, the board can be adjusted in height thanks to the metal supporting frame. The current LiftACube game makes use of six Sifteo Cubes, five of which are attached to the sensor board (figure 3) and one cube is ready to be lifted freely in space by a patient.

#### Interactions

In LiftACube, we incorporated some fine motor movements besides the gross motor movement of lifting a Sifteo Cube. Mild to severe patients suffering from disabilities in both gross and fine motor movements, benefit from a game concept with interactions designed to train both gross and fine motor movements. We chose to support all fine motor movements supported by the Sifteo Cubes (see Figure 2: neighboring, pressing, shaking and flipping) as explicit interactions in the game except for tilting, for the following reasons. When interpreting events of the Sifteo Cubes both shaking and flipping are initiated by tilting a cube, which makes using tilt as a separate target movement not straightforward for the patient and the system. Also, our Sifteo Cubes do not provide information on the particular angle, so recognition of exact rotations is hard.

#### Motivating game

For LiftACube, we developed a simple game concept to support motivating training for patients with a neurological disorder. Our game is based on the daily activity of opening a lock with a key. At the start, five cubes are placed on the sensor board. If any cube is detached from the sensor board, the game pauses until it is placed back. For a more extensive description of the LiftACube setup, interactions, game, and feedback we refer to [7].



**Figure 4: Locks & keys in 5 colors with bonus bomb and star.**

Four of the cubes on the sensor board show a lock in one of five colors (fig. 4) and the remaining cube on the board shows the score. The cube that can be freely moved around by the patient shows a key in one of these five colors. The purpose of our game is to lift the free cube and neighbor it with a cube on the board which displays a lock in the same color of the key on the free cube, in order to collect game points. Additionally, the free cube needs to be placed on the correct side of the cube on the board. After stabilizing the free cube for three seconds, visual and audio feedback is given to notify the action was correct and a point is added to the score cube. Visual feedback displayed on the Sifteo Cube on the board and the matching cube next to it consists of a smiling face for a match and a sad face for a mismatch. Feedback on the cube on the board is automatically reset by showing a new randomly chosen lock. Before a new key is shown on the free cube, this cube needs to be placed in the slot on the table. If the generated key on that cube does not match any lock, the free cube needs to be shaken to randomly set a new key. The game ends after thirty points.

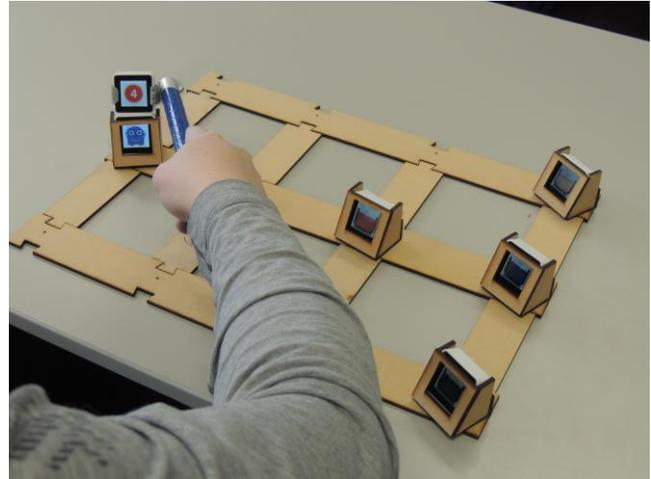
To make the game more challenging, a bomb and star (fig. 4) are added to the game which require fine locomotion. A bomb appears instead of a key on the free cube. If the cube with a bomb is not shaken within six seconds, the patient loses two points. The star bonus element appears on one of the cubes on the board and adds two points after pressing the screen of this cube within three seconds.

### REACHACUBE - REACHING & TRANSPORT

Our PhysiCube system contains a second training concept ReachACube. The ReachACube system focuses on providing physical training for two skill components for the upper limbs with the neighboring fine motor movement. By combining ReachACube with LiftACube, our PhysiCube system provides training for the upper limbs for three gross movement directions and four fine motor movements.

#### Goal

The ReachACube setup is shown in figures 1 and 5, and this tangible game focuses on the gross motor movements transporting (left-right) and reaching (back-forward) for an object. Reaching and transporting are in daily activities equally important as lifting. Furthermore, these movements require stabilizing the object before completing other skill components that are part of the daily activity. In contrast to LiftACube, the ReachACube game can provide training on the abovementioned skill components separately or on the combination of the skill components reaching and transport (with integrated training of the stabilizing activity). The fine motor movements of the Sifteo Cubes are not included in this prototype due to the setup of our frame and handle.



**Figure 5: ReachACube prototype with wooden supportive frame and metal handle for Sifteo Cubes.**

#### Technical setup

The Sifteo Cubes need to be placed at the level of the table in various positions depending on the skill component(s) to be trained, reaching and/or transporting an object. However, light reflections on the small screens of the Sifteo Cubes make it hard for patients to see and interpret the displayed images. Another caveat is that cubes can accidentally be knocked over or pushed away from the target training positions. Therefore, a supportive frame realized in wood is the central component of the ReachACube setup. The wooden frame contains five slots where the Sifteo Cubes can be placed in an upright position (fig. 5). The supportive frame can easily be extended to provide additional slots for the cubes, in this way increasing the flexibility of the training situations. Our cube slots are connected to the frame with a screw and wing bolt. This allows rotating the slots to face the patient and rearrange them depending on the skill components to be trained. We tilted the cubes in the slots to seventy degrees to reduce the reflections on the screen and make the display more accessible to the patient. However, the tilted position complicates neighboring cubes. Therefore, we attached a handle to the free cube (fig. 6). In this way, a patient can not only better move the free cube in general, but can neighbor it easier with those in the slots as clarified below. The handle has the advantage that its thickness can be personalized to facilitate the patient's grip.

#### Interactions

ReachACube provides gross and fine motor movements in the training of the upper limbs. The gross motor movements focus on moving the handle with the free cube. As for fine motor movements, the patient will mainly neighbor the free cube with one of the cubes in the holders on the wooden frame. This neighboring action should be carried out precisely and the free cube therefore is indirectly moved by the patient through the attached handle rather than directly manipulated. Before neighboring the cubes, this involves tilting the free cube to seventy degrees, which is also the

slope of the cube in the slot for optimal display readability. For most patients that are target users of this tangible game, this precise matching of the tilt angle of both cubes and neighboring are too difficult without the handle.

### Motivating game

For ReachACube, we developed a tangible game concept that requires the patient to repetitively neighbor cubes in a pleasant way.

Before starting, a therapist or family member sets up the frame by placing all slots on appropriate target training positions as determined by a therapist. By aligning slots on the frame horizontally or in depth, a patient will be training the transport or the reaching skill component separately. By combining horizontally and in depth placed slots, both skills are challenged in the training session. We use three to five Sifteo Cubes in ReachACube, to personalize the game depending on the required difficulty. When the game is initiated, 'Press to start' appears on the display of each cube. When the patient is ready and presses only the screen of the cube on our handle, the training will start.

Once the patient has pressed the handle cube's screen, a black fruit piece appears on its display (figure 5), while the background color indicates the color the fruit piece needs to be colored in. For three seconds, the background color slowly fades to black as a progress indicator, to show how much time is left to color the fruit. Coloring the fruit is realized by neighboring the handle cube with a cube in a slot, displaying a paint bucket with the same color as the free cube's background (figure 6b). To give feedback on successful task execution, an animation shows the fruit being dipped in the paint bucket and coming out correctly colored. Then the patient needs to move the handle cube to the blue avatar on a cube in the holders. By matching with this cube, the avatar will eat the fruit and one point will be added to the score (figure 6a). The paint buckets will randomly change position to avoid boredom and a new fruit piece will show. Our game ends at twenty-five points.

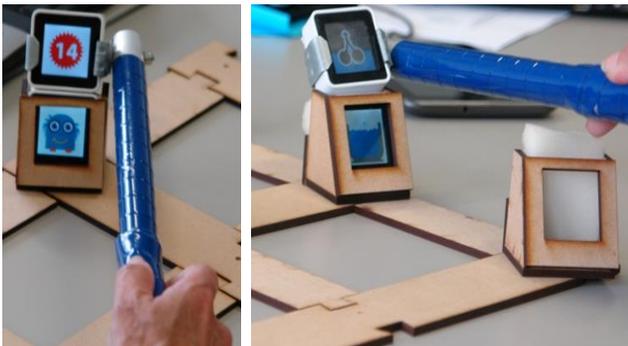


Figure 6: a. Matching a fruit piece with the correct paint bucket (left) and b. after giving the fruit to the avatar (right)



Figure 7: Therapists playing with ReachACube.

## RESULTS: VISION OF PHYSIOTHERAPISTS ON NOVEL TRAINING SYSTEMS AND TANGIBLE INTERACTION

### Design of evaluation

Both prototypes were evaluated in an initial qualitative study with therapists to assess the potential of PhysiCube in daily neurological rehabilitation practice. In this stage, the therapist decides to what extent the system fulfills the needs of the target patients. This approach contributes in finding the right balance between initial technology and exploration with therapists, and more intensive collaboration with patients in a user-centered follow-up trajectory to fine-tune the initial concepts and design additional games. We included two therapists treating paraplegia patients, one attending to Cerebral Palsy patients, two therapists working with CVA patients for the evaluation of LiftACube and seven therapists treating MS patients in the evaluation of ReachACube.

After shortly explaining the interactions and game play, each therapist played with our prototypes (figure 7). During and after playing with each prototype, the therapists explained their vision and opinion on our system and discussed with each other and with the researchers. At the end, the therapists were thanked for their participation.

### Using the 'Sifteo cubes' as a pervasive technology and tangible object for rehabilitation

Overall, the therapists were very positive and enthusiastic about the Sifteo Cubes as tangible training objects. They enjoy exercising with our cubes and declare that the cubes provided a lot of variation possibilities for physical training. They stated that these cubes offered many possibilities for neurorehabilitation, and that they would definitely use our systems for their patients once it is proven to be effective.

#### Technical setup

The form factor of our Sifteo Cubes received some mixed feedback. Most therapists found the cubes very small and hard to handle precisely. At the same time, this small size is challenging and reminds patients to focus on their grip during training. Different sizes of cubes are beneficial to support various levels of physical disabilities during the rehabilitation stages. The cube's thickness suits most patients and should not be any smaller. The material for the

cube's container is both hard and smooth, which supports a tight grip on the cube. Most therapists also stated that devices with different form factors will be needed to practice different skill components and to train for different goals (e.g. to prepare for handling different objects of daily living). The cubic container works well for fine locomotion training, while a ball or cylinder is more suited for rotations and gross motor movements.

Finally, all therapists mentioned that the displays of the Sifteo Cubes are very small, which makes it hard to see the game images. This problem was mentioned, even if we already optimized the graphical design by using large forms in distinctive colors. Furthermore, the colors changed depending on the light conditions and point of view.

#### *Interaction*

Sifteo Cubes can be used to train gross and fine motor movements of the upper limbs. However, therapists advised to make training exercises and games focusing on either fine or gross motor movements. A patient suffering from severe disabilities will more likely benefit from gross motor training without fine motor training. In contrary, patients with only starting or mild disabilities will have to train fine motor movements as large movements are still doable. When providing fine locomotion training, we need to clearly map one fine motor movement on one game action to lower the cognitive load for the patients.

The therapists suggested tangible interactions for fine motor movements that are expected to be beneficial in physical therapy for particular patient groups. For instance, shaking a cube is not a good action for CVA patients as they often have a weak grip or shake their body instead of their arm. On the other hand, the therapist for Cerebral Palsy patients emphasized that shaking for a substantial while is a good action to train with children with this disability. Neighboring cubes as an interaction technique was an unfamiliar but appreciated functionality. However, our version of Sifteo Cubes requires very precise neighboring, which therapists stated is hard for patients to perform. Possibly, this precision forces them to make compensating movements (e.g. bending forward) to complete the neighboring action. Therapists questioned the possibility to include tilting in the training because of the importance of this movement in daily activities. Detection of the arm being used and the direction of rotating can even enhance the value of this physical interaction.

Finally, the Sifteo Cube and handle can be handled in a personalized manner and be switched freely between both hands. Therapists found this both positive and negative. On one hand, a personalized grip is important in physical therapy, but on the other hand a wrong grip may result in compensations during the training.

#### **Technical supportive frame**

The supportive frames of the prototypes that hold the Sifteo Cubes were welcomed by the therapists. Adaptability in

form and range to support patients with diverse capabilities, was very much appreciated.

Therapists mentioned that stability (as provided in both prototypes) is very important because patients will use the frame as extra support during the training. After testing LiftACube, the therapists suggested two changes for the sensor board. First, deeper slots are better suited to keep the Sifteo Cubes in place, as the holders in ReachACube. Secondly, the sensor board needed to be tilted backwards to facilitate neighboring of the free and attached cube. Indeed, this action needs to be carried out very precisely and currently requires tilting the free cube backwards with the fingers. Therapists stated that very precise fine locomotion is not being possible for all types and stages of physical disabilities, a decision to be made by the guiding therapist. Furthermore, by tilting the board backwards, the hands do not occlude the cube's screen.

Compensating movements (such as bending forward or lifting one's shoulder too much) are associated with a wrong performance of the task and may be devastating for the patient's progress and health condition. Therefore, both LiftACube and ReachACube should ideally incorporate technologies to detect which arm is used in training and if compensations are made by the patient. Most patients have one severely and one less severely disabled arm. The purpose of the physical therapy is to regain abilities in both arms by training even if it is challenging. If we can detect which arm is used by the patient, we can personalize the training and interactions to match the abilities of the trained arm and avoid that patients have to make compensations. One therapist also mentioned that training both hands at the same time with appropriate tangible games can be valuable for coordination training.

#### **Motivating games and exercises**

The general impression of our exergames was very positive. Therapists stated that the prototypes provided a challenging physical training on skill components. Our games also reduced the focus of the repetitive character of physical therapy, which made our training more motivating. In this section, we will describe the results for two important parts of tangible games; the content and feedback.

#### *Content*

Therapists found our games pleasant and challenging, and they were looking forward to fine-tuning these in collaboration with the patients. They stated that the games should be introduced to the patient with some explanation (by a therapist or a tutorial in the game) to avoid cognitive disabilities to interfere with the game play. Next, these games should be self-explanatory to remind patients how to play them and which interactions can be used in the game when training in their residential setting where therapists are not available.

One of the guidelines to be considered when elaborating the prototypes in a user-centered approach with the patients is

to allow the therapist to program the training and adjust the exercises to the patient's abilities and progress. This need for flexibility and game parameters was confirmed by the therapists. Furthermore, by providing more variations in games and skill components we keep the patient motivated for the physical therapy.

Finally, one of the therapists mentioned that playing music when patients perform correct movements can be used as a motivating factor, to help the patient focus on correct performance of movements.

#### *Feedback*

In both games, we used timers to present the time left to handle events (such as the bonus star or bomb in LiftACube or the fruit pieces in ReachACube) or to show how long a patient needs to stabilize before the action is detected as correct. The timer indicating how long a patient still needed to stabilize an object, was appreciated much by the therapists. They mentioned that the timer needs to give patients time enough (e.g. three seconds) to discover and react on the event depending on their disabilities. The requested stabilization time will be personalized in the final games to make the therapy challenging and effective.

The audio feedback is useful and pleasant, but needs more variations to represent events in the games. If event sounds are alike, patients are not able to distinguish these sounds and determine the actions to perform.

#### **DISCUSSION AND LIMITATIONS**

We evaluated PhysiCube with physiotherapists, which treat persons with physical disabilities due to a neurological disorder. A user-centered follow-up process to fine-tune the games with continuing evaluation, and a thorough study of the clinical effect of our system PhysiCube is an important part of our research. As our research focuses on pervasive training systems in the residential setting, this study should include patients to train with PhysiCube in their home. In collaboration with therapists, standard clinical assessment scales (e.g. Fugl-Meyer, ARAT or Wolf motor test metrics) will be used to estimate the patient's progress.

As therapists are not available in the residential environment to check and correct the patient's movements, motion detection technologies can be used and different performance data can be logged during the training. This information can be used for real-time analysis of the performance data in future adaptive versions of the systems, but also for data analysis in the rehab centers for remote follow-up and adjustments of the parameters.

The therapists also confirm the need for a therapist interface to select training exercises and set the exercise parameters (e.g. number of repetitions, time) to personalize the physical therapy to the patient's abilities. As some of the therapists and researchers are familiar with our therapist interface for (neuro-)rehabilitation robotics in the rehab center, it is investigated to extend that interface. To provide physical therapy in the residential setting, this therapist

interface has to be remotely accessible for a therapist to check a patient's exercising data and change the training parameters to adjust the therapy to the patient's progress. Also, the patient's interface for transferring data or requesting feedback needs a careful design.

To stimulate reuse and further developments, we release the models and prototype software that were used to create the physical setups. In contrast to most current professional neurorehabilitation setups, with this work we aim for accessible and affordable setups. The hardware (six Sifteo Cubes with base station) of our current PhysiCube system costs approximately 175€ which is at least fifty-fold less expensive than the hardware of robotic systems. Since most parts of our physical setup were created in a local Fab Lab – a freely accessible workshop with machines that allow for digital fabrication. Fab Labs are widespread and with the available machinery everyone is able to fabricate the different physical components that are required to create the setups discussed in this paper. The assembly of these components is straightforward. The software is distributed using the existing Sifteo Cubes online distribution platform. Once the cubes are put in place, the setup is operational and can be used for training in a residential setting.

#### **CONCLUSION**

In this paper, we presented our pervasive rehabilitation system PhysiCube with our two prototypes 'LiftACube' and 'ReachACube' for upper limb training in the residential environment. Both prototypes use a low-cost, tangible and pervasive game technology Sifteo Cubes with custom-made supportive frames to provide physical therapy. Together, the systems provide motivating rehabilitation games to train patients on the skill components to lift and stabilize an object on a specific height, and to reach for and transport an object. The evaluation with therapists provided valuable feedback on pervasive training systems in a residential setting. As such, the current evaluation with therapists had a more formative character, but is a very important stage as it provides input for an efficient user-centered follow-up trajectory to elaborate and fine-tune the games with patients. These therapists showed great appreciation for PhysiCube and stated that they would use the system in therapy once the effectiveness for physical therapy has been verified. Some therapists mentioned they love to see new games in the system and asked when it would be commercially available for patients.

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