Integrating Serious Games and Tangible Objects for Functional Handgrip Training: A User Study of Handly in Persons with Multiple Sclerosis.

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ABSTRACT

We present Handly, an integrated upper-limb rehabilitation system for persons with a neurological disorder. Handly consists of tangibles for training four hand tasks with specific functional handgrips and a motivational game. These persons need intensive personalized therapy in order to sustain or enhance their abilities and aptitude in daily activities. Conventional approaches require intense support by a therapist or usage of expensive robots, both of which are not a sustainable model of training. Handly combines tangibles specifically designed for repetitive task-oriented motor skill training of typical daily activities with serious gaming, thus offering a comprehensive approach. A feedback mechanism guides the user and an accessible game environment stimulates individual training. We performed an initial evaluation of Handly with eight persons with Multiple Sclerosis. We show that a tangible-virtual environment for intensive upper-limb rehabilitation is feasible and that this approach is highly appreciated by the patients.

Author Keywords

Neurorehabilitation; occupational therapy; tangible objects; pervasive serious games; handgrip tasks.

ACM Classification Keywords

C.3 **[Special-purpose and application-based systems]**: Real-time and embedded systems; H.5.2 **[User interfaces]**: Prototyping, Evaluation & User-centered Design; J.3 **[Life and Medical Sciences]**: Health.

INTRODUCTION

A neurological disorder [37] like stroke or Multiple Sclerosis is a medical condition in which the nerves of the central (CNS - brain and spinal cord) or peripheral nerve system are damaged by trauma or disease. Due to these nerve damages, persons with a neurological disorder experience a combination of functional, cognitive and/or emotional disabilities that affect their possibilities to participate in daily or social activities. Depending on the progress of the disease and the specific symptoms the person experiences, these disabilities can also affect the upper limbs including the hands. As we use our hands in many daily activities such as opening a bottle, unlocking a door, sustaining and when possible recovering of hand function is essential to improve the quality of life of persons with a neurological disorder.

Whereas Handly focuses on therapy for various neurological disorders that can cause functional disabilities in the hands, we chose to include persons with Multiple Sclerosis in our user study of Handly. Multiple Sclerosis (MS) is one of the most common neurological disorders and affects about 2.5 million persons worldwide [34, 37] and starting in adulthood (20-40 years old). Persons with MS are potential target users for Handly due to the wide variety of disabilities (e.g. motor or cognitive dysfunctions, fatigue, and visual impairments) they encounter. Moreover, upper limb dysfunction is prevalent, and often occurs bilaterally over time [1, 19] in contrary to disorders such as stroke, which leads to serious limitation in independent performance of daily life activities involving object manipulation. Because MS is a chronic disease that requires life-long rehabilitation, the treatment cost is significantly high (section 'discussion') especially if dependency in daily life is increasing [34, 37]. Positively, a recent systematic review [17] indicated that conventional intensive therapy for the upper limb [8, 36] can sustain or enhance the abilities of a MS patient by providing intensive personalized training for part of the affected skills [16]. Therapy involves one-to-one sessions in a rehabilitation center under supervision of a therapist and includes exercises on the interaction with or manipulation of objects similar to daily activities. However, a high training dosage including of a high number of movements is advocated in order to reach clinical notable improvements [18].

Research on technology-supported upper-limb therapy for persons with a neurological disorder (e.g. Cerebrovascular Accident, Multiple Sclerosis, Cerebral Palsy, etc.) includes robots, exoskeletons, interactive surfaces and tangibles (section 'related work'). The advantage of technology-supported rehabilitation is that a patient can train a high number of repetitions in a stimulating game environment and with feelings of achievement rather than failure in real-life

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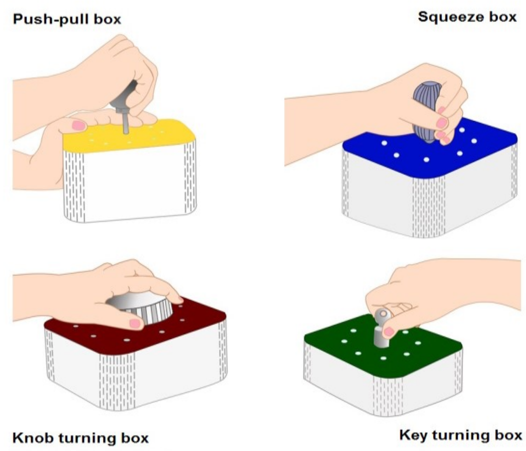

Figure 1. Overview of the four hand tasks (and functional grips) supported by Handly

movements [20, 21]. However, most systems focus on rehabilitation of the arms (shoulder, elbow and forearm) often not reaching improvements in real-life functional tasks [9, 24]. Only few devices include exercises for the hands, but then mainly on body function (movement amplitude, strength) and not activity (object manipulation) level. Even though these systems use serious games for motivation, the games that train on hand tasks, miss intuitive feedback and lack a natural mapping between the interactions with the device and visualizations in the game.

We developed a training system, *Handly*, to train four hand movements (tasks) with specific handgrips for persons with neurological disorders. Our system consists of four tangible training boxes, which each present one essential grip and associated hand task: (1) *push-pull*, (2) *squeezing*, (3) *knob turning* and (4) *key turning* (Figure 1). The individual hand tasks that need to be trained were identified by consulting researchers with a physiotherapy background, experts in the field (e.g. occupational therapists) and scanning existing literature on upper-limb rehabilitation [29]. We focused four hand tasks that are thought to include essential handgrips to be trained during therapy [13, 32]. To drive the training, Handly includes a serious game that uses various exercises as an essential part of the gameplay. The game supports both training at a single task level, focusing on a single grip with one training box, and at a more complex level combining multiple tasks and corresponding boxes. We conducted a user study with eight MS patients to evaluate the user experience and to estimate the potential of Handly for further exploration in rehabilitation.

In this paper, we offer an overview of the design and evaluation of Handly; the technical setup of our tangible training boxes; the serious game concept; and the results of our user study. Our work makes the following contributions:

- A hand-training system for patients that entangles gameplay and special-purpose tangible interaction.
- An exploration and implementation of feedback and feedforward to support motivation.
- Special-purpose tangible boxes requiring functional grips during tasks that mimic hand use in activities of daily living.
- A game-driven training approach that allows patients to vary the different types of hand task training in one game session, thus allowing for a variating and motivating training regime.
- An initial evaluation and discussion of our setup using tangible grips that mimic hand using during daily activities and serious game for hand therapy.

RELATED WORK

In recent years, we have observed an expansive growth in serious games often integrated with robotic systems and exoskeletons as well as (wearable) sensors and tangibles. Previous work has shown that virtual games that maintain therapeutic principles have potential for increasing motivation and lead to better training results [20, 21]. Handly explores the usage of a serious game integrated with a tangible device for training hand function.

Robots And Exoskeletons

Robots have been introduced to allow for high-intensity training in virtual learning environments but most often focus on proximal arm function, and remain typically on motor function level (movement amplitude, strength) also if hand muscles are involved [9, 24, 31]. Robotic therapy such as Gentle/s [22], dual robot of Jackson et al. [12] has proven to be as effective as dosage-matched therapy exercises [15] and inspired us for the design of our serious game. Gentle/s (for stroke patients) and I-TRAVLE [9, 25] (for stroke and MS patients) present a training environment with serious games for arm movements' skills. The I-TRAVLE training environment provides two types of exercises (e.g. basic levels with focus on one skill, and serious games combining different skills), and inspired us to include exercises with different complexity. In clinical studies, patients reported improvement of their functional abilities in daily activities. The commercial robot AMADEO of Tyromotion [31] trains finger flexion and extension on a motor functional level and includes virtual therapy games. The system also allows measuring the active range of motion and adapts the exercises to fit the user's needs. Armeo Spring [10] is an exoskeleton for upper limb therapy for persons with moderate to severe functional disabilities. Their games present intermediate feedback on performance and assesses for the active motor abilities and coordination of the user.

With Handly, we designed game elements to provide strong visual cues and natural mappings that integrate four hand tasks as its core interaction techniques (Figure 5). This makes the tangible interface easy to understand and use for persons with a neurological disorder. In addition, the mobile and easy set-up of Handly allows therapists to use the system in training sessions at the rehabilitation center.

Tangibles In Neurorehabilitation

Daily activities involve various complex manipulation of objects, so therapists strongly advise task-oriented training with multiple real-life tangible objects [33]. Tangible devices use the form factors of daily objects in combination with sensors and technology for enhancing the therapy and allow assessment of trained ADL skills. The related work on tangible systems for upper-limb training gave us inspiration for our tangible objects and for including a good mapping onto the game visualizations. To drive the training and improve adherence these systems include serious games. Vandermaesen et al. [35] developed a tangible system for gross and fine motor movements for the arms using sifteo cubes. This system consists of two setups for arm training on the movement directions of lifting (up-down), reaching (back-forward) and transporting (left-right). In the lifting system, the authors included fine motor movements such as shaking a cube, pressing the screen and flipping the cube. An evaluation with MS and stroke patients focused on the system's usability. Results showed appreciation and potential for combining a simple game and physical training objects. Yet this system focused on arm movement skills and did not include training for hand tasks. With Handly, we focused on therapeutically principled motivational games with tangibles manipulated in a real-life functional way [30, 31]. Beursgens et al [3] use a knife and fork in combination with a touch surface for exercising on the activity of eating with knife and fork. In their game, the user needs to catch bugs that are running around on a plate of food. Results of a user study with persons after a stroke showed that they liked the game because they could relate this to daily activity. The participants appreciated the variation in training schemes.

The Rejoyce system of Kowalczewski et al [13, 14] and e-link of biometrics [11] are commercially available systems for rehabilitation of hand tasks. The Rejoyce integrates eight handgrips on a single device. The manufacturers mounted the handgrips on a flexible arm that allows moving them to a specific target position in a 3D space to perform the related hand task. Serious games such as driving a car present training exercises, but miss visual reminders of the hand task/grip in the game. There is no visual feedback of performance on the device available. The feedback on the screen is not related to what the patient is doing, in which case the relation between the game feedback and the hand movement is lost. Results from clinical trial show a larger improvement on the Action Research Arm Test (ARAT clinical test) compared to conventional therapy. Even though Rejoyce is advocated as a home-based rehabilitation tool, the cost of six weeks therapy with this system is 4000 dollars, which is quite expensive for persons with MS whom requires life-long therapy. The e-link system of Biometrics [11] is a clinical evaluation and exercising tool for hand therapy. This system exists in a wired and wireless system that only differ on how the sensors and training objects connect to the computer. The wireless system consists of wearable sensors for the arm and hand to measure the active joint movement or EMG signals during the exercise. Using only the wireless sensors, the user can perform training of hand tasks but does not have a physical handgrip for the training. The training objects include a dynamometer, pinch meter, a goniometer for measuring the range of motion, force plates and an upper limb exercises for training arm movements with different handgrips such as a key, disc, cylinder. E-link also includes serious games (e.g. moving a bucket to catch apples) as exercises but similar to other systems, the game is neither visually nor conceptually linked to the performed hand task.

TANGIBLE HANDLES FOR HAND TASK TRAINING

As rehabilitation programs provide intense physical therapy to maximize training effects, it is important to fit the interactive tangibles and game concept optimally to the context of use. Therefore, we involved four therapists in the design phase of the tangibles (handgrips and corresponding movements) and the game concept (e.g. training volume, data logging during the session). Handly uses four separate tangible controls which function as grips for four hand tasks; *push-pull, squeezing*, *key turning* and *knob turning*. We implemented each hand task as a separate box with a grip (Figure 2) that we connected to a computer running the game. The game allows for different training programs that focus on training individual hand tasks or switching between hand tasks in order to complete the game. This section describes the technical setup of our boxes and the design of the game.

We used white-painted wood (fabricated with a laser-cutter) to create four boxes. On top of the box, a colorful plexiglass plate provides a comfortable and smooth surface for the hand during the interaction. Differently colored plates create an attractive, playful appeal and keep the box easily distinctive for the user. In the middle of this plate, the handgrips that act as tangible control are situated. An Arduino microcontroller and sensor measuring the execution of the hand task with these grips are inside the boxes. The boxes are 10 by 10 cm and come in two heights (9 cm for squeeze and push-pull; and 7 cm for key and knob turning) depending on the sensor.

Underneath the top layer, eight LEDs form a circle around the handgrip. When an exercise starts in the game, Handly activates the box with the corresponding handgrip causing all LEDs to blink three times to get the attention. Moreover, the LEDs inform a user of the performance of the hand task. For example, when turning the key to the right, the LEDs gradually turn on in clockwise direction following the hand movement to give instant visual feedback. LEDs gradually fade in counter clockwise direction when turning the key to the left. Whereas the knob works similar to the key, the LEDs in our squeeze box change depending on the strength applied on the grip. For the push-pull box, LEDs gradually turn on when pushing the grip downwards and respectively fade when pulling the grip. When after the exercise, all LEDs turn off. This visual feedback allow more patients to train with Handly by supporting them during an exercise. First, patients might not be able to follow the game feedback on a separate screen while performing a hand task due to their cognitive

Figure 2. Four tangible training boxes with embedded sensors and feedback for different handgrips and tasks.

dysfunctions. The LEDs present in-situ feedback that the patient would miss in the game. Second, persons with limited hand function need visual feedback to determine if they correctly performed the exercise. The LEDs help the patients by showing augmented feedback providing a direct relation between the moving hand and the reaction of the system/box.

The Arduino microcontroller inside each box checks and communicates the sensor value to the computer -connected through a USB cable- running the motivational game. In addition, it also controls the LEDs that we embedded in the box. The sensors – *a slider for push-pull, a potentiometer for both turning boxes and air pressure sensor for squeeze* - connect to the handgrip and measure the performed hand tasks. The handgrip of the squeeze box uses a balloon pipet, which allows for a soft and personalized grip. The key turning box uses a real key and lock, whereas the knob and ball grip are 3D printed handgrips in a larger format to allow for an easier grip for persons with hand weakness. The box supporting push and pull uses a spring that acts as a simple force feedback mechanism while pulling the grip. With the open architecture of our boxes, we can easily replace this spring by a stronger or weaker spring depending on the user.

The range of movement for the handgrip is in the current setup based on our previous research experience with MS patients. In this sense, the Handly prototype is a proof of concept that will be subject to optimization in an iterative process. In our user study, participants performed the four hand tasks with a fixed active range of motion of the box. Persons, who are able to complete these movements, can use Handly for practice on movement speed and automatization. For next iterations, this movement range will be determined in collaboration with a group of persons with neurological disorders and therapists. This allows installing an individual active range of motion before the training session according to the patient's baseline abilities. To stimulate reuse in other research and further development, we release the blueprints and prototype software that we used to create the boxes.

SERIOUS GAME FOR TRAINING HAND TASKS

Intensive, personalized task-oriented physical therapy has proven to be effective for upper-limb rehabilitation for persons with a neurological disorder [4, 6, 7, 23]. Persons that experience functional disabilities in their upper limbs often find occupational therapy very challenging and can get seriously demotivated over time due to the typically slow progress and repetitive nature of the training. We use a game as the driver for the different exercises they need to perform as part of their therapy. The game combines motivational and entertaining aspects that allows for personalized exercises keeping the user motivated to continue his therapy by distracting him from the repetitive nature of the training. The four therapists involved in the design process also informed the design of the serious game (e.g. training settings, required results and training volume to present in the visualization).

In this section, we describe the four core components of our serious game for Handly: (1) the settings for the training session; (2) the game environment, (3) visualization of the hand tasks and training exercises; and (4) the overview of results shown at the end of the training.

Settings

At the start, a therapist can adjust parameters influencing the training effort depending on the user's abilities and therapy progress. We include a setting for the maximal training time. When the game ends, it presents an overview of the training results (as shown in Figure 4), even if the user did not complete all requested repetitions. The game ends when time is up, or when the user performed all requested repetitions. Handly allows limiting the training session time to avoid the occurrence of muscle fatigue, which occurs frequently in persons with Multiple Sclerosis when performing robot-mediated training [26, 28].

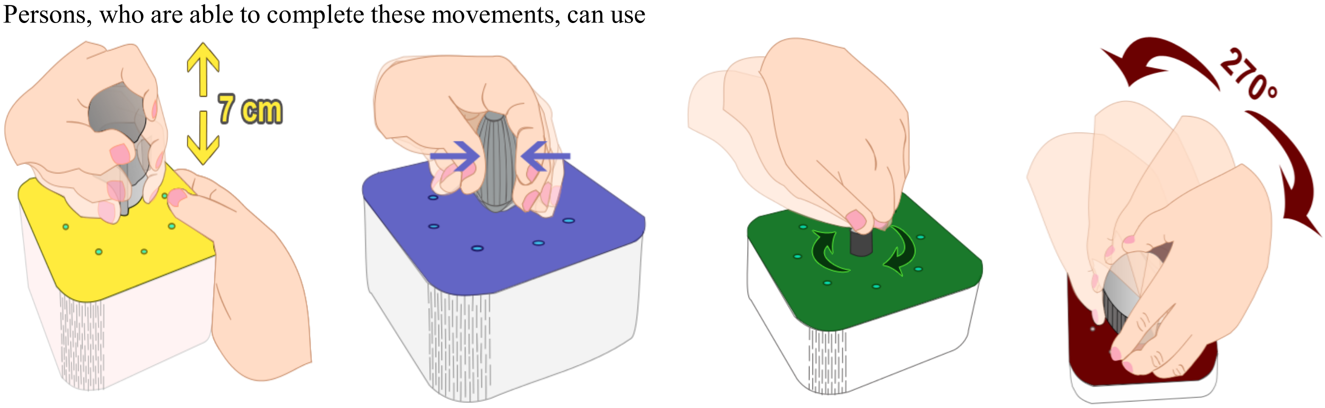

Figure 3. Overview of movements and ranges of motion with (A) push and pull, (B) squeeze, (C) key turn and (D) knob turn.

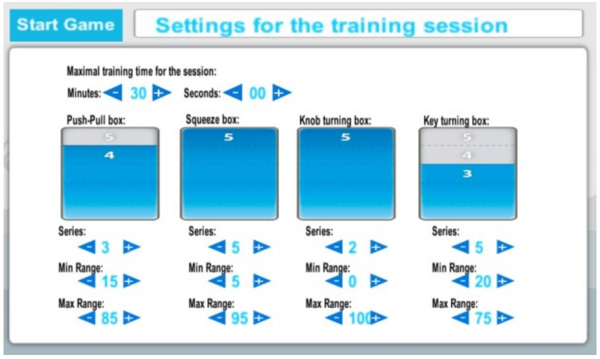

Figure 4. Overview of the settings for the motivational game

We can separately adjust the settings indicating the training volume for each training box. Handly uses two related parameters to determine the training volume. First, the amount of hand task repetitions when the game includes that specific box (in order to fasten up motor learning and retention of skills, it is important to include 'distributed practice' exercises) and secondly the number of times that box (and thus that particular hand task) is offered by the game during the training. Finally, for each box, the mapping for the handgrip range (Figure 3) can be determined. This setting allows us to keep the game challenging and feasible for persons with a limited range of motion or having muscle weakness. For the boxes with key and knob turning hand tasks, the ranges indicate the furthest point to reach by the user when turning the grip in both directions (turning left and right). The squeeze box' range indicates the minimal and respectively maximal pressure to apply to the grip. The push-pull minimal value represents the lowest point to push, and the maximal value points to the highest pull position.

Game Environment With Hand Task Training Exercises

For the game, we focused on a simple platform game (Figure 5) to investigate different motivational aspects. In our game, a monkey avatar encounters different obstacles on its way to the end portal of the virtual world. The user navigates this monkey avatar through the environment by unblocking the obstacles using the corresponding tangible training boxes. The avatar stops at an obstacle and the appropriate hand task box will activate, so the user can practice giving the monkey passage and gradually escort the avatar through the game environment. Depending on the training volume, a user needs to perform the corresponding hand task one to five times to solve the obstacle. The game displays the elapsed training time and game score to indicate the progress of the training session to the user. The score increases with 5 points for every completed hand task (e.g. squeezing the balloon a single time results in 5 points).

The game includes four types of obstacles corresponding to and presenting a visual link to the four actual hand tasks that a patient can train in the Handly setup. Quick recognition of the training exercise is necessary, as we strive for enhanced aptitude of the user and thus use a time-based training strategy for solving the obstacles. The visual reminders in the game, that allows the user to link the obstacles to the hand tasks, minimize time to discover this hand task and focus on actual performance of the task. The handgrips on the tangible training boxes act as direct manipulation controls for the obstacles in the game. The mapping of the physical actions carried out with the handgrip on their visualization in the game turns out to be a contributing factor to player experience. In fact, Handly intrinsically combines several techniques that have potential to increase play engagement and thus involve the user to such a level in the game that the direct training purpose shifts to the background. On top of the value of gamification as a motivating technique, physical interaction with the tangibles augments the user's feeling of control and enhances "immersion" in the game. In the remainder of this section, we will discuss four obstacles that we included in the game and the corresponding task that patients train by these obstacles.

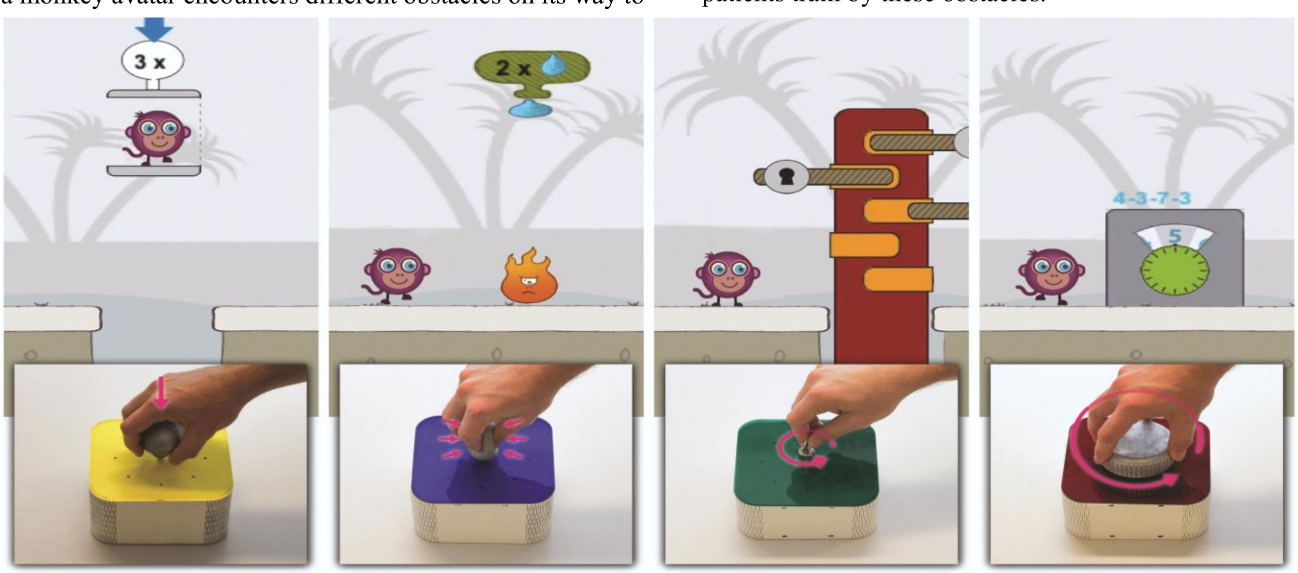

Figure 5. With Handly, we designed game elements to provide strong visual cues and natural mappings that integrate four different hand tasks as its core interaction techniques. This makes the interface easy to understand and use.

The Elevator obstacle for training the push-pull hand task

The *elevator* obstacle (shown in Figure 5-A) matches the push-pull box with the form factor of the sphere or ball being a visual cue for the ball grip on the push-pull box. When the avatar encounters the elevator blocking its route in the game world, the monkey waits in the elevator for the user to move the elevator using the ball grip on the box. The direction of the arrow underneath the obstacle suggests the direction for the push-pull action; an up arrow indicates a pull action to lift the elevator until its maximal height (corresponding to the max value in the setting) after which it is followed by "pushing" the elevator down.

The Water Dropper for training the squeeze hand task

The *fire and the water dropper* –shown in Figure 5-B - together match the hand task with the squeeze box. To extinguish the fire, the user causes water to drip out the dropper by *squeezing* the balloon on the box. The strength applied to the grip determines the expansion of the drop. When the water dropper reaches its maximal size by squeezing the balloon up to the corresponding max value of the box setting, a water drop falls from the reservoir down on the fire. A new water drop is set after releasing the grip until the minimal setting. The number in the water dropper indicates how many repetitions of the squeeze and release hand task the patient needs to perform to put out the fire, thus overcome the obstacle.

The Wall obstacle for training the key turning hand task

The *red wall* obstacle (Figure 5-C) presents with some locking bars on both sides, as abstract visual cues for a locking mechanism of a door, thus conceptually linking to the *key turning* box. The user can open the locks one by one –starting with the lowest lock on the right side— by turning the key in the right direction. Left side locks unlock when the key turns counter clockwise until reaching the minimal value of the range, and similarly turning the key clockwise until the max value of the range corresponding to the box opens right side locks. While turning the key, bars sliding out of the wall function as progress bars for completion of the hand task. Only after opening all locks, the wall slides down in the hole and allows passage for the monkey.

The Safe obstacle for training the knob turn hand task

The fourth kind of obstacle that is part of the game concept is a *safe with a code* (shown in Figure 5-D). For this obstacle, the visual cue to the tangible box with the *turning knob* includes as the knob on the front side of the safe. The digit 0-9 near the green turning knob inside the safe indicates how far the knob grip on the box is turned, and therefore presents the user with feedback on the progress during this knob turning hand task. The goal when the monkey meets this obstacle is deciphering the safe's code by turning the knob grip on the box. Once the correct digit displays, the game erases this digit from the code. After the code is deciphered, the safe disappears and the avatar can continue his path.

Feedback On Training Performance

After a session is completed, the game environment presents feedback on the performance to the user in an accessible way, as shown in Figure 6. We present the performance time, the training volume, range of motion and performed repetitions for each training box in textual and visual format. As many patients have a limited range of motion, some exercises focus on extending this range. Therefore, we include the performed range of motion for each box to inform the user on his status. When users train over longer periods, they will improve in their movement performance and become faster. Therefore, we include the (minimal, median, maximum) performance time to indicate by comparison with previous results the improvement in speed. Similar to the time, the results present the time used to complete the full training session, which will decrease in long-term therapy whereas the game score will increase when a patient completes more movements in one session. The volume is a reminder of the training volume that was set before the game and helps for a therapist to overview how many repetitions unblocked an obstacle. Finally, the completed repetitions indicate the number of successfully executed movements with the box and will in comparison with previous results increase when the user improves.

Tele-rehabilitation systems[1] for upper limb training [5] enable new prospects for therapy with remote supervision of a therapist expanding provision of therapy beyond the rehabilitation center to the residential setting of persons with a neurological disorder. Our training results overview intended to inform the user on his performance as reflected through game performance. By comparison with previous results, the user can be motivated to continue training to improve these results in next sessions. Training results and game parameters are stored for further investigation by a therapist in light of decisions on training adaptation. The therapist can use the information to set training properties for next sessions and possibly decide to schedule a face-to-face meeting with the patient. Handly is supported by a previous research system that includes a tele-monitoring component for therapists, which was not included in the current user study we report on.

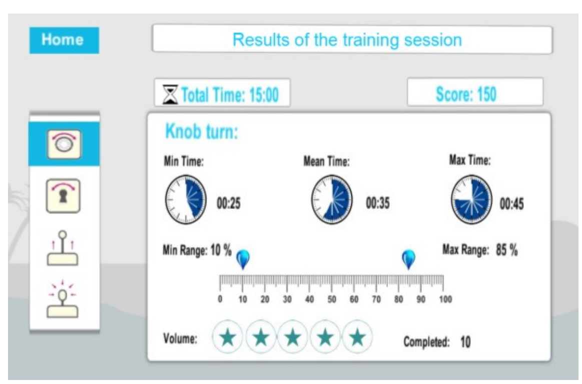

Figure 6. Overview of the results for the knob-turning box.

[1] http://i-travle.tumblr.com

EVALUATION OF HANDLY WITH PERSONS WITH MS

From a HCI perspective, evaluating the system's usability with potential end users is important to fit the system to the user's needs and expectations. For the involved researchers with a physiotherapy background, this stage is crucial as it informs the team on the potential of Handly for deployment in long-term studies on hand task training in a rehabilitation center or in a tele-rehabilitation setting for training at home. The initial study is part of one of the first iteration of the system in the development process. We focused on usability issues and refining Handly to avoid technical or practical issues when letting patients train with the system for longer periods. Therefore, at this moment, we did not conduct a long-term effectivity study. The design and development of Handly was done in close collaboration with researchers that have a physiotherapy background and expert practitioners. Because Handly uses similar handgrips (based on objects in daily living activities) and exercises as in conventional therapy, we expect it has a comparable therapeutic effect. However, training intervention studies are required to assess the effectiveness of Handly from a therapeutic perspective.

Initial User Study

Before the study reported in this paper, we set up a pilot study with five healthy persons with a background in technology for healthcare to refine our experimental design. Therapists that were involved in the design process informed the experimental design and gave clearance to evaluate Handly with patients. Therefore, we conducted a user study with eight persons with MS (approved by the ethical commission). This user study with persons with MS evaluated the user experience with tangible training boxes for hand tasks, the proposed design of the tangible boxes and handgrips, and the entangled serious game for hand task training. This aim includes evaluating the form factor of and interactions with the four boxes functioning as a training device for persons with reduced upper limb strength and/or range of motion. We explored different designs and concepts in our game in search for good visualizations of the hand task exercises, as well as motivating factors for this game.

Procedure

Each participant played five levels/sessions of the serious game performing the hand tasks in their own manner, similar to the way they would deal with that particular handgrip during daily activities. They only received one instruction; to provide counter weight on the push-pull box with their free hand to avoid sliding of the box on the unexpectedly slippery table surface in the rehabilitation centre (in contrast to the pilot study in the lab when designing the experiment). To introduce the tangible boxes to the participants and learn how to interact with the game using the handgrips, the participants played a short level/session of the game using one particular box. The maximal training time for this introductory level was five minutes, during which the participant led the avatar through five obstacles using five repetitions of the hand task related to the tangible box and obstacle. We repeated this same procedure to introduce the participants to the other three boxes. We balanced the order, in which a person used the boxes to compensate for a possible learning effect in interacting with consecutive grips. After the introductory levels consisting of a single training box, the participants played an advanced level (with the maximal training time of 10 minutes with two obstacles for each box; five repetitions per obstacle) in which all four boxes are consecutively presented in a random order. This advanced training level requires the hand to switch to another tangible box as soon as the corresponding obstacle appeared in the world. We used observations as data collection approach to investigate how participants used their hands while working with the Handly setup, to see their reactions to the serious game, and to keep track of difficulties experienced while playing and of unexpected technical problems.

Besides the observations, we conducted a semi-structured interview with the participants after playing with Handly to gather information on their perspective on the prototype. The first part of our interview focused on the design of the tangible boxes including the handgrips and the performed hand tasks. In addition to answering open questions on their experiences, participants scored (0-10) each box on eleven aspects related to the design of the box and the handgrip (selected from different usability questionnaires to evaluate several aspects of the tangible boxes). The open questions focused on the participants' game experience, motivation through the game and the visualization of the hand tasks in the game world. The patients revealed their scores (0-10) for seventeen aspects of the game design (selected from several game experience questionnaires to get an extensive overview of the experience with the virtual-tangible setup).

Participants

Our user study with Handly focused on the design and concept of tangible training objects with different handgrips that support essential hand tasks for persons with a neurological disorder. Therapists from a local rehabilitation center, whom were not involved in the design process, selected participants with the following criteria. Eligible persons experience problems with their hands due to a limited range of motion and/or muscle weakness. Participants must be able to perform the tasks without suspension support or external tools as these are commonly not available at home. They were also required to have the cognitive abilities to understand the instructions.

Eight persons with Multiple Sclerosis (four persons with primary progressive MS, two with secondary progressive MS, 1 person with Relapse Remitting MS and 1 person with neuromyelitis optica that closely relates to MS) participated in our user study. We included five men and three women, age varying between 24 and 68 years old (average age of 46 years). All participants follow conventional therapy in the rehabilitation center Revalidatie & MS Centrum Overpelt. Three persons received their diagnosis less than 5 years ago, three between 6 and 10 years ago and the remaining between 11 and 15 years ago. Six persons were able to perform the

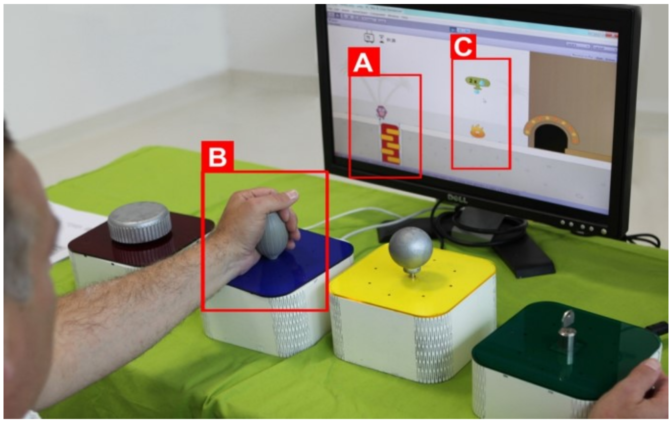

Figure 7. The participant just completed the key turning obstacle (a), and is already preparing for the next obstacle - squeeze (b) before the avatar reached this obstacle (c).

tasks with their most disabled hand (as research regarding technology-supported neurorehabilitation uses the most affected hand). Two participants were too weak in the most affected hand to train without support and we asked them to use their other hand (also affected by muscle weakness).

Results

Designing tangible training objects for hand task training

In the observations and in the first part of our interview, we focused on the technical design and usage of the tangible training boxes including handgrips. All participants stated that at least one or two boxes were directly useful for their therapy as they experienced problems in performing these hand tasks in daily activities. In general, six participants greatly appreciated the design of the boxes. The white box in combination with a colorful top layer and blue LEDs were appealing/charming and made the participants curious to try out the system. The other persons stated that they were not interested in technology or games in general and had no preference to use Handly over conventional therapy.

Our tangible boxes are quite large due to the embedded sensors in the current prototype. However, it turns out that all participants appreciated the size because they could rest their hand on the top surface while interacting with the grip or waiting for the next obstacles in the game. This size restrained participants to voluntary move or rotate the boxes making the exercises easier to perform. The weight of the boxes has increase in future prototypes to avoid involuntary moving a box while performing the task (e.g. the push-pull box lifted in total when pulling the ball grip without providing counterbalance with the free hand). All participants held their free hand in a relaxed position (in front of them, on the table) while performing the hand task, and only used their non-exercising hand to provide some counterweight to stop involuntary moving boxes.

Three persons reported that their hand occluded some LEDs when performing the exercise limiting to some extent the provision of instant feedback. However, they did not experience this as a major problem because the game also shows real-time feedback on their performance with the visualization of the obstacle. In the case of the knob-turning box, the red top layer masked the blue LEDs, which created some initial confusion. When first playing with this box, all participants were waiting for the LEDs to start blinking before turning the knob, but after a few tries, they perceived the blinking LEDs better and used the visualization in the game to estimate their performance in the hand task.

As for the design of the handgrips, all patients evaluated the ball grip for push-pull tasks and the balloon grip to squeeze very positive. The key grip generally scored well with the patients, but two participants reported having problems with turning a key in daily life and found the size of the current key grip too small. They suggested having a larger key or a clip-on for a larger surface on the key. The participants compared the knob grip with a bottle cap, and therefore stated that the current size was too large to be challenging. Two persons asked for resistance on the different grips to adapt the training difficulty to the progress of their disease. Taken together, the tangible handgrips were very relevant but sizes should be modular to adapt to individual needs.

Performing hand tasks with tangible handgrips

All participants understood directly how to use the handgrip without additional instructions thanks to the conceptual link to daily objects and activities. For all boxes, one trial was sufficient for the participant to be acquainted to their use and function. Whereas all participants in the beginning carefully turned the knob to match the correct digit in the code, two persons started moving less accurate and turned the knob from zero to nine and back to zero in which case they also reached the next digit. Both persons reported in the interview that they changed their behavior due to a lack of verification and stabilization of the knob grip. The grip of the push-pull box reminded some persons of a joystick controller, so they tried to move it similarly in the first try.

The observation and video recordings revealed that patients used the LEDs to know when to start performing the hand task to solve an obstacle. These blinking LEDs drove them to take the handgrip and start moving. Four participants looked at the LEDs during the exercise and regularly switched their attention between the box and game while performing the hand task. We clearly noticed that the exercise seriously challenged these persons and required them to focus on their hand while performing certain tasks. This resulted in slower performance or difficulty in grasping the grip. The LEDs gave an indication of their performance and their position in the range of the grip (near to or far from the boundaries). Other participants focused on the real-time feedback in the game and barely looked at the box.

Motivational aspects of the game

The second part of the interview focused on motivational aspects of the game. Overall, patients considered the game as very appealing and appreciated it as an alternative for conventional training approaches. The simple game concept and game environment, that we tried not to overload with nonreciprocal game objects, scored very well and were not overwhelming, which is particularly important for our target group. All participants were convinced they would strongly suggest Handly to persons with similar hand problems, but asked for more games for long-term training.

In the beginning of the evaluation session, their curiosity to figure out how the handgrip and obstacle work drove them to engage with Handly and focus on the presented exercise. The participants reported the combination of different types of obstacles and hand tasks within one game session, which implied switching boxes during the game, to be an engaging and motivating aspect. They liked the concept of obstacles that closely relate to the trained task, but still suggested to include additional obstacles and alternative visualizations for each hand task, especially when using the system for long-term training. Two participants also missed an overall game goal such as finding the end portal before losing all lives, which is a straightforward extension of this prototype.

The visualizations of the obstacles were understandable to all participants. They especially liked the visual indications for the number of repetitions in the obstacle (e.g. number in the water dropper of the squeeze obstacle). The real-time visual feedback of the task – as opposed to only tangible, physical feedback of the handgrip - helped the participants to focus on their performance. All patients explicitly mentioned they used this feedback to check how well they were doing, and that it gave a sense of satisfaction. In the elevator obstacle (as shown in Figure 5-A), we used arrows for visualizing the movement direction (e.g. push or pull), but did not mark the target position for the hand task, which resulted in the beginning in participants pushing and pulling the handgrip but not clearly understanding how far the grip had to move. The participants suggested placing arrows on the target positions and marking direction with other visualizations.

After completing an obstacle, the avatar walks to the next obstacle without user intervention, giving the participants a feeling of making progress in the session. Furthermore, this idle time gave the participants a moment to look at the next obstacle in the game environment and prepare themselves to perform this hand task (Figure 7). Six participants stated that seeing a next obstacle coming up engaged them in the game and kept them focused on the task. The video recordings and observations supported this finding, and showed that all participants recognized the next obstacle and instead of returning to a neutral resting position, moved their hand to the tangible box of the upcoming obstacle. Yet the participants waited patiently until the box activated before grasping and using the grip. Patients foresee that – with improved avatar speed and variation in obstacles – having to act fast and pick the corresponding box for an obstacle would also challenge them on a cognitive level. Two persons compared the obstacles' preview to the game Tetris in which shows the next block to let the player place the current block in a tactical manner.

DISCUSSION AND LIMITATIONS

Conventional therapy for the upper-limbs consists typically of 30-min sessions for three times a week in a rehabilitation center under supervision of a therapist. Patients report that scheduling transport and sessions in combination with the intensive and repetitive training make therapy adherence difficult. Costs increase e.g. due to the staffing for the one to one sessions, transport to and from the center. The capacity of rehabilitation centers is limited for hospitalized as well as ambulant patients. This capacity can increase when setups as Handly find their way into home-based training and partially replace center-based training. Results showed that Handly can provide a good solution for the predefined problem, and is likely to be relevant for therapy for other neurological disorders or for motor learning for healthy persons.

We investigated the usability of the tangible boxes and motivational aspects of a game concept for hand task training. Overall, the participants greatly appreciated Handly in a short-term session with the system. They were able to perform all tasks with the given grips and play the game. Our user study revealed minor usability issues with the current prototype such as the involuntary movements, the knob handgrip's size, and the visibility of the LEDs. As for our motivational game, this user study revealed that the real-time feedback on performed actions in the obstacle visualization, the training session where users had to switch between hand tasks and preview (feedforward) of the next obstacles were attractive and engaging game aspects. The current implementation of the tangibles and game includes a limited check of the accuracy of the exercises. For improving the timing accuracy, we can add a stabilization timer on the correct target. On the downside, this might interfere with the game play and make playing the game less fluent.

Fitts and Posner define three stages of motor learning [29 – page 32]. In the first stage (cognitive learning stage), persons with physical disabilities learn the correct movement path for a hand task while looking at their hand and the object. In the second stage (associative phase), a person knows the correct path and can correct mistakes when observing his movement. In the third stage (autonomous phase), the patient needs to focus on other elements in the environment and be able to correct movements without looking at his hand. The LEDs on the box in combination with real-time feedback in the game have a potential value for persons with physical dysfunctions during this motor learning process. In the first stages when the user is learning the task, the LEDs will present performance feedback that he otherwise would miss in the game. Whereas the feedback in the game can support patients with sufficient motor skills in the next stages. Moreover, these LEDs can support persons with cognitive disabilities to understand how to execute a motor task until their motor skills are sufficient to move to the next stage.

The user study we conducted did not measure the adherence to the long-term training, nor investigate the system's effectiveness. Although we expect the therapeutic effects of

Handly to be at least equal to the effect of conventional therapy - Handly offers the same hand task exercises and grips on a functional level. The next step for the validation of Handly is to conduct a proof of concept intervention with at least 10 subjects to see if the hand function is improving by using clinical testing and subjective surveys on perceived performance (e.g. MAL, ABILHAND). Depending on the results of the intermediate study, we conduct a randomized controlled trial or intervention study in combination with conventional therapy for hand task training or apply Handly in the residential environment of the person with MS.

We can extend Handly with new grips [13] to increase the set of possible exercises such as a steering wheel for two-handed turning, or a T-grip for push-pull. Using different sizes and materials can provide more difficulty levels for the current exercises. These additional grips, in combination with a wider variation in exercise difficulty (time constraints, accuracy) and in level design (new games/obstacles or sequences of actions to complete a repetition), allow us to engage patients for long-term training. In the current setup, we manually adapt the difficulty level for the obstacles to the patients' abilities whereas the level is randomly build by the system. Previous research on adaptive personalized training in robot-supported therapy for MS patients [27] and home-based therapy for stroke patients [2] showed the potential of adaptation in technology-supported training systems to increase the patients' motivation and minimized therapists' involvement. In the next iterations of the Handly prototype, we can investigate different adaptive algorithms for hand task therapy to automate the personalization process using the patient's performance data from different sessions. Together with integration in our tele-monitoring system, automated adaptive training settings is a next step/prototype towards home-based physical therapy.

CONCLUSION

In collaboration with occupational therapists, we designed and evaluated Handly, an innovative setup for training of hand movements (tasks) in a neurorehabilitation context. The serious game intensively uses four tangible boxes for training of different handgrips and tasks. Both the virtual gaming environment and the tangible controls integrated instant feedback on training performance. We elaborated on the results of an initial user study with eight persons with Multiple Sclerosis. Our results showed great appreciation for exercising with the tangibles and gave insights into hand task training and motivational aspects of serious games in the context of hand task training. In-depth research on the use of feedback and feedforward in relation to tangibles for upper-limb rehabilitation, and research regarding motivational and therapeutic effects are future research directions.

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