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Watering the flowers: virtual haptic environments for training of forearm rotation in persons with central nervous deficits.

Tom De Weyer, Sofie Notelaers, Karin Coninx
Expertise Centre for Digital Media
Hasselt University – tUL -- IBBT
Diepenbeek, Belgium
+3211268411
{tom.deweyer, sofie.notelaers, karin.coninx}@uhasselt.be

Peter Feys, Ilse Lamers, Geert Alders
Rehabilitation Research Center - REVAL
PHL University College, Dpt. Healthcare
Hasselt, Belgium
+3211294983
{peter.feys,ilse.lamers,galders}@mail.phl.be

Richard Geers
Adelante Centre of Expertise
In Rehabilitation and cardiology
Hoensbroek, Netherlands
+31455282358
r.geers@adelante-zorggroep.nl

ABSTRACT
Persons with central nervous deficits, such as MS and stroke patients, can benefit a lot from suitable training approaches that enhance their ability to perform activities in daily life. As performing rotations with the forearm (pro- and supination movements) is essential in many daily tasks, we use this as an example to illustrate our structured rehabilitation approach for the upper extremities. The results of the patient-centric design and development of the rehabilitation robotics system are illustrated, and several levels of interactive training exercises in virtual haptic environments are shown. Considerations regarding the system setup as well as hardware adjustments to the haptic device and peripheral equipment are described. Evaluations with patients and therapists demonstrate the importance of the patient-centric approach and reveal appreciation for the resulting interactive training system.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and presentation**]: User Interfaces - *User-centered Design,Haptic I/O*

J.3 [**Life And Medical Sciences]**: Health

General Terms
Design, Experimentation, Human Factors.

Keywords
Rehabilitation robotics, haptics, upper extremity motor training.

1. INTRODUCTION
Multiple Sclerosis (MS) is a chronic and progressive disorder of the central nervous system, resulting in symptoms such as impairments of strength, muscle tone, sensation, co-ordination, balance, as well as visual and cognitive problems. A stroke is a sudden loss of brain function(s) due to disturbance in the blood supply to the brain. This can be due to ischemia (lack of blood flow) caused by blockage (thrombosis, arterial embolism), or a hemorrhage (leakage of blood). As a result, the affected area of the brain is unable to function, leading to inability to move one or more limbs on one side of the body, inability to understand or formulate speech, inability to see one side of the visual field, and cognitive impairments. An important part of therapy in both stroke and MS consists of physical and occupational training including exercise therapy. Training duration and training intensity are considered to be key factors for a successful neurological rehabilitation [1]. In this regard, a difficult to treat problem is upper limb dysfunction, which has immediate impact on functional independence in daily life.

In the context of the Interreg IV project "Rehabilitation robotics" we investigate how patient-centric robot-assisted rehabilitation can fulfill these needs and contribute to the motivation of the patient to keep up the training efforts. Because robot-assisted rehabilitation and virtual environment (VE) technologies have proven to be promising tools in addition to traditional therapy to create an even more effective exercise training [2][3], these technologies are combined in the rehabilitation system we have created [4]. Using a haptic robot as the central hardware component, a software and hardware system setup has been realized to support systematic and personalized training for MS and stroke patients. A patient interface and a therapist interface are part of the overall interactive software application. The patient interface gives access to training exercises and games in virtual environments using haptic feedback [4]. The module for therapists allows to define, to personalize, and to monitor the training [5].

The term "patient-centric" refers to a vision as well as to the methodological approach used to realize the system. As patients (and therapists) are the primary target users, it is of utmost importance to serve their needs. Therefore, the development methodology being used adheres to user-centered design and

involves patients as well as therapists, clinicians, software- and interaction specialists.

A detailed description of the different phases of the development process, including patient studies to assess the clinical relevance and usability of the interactive system, and of the details of the resulting system, is beyond the scope of this paper. Here, we will focus on one particular aspect of the training (rotation of the forearm; pro- and supination) and illustrate how the patient-centric approach influences different levels of the system (training exercises, software supporting the therapist's job and adaptation of hardware/interaction devices).

Though visual appealing, easy to use training tasks in the virtual environment and games definitely play a role to motivate the patient for continued training efforts, a specific selection of the training exercises is necessary to strive for a successful rehabilitation trajectory. The activities to be trained on should be meaningful to support functional recovery [6] in order to keep up the motivation of the patient. The method applied in our project was inspired by the T-TOAT (Technology supported Task-Oriented Arm Training) method, which allows integration of daily tasks into technology supported training [7]. In this method an activity of daily life skill (ADL skill) is divided into components (segmentation) following a task analysis, subsequently, these components can be practiced: first isolated and later in combination with other components. In our haptics-based rehabilitation system we continue on this method by providing basic training exercises which include only one skill component, but also more advanced training exercises (or games) which combine multiple skill components.

As mentioned above, this paper focuses on the pro- and supination skill component and the possibilities of the training system to facilitate pro- and supination of the forearm. Activities of daily life (ADL), such as eating/drinking, writing, combing hair, which are meaningful for the patient, necessitate rotation of the forearm (pro- and supination). Another day to day example where pro- and supination of the forearm plays an important role is turning a key in a lock, and many other examples can be found where forearm rotation is inevitable to successfully complete a task in a patient's daily life.

This paper clarifies how pro- and supination is supported in our robot-assisted rehabilitation system. Next to a general overview of the system setup, we describe the interactive software applications in the virtual environment to train the basic skill component pro- and supination as well as a simple game ("Watering the flowers") to combine this skill component with other skill components. The patient-centric approach is also found in the description of the personalization infrastructure for the training exercises. Furthermore, we explain how the existing ADL gimbal had to be altered for patients to be able to perform this skill component.

2. SYSTEM SETUP

For the purpose of understandability and to place software and hardware design decisions in the appropriate context, we will first present a general overview of the system setup and the training exercises.

Figure 1 shows an overview of the system setup. The central component of the system is the MOOG HapticMaster [8] that functions as an output device, providing haptic feedback during the training by guiding or hindering the patient with exerted forces, but also as an input device, allowing the patient to interact with the software applications that deliver the training exercises. As will be detailed further, the HapticMaster was mainly chosen because of its abilities to provide a relatively large workspace and to exert a desired range of forces.

The HapticMaster is equipped with an ADL gimbal, which is the peripheral device where the user can place her hand and that is designed by MOOG to support activities of daily life (ADL). The patient is sitting in front of the HapticMaster in such a way that the bar of the device cannot come in contact with the patient. The patient's hand is placed in the gimbal and secured into the attached brace. Both the haptic device and the gimbal, and in particular the adaptations that were done in the context of the pro- and supination training, are described in detail further in this paper.

A large display / TV screen is placed behind the HapticMaster, approximately 1.5m in front of the patient. This Full HD 40" TV screen (Samsung) is used to project the exercises to the patients. The smaller screen that is visible in Figure 1 to the left of the large patient's display is the therapist interface, which can also be located in another place but usually it will be nearby the location where the patient is training under supervision of the therapist.

Figure 1 also shows the use of a Sling device manufactured by FOCAL [9] for those patients needing a substantial anti-gravity support to be able to perform the training exercises.

Before we provide details on the hardware and adjustments made for the particular MS- and stroke training context, the next section will describe the patient's view of the system and the pro- and supination training exercises on different levels of complexity.

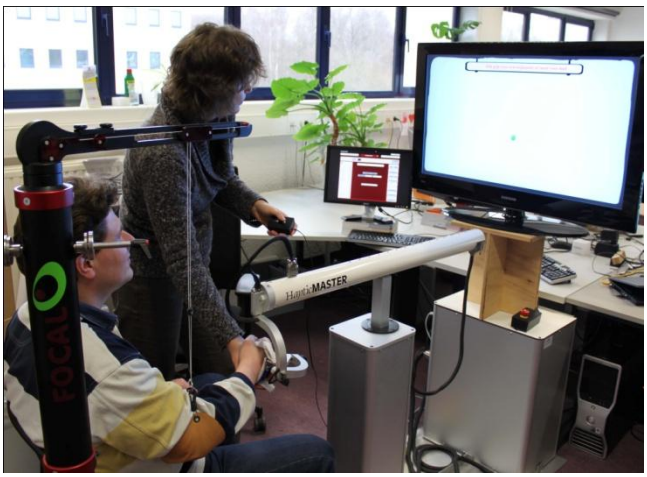

Figure 1: Hardware Setup, including haptic master, sling and visual display

3. PRO- AND SUPINATION TRAINING EXERCISES

We will focus on a description of pro- and supination training exercises to illustrate how the abovementioned setup is used in the context of rehabilitation of MS and stroke patients. This particular kind of training exercises is indeed representative for the approach and purpose of the system, as its relevance shows from the fact that many daily life activities consist of movements which require rotation of the forearm. Simple activities as drinking or opening a door are not feasible if a patient cannot turn his forearm. Therefore, in a patient-centric rehabilitation system, patients should be able to effectively train this particular kind of movement.

Exercises for training the pro- and supination movement are offered as interactive applications on two levels in the virtual environment of our rehabilitation system. The first level trains the skill component in isolation, and therefore the relatively simple training exercise focuses solely on the pro- and supination. The training on the more advanced level combines the pro- and supination of the forearm with several types of other movements such as lifting and transporting. This resembles more the activities in daily life, where patients also have to move their arm to a certain position, stabilize it at the correct position and then make a pro- and supination movement. For example, when they want to drink from a glass, they need to take a glass and bring it to their lips while maintaining the same orientation, stabilize the glass and then pronate the forearm to drink from the glass.

Before describing the pro- and supination training tasks on the two levels, we will clarify the personalization infrastructure that is incorporated in the rehabilitation system to take into account the different capabilities of patients.

3.1 Personalization of Exercises

Patients' abilities for upper limb usage differ a lot for individual patients, and some will have more trouble with turning their forearm than others. So (1) a way to measure these differences needs to be determined, and (2) afterwards training expectations and the setup of the training program has to be adjusted according to these measurements. This personalization approach ensures that the effort for training exercises is within the capability of the patient, and does not ask for movements of the arm and hand that are impossible or harmful.

To realize the first aspect of the personalization infrastructure, measuring the individual differences between patients, we created calibration applications to measure the active range of motion (ROM) of the patient. These applications will be used by the therapist before the patient executes the training exercises.

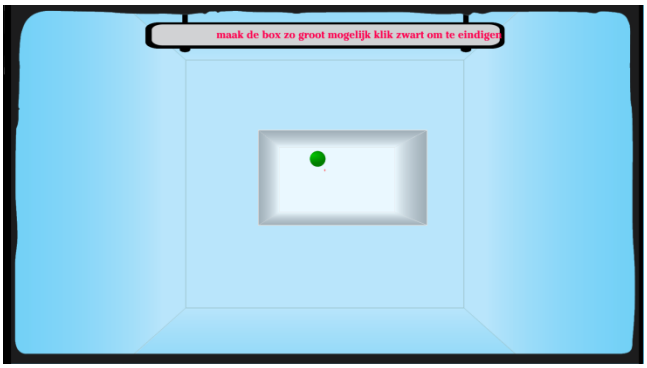

Figure 2: Active ROM Application

First of all the active ROM (Figure 2) of the arm has to be determined. The patient will have to move his arm as far as possible in every direction, without using compensations of the upper body. The HapticMaster device follows the movement but does not deliver extra support for the patient. The software records the outer limits and stores this information in a central database. Each subsequent training exercise will take these values into account, ensuring the distance of movements within the exercises does not surpass these values. This is done by scaling the actual movements of the HapticMaster to the required movements whilst the patient performs the exercise.

A similar procedure is used to record the patient's active ROM of pro- and supination (Figure 3). Before measuring this value the therapist must decide at which position of the arm the rotation has to be performed, as the active ROM of pro- and supination probably changes for different arm positions. It is the task of the therapist to select an appropriate position and confirm it by means of the remote buttons he disposes of (see 4.3). Once a position is selected the HapticMaster will restrict the movements of the arm and measure the correct angles of the gimbal, calculating pro- and supination angles. These values are also stored in the database.

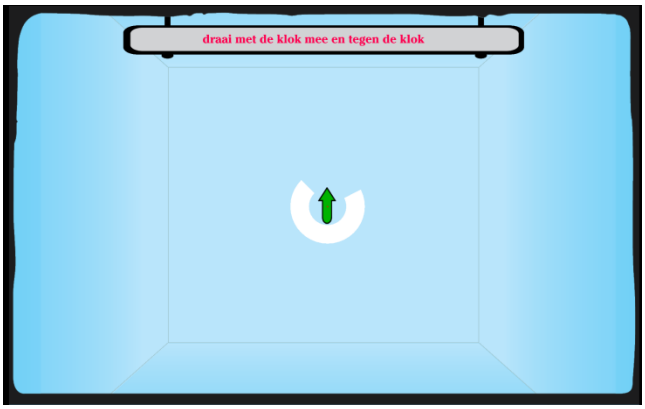

Figure 3: active pro- and supination application

The basic training exercise, that trains the pro- and supination movement in isolation of other skill components, will not require any orientations outside these measured angles. Similarly, the advanced exercise will correlate the measured rotations to requested actions in the simple game, such as turning the bottle.

3.2 Basic Pro- and Supination Skill Component

This exercise is designed specifically for training only the pro- and supination movement. The design is kept simple so that there are no distracting factors like constantly moving their hand to a new position. It enables the patient to concentrate completely on performing the correct pro- and supination movement.

The goal of the exercise is to train the patients to reach certain orientations of the hand indicated by the interactive application. The patient has to perform several repetitions in a given time. For each repetition the patient needs to rotate his/her forearm differently. These orientations are chosen randomly within the patient's maximum pro- and supination angles.

When the exercise begins the patient is guided by the HapticMaster to a certain position in space. This position is determined by the therapist and corresponds to a certain percentage (determined by the difficulty level) of the patient's active ROM measured by the system as explained in the previous subsection. On arrival at the correct position the HapticMaster will be fixed, so the patient cannot deviate from this position.

The visual design of the application is shown in Figure 4. The green object in the middle of the screen can be controlled by the patient by pro- and supinating his or her arm, and is in fact the cursor in the simple virtual environment that is shown. Since the HapticMaster has been fixed by the software after guiding the patient to an appropriate position, the patient can only rotate the

gimbal and intuitively control the virtual object, and therefore practices exactly the pro- and supination skill component.

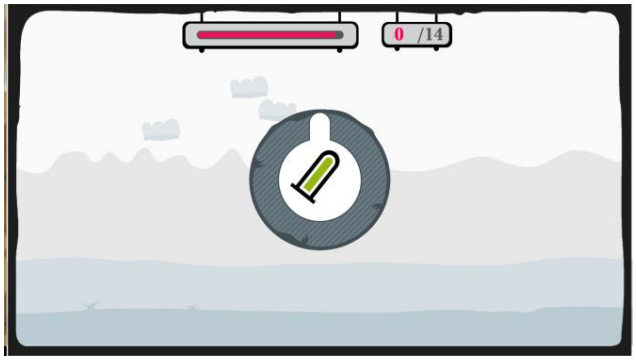

Figure 4: Basic Turn Exercise

The cursor is enclosed by a gray outer disk. Within this disk lies a white opening which fits the cursor. To complete the exercise, the patient needs to pro- or supinate the forearm in such a way that the green object is positioned in line with the white opening in the outer ring. When the patient reaches the correct angle, a timer will appear and start the countdown. The patient needs to keep the correct angle for the duration of the timer. When the patient is not able to keep the correct angle, the timer will reset and the patient has to start all over. If she succeeds to achieve the goal, the white opening is turned to a new angle and the patient has to turn the green object to the correct angle once again. The new angle is determined at random taking into account the active ROM of the patient. The application will end if the time has run out or if the maximum number of repetitions (as defined by the therapist) is reached.

3.3 Advanced Pro-and Supination Exercise

The training exercises on the more complex level in our rehabilitation system focus on the pro- and supination of the forearm combined with other skill components. In the context of this paper, we present one example of this kind of training exercises, called "Watering Flowers". The training exercise takes the form of a simple game and is based on a realistic task, namely watering the flowers. In this particular game, the patient has to combine several movements (such as pro- and supination, transport, lifting …) similar to movements that are performed in daily life.

The patient's task, that plays the role of a simple game concept, consists of watering flowers by giving them the right type (say color) and amount of water. The visual feedback of a successful action is growing flowers. The goal is to collect as much points as possible within a certain time limit, by picking fully grown flowers. The patient only needs to water the flowers until they are fully grown, the picking goes automatically. So, motivational feedback is provided to stimulate continued training effort.

Figure 5 shows the virtual training environment. In this figure the cursor is represented by a hand holding a bottle which can be filled with colored water. A bottle requires a precise movement because the bottleneck is very small. Alternatively, a glass with wider top side and thus urging for less precise movement is available. Depending on the skills of the patient the one or the other can be selected.

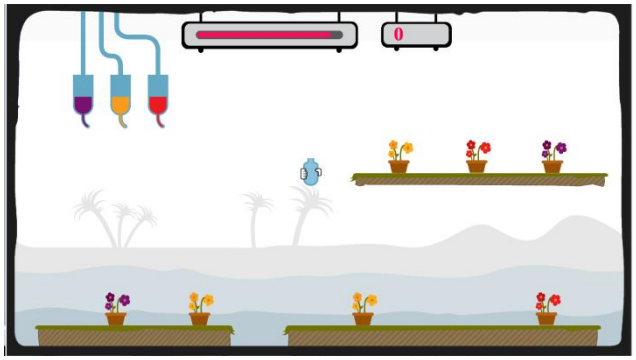

Figure 5: Advanced turn exercise

By holding the top of the bottle/glass beneath one of the water containers, located in the top-left corner of the screen, the bottle/glass can be filled. This action requires that the patient can transport his arm to a certain position, assume the correct orientation and hold this pose for a few moments. The weight of the bottle/glass will also be adjusted according to the amount of water in the bottle.

Having a filled bottle/glass the patient can choose one of the flowerpots located in the environment. To water flowers the patient first needs to transport the bottle/glass with the correct orientation to the flower pot, otherwise spilling the water as in a real life environment. Next he needs to make a pouring movement by rotating his forearm so the opening will be downwards. When the correctly colored water is giving to the flowers they will grow, otherwise they will wither. When enough water is given and the flower is fully grown, points are added to the score while flowers that wither will decrease the score. When no water is giving to a flower for a given time it will degrade gradually, thus motivating the patient to water different flower pots.

In the simple game environment for this exercise, pro- and supination of the forearm has to be performed at several positions in the training environment. Orientations must be maintained by the patient while moving and while filling the bottle/glass.

4. ADJUSTMENTS TO HARDWARE SETUP

Above, we have described the general system setup including hardware and the interactive software applications on different levels to allow the patient to perform the training tasks. In this section we will elaborate on considerations about the system setup that is used and on necessary adaptations that were made to the hardware to sufficiently support the patient's training.

4.1 HapticMaster

The advantages of the haptic device that is being used, a HapticMaster [8], are that the device has a large workspace and it can generate forces up to 200N. These advantages make the HapticMaster suitable for use in rehabilitation of the upper limbs. The HapticMaster uses admittance control, meaning that forces exerted by the user are measured and which results in movement by the device. This is in contrast with many common haptic devices, like the Phantom, which are impedance controlled, where the user's movements are measured and reaction forces are fed back to the user. Because the HapticMaster is always moved by forces exerted at the gimbal (where the patient's hand is attached)

and not by movements of the user, it can be larger and weigh more in contrast to the impedance controlled haptic devices. This results in the availability of a bigger workspace and more force than is offered by impedance controlled haptic devices. The HapticMaster is normally equipped with a knob to move the device around. This is not very handy for patients, since they are required to hold on to the knob during the whole execution of the training exercises. Another shortcoming is the fact that rotations cannot be measured when using the knob. We therefore use the ADL gimbal where the hand of patients can be strapped in.

4.2 ADL Gimbal

Regarding the use of the ADL gimbal, we discuss considerations regarding the patient's hand positioning as well as a hardware adaptation.

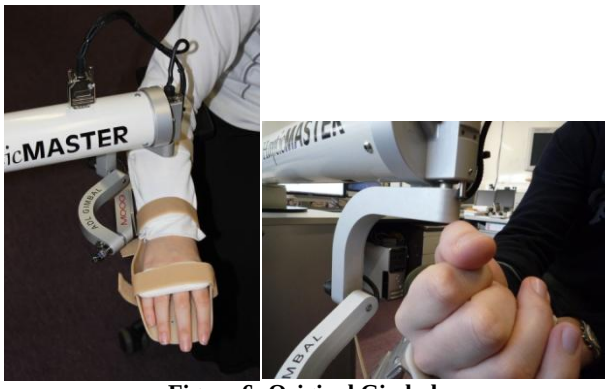

Figure 6: Original Gimbal

In order to perform the exercises to train the pro- and supination skill component, the existing ADL gimbal provided by MOOG for the HapticMaster had to be altered due to the following problem.

The standard active ADL gimbal as seen in Figure 6 measures the rotations of its joints, and thus provides the application with the knowledge of its orientation. As can be seen in the left picture of Figure 6 the gimbal is originally designed for attachment on the lower arm. However in our setup, we need to attach the gimbal on the hand in order to acquire forearm rotation since we want to train the pro- and supination of the forearm orientation in the exercises and not the lower arm. A hand splint was created to support the hand around the ulnar part of the hand instead of the lower arm. But although the gimbal works perfectly with the lower arm attached to it, it works less perfect when the hand is attached at the center of the gimbal. The main problem between the two attachments is the fact that the hand has more freedom of movement than the lower arm. When the hand is rotated (as a consequence of rotating the forearm) as seen in the right picture of Figure 6, the thumb touches the gimbal. We tried several possible attachments of the hand in this gimbal but none of the prototypes gave a satisfying result. There were always some positions where the hand touched the gimbal or even the HapticMaster, the latter resulting in uncontrolled movement of the HapticMaster. In cooperation with MOOG[8,10], the manufacturer of the ADL gimbal, possible solutions to overcome this problem were thought of.

At first some alternative attachment positions of the hand were tried out. One of the suggestions, namely attaching the hand in an angle (20 degrees)with the final joint of the gimbal closest to the hand, gave a better result. We also lowered the hand, which brought the center of rotation of the gimbal and the hand further away from each other thus giving more space for the rotation of the hand. Although in theory the offset of the center of rotation should give some problems, it turns out that in practice it felt the same for the user. Unfortunately this did not fulfill the requirements as the patient's hand still touched the device in some situations. A further and currently final adjustment was extending the radius of the first two joints by 2 cm. This gave the hand enough room to rotate freely, as shown in Figure 7.

Figure 7: Adjusted gimbal

4.3 Safety and Flexibility Considerations

In this section we describe some final features of the system setup and small adjustments to ensure a safe and flexible rehabilitation system for the patient as well as the therapist.

To guarantee the safety of its users, the HapticMaster is always equipped with a panic button. The disadvantage of this standard button is that its activation shuts down the power of the device and, by its design, gravity will slowly position the bar of the device in its lowest position that is not touching the patient's limbs or trunk. In our setup a software panic button is used which will lock the device in its current position. This has the advantage that the application can continue when the switch is released.

In some interactive applications of our rehabilitation robotics solution, for example the calibration, the therapist needs to guide the hand of the patient to a start position and click a button to confirm this position to the system. So for the comfort of the therapist two remote switches are added to the system. The therapist can use them with one hand while placing or holding the patient's hand in the correct position with his/her other hand.

For those patients who are only able to move their arm while the therapist supports the arm, the system is able to provide anti-gravity support by providing an upward force with the HapticMaster, which resembles the therapists support *[paper on anti-gravity is submitted to ICORR, ref when accepted]*. But since this support is only located at the hand, extra support to the elbow can be given when this is mandatory for a weaker patient to keep his/her elbow in a normal position. This is done by the use of a sling device such as the one manufactured by FOCAL[9] (see Figure 1).

5. CONCLUSION AND ONGOING R&D

A system setup and interactive applications for upper limb training of MS and stroke patients has been presented in this paper. We have emphasized the fact that the design and development of a rehabilitation robotics system to support the

training, adheres to a patient-centric approach. Besides close cooperation of the multidisciplinary team with patients during the design, development and evaluation of the interactive software and games of the rehab system, this implies thorough consideration of the system setup.

The inclusion of pro- and supination training of the forearm is very important in the rehabilitation of MS and stroke patients, who want to be able to perform more daily activities without help. Therefore, we have shown the interactive training exercises for pro- and supination to illustrate the approach of our rehab system. Interactive exercises at a basic skill component level but also combined with other movements in a simple game ("Watering Flowers") have shown the structured approach of interactive training in our patient-centric approach. Furthermore, we have described details regarding the fine-tuning of software and hardware (e.g. gimbal) for patients as well as therapists.

The training has been personalized by checking the patient's active range of pro- and supination of their forearm, and by measuring the active ROM of the arm. These values determine the constraints for the exercises to ensure that patients' abilities are taken into account.

Several other skill components and training games have been developed and were tested with patients. Mobile patients visited the lab, but more extensive system evaluation sessions were organized in rehabilitation centers. Evaluations with patients and therapists demonstrate the importance of the patient-centric approach and reveal appreciation for the resulting interactive training system. While further efficacy testing from a medical point of view takes place, the system is extended with additional training exercises and advanced features are added. For example, giving the therapist more control on the location of the orientations (instead of using a random orientation in the active orientation ROM) is investigated. Also, giving the patient more pronation orientations and more supination movements are considered, or encourage the patient to extend her capabilities by presenting orientations which are on the edge of her ROM.

6. ACKNOWLEDGMENTS

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