

SleeveAR: Augmented Reality for Rehabilitation using Realtime Feedback

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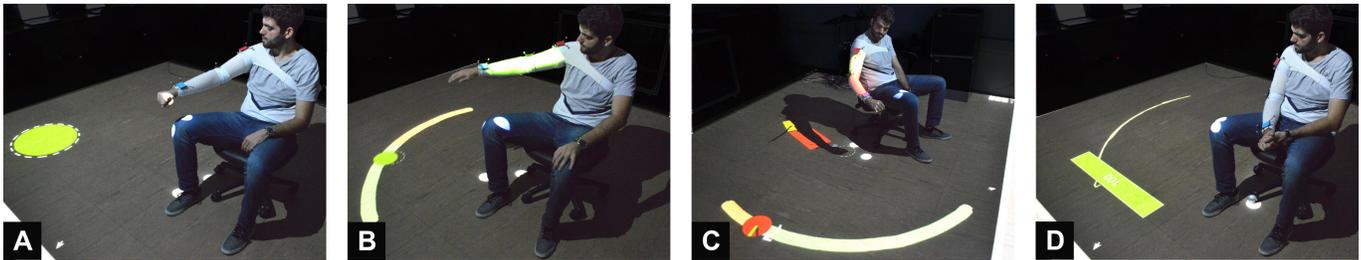


Figure 1. SleeveAR addresses new active projection-based strategies for providing user feedback during rehabilitation exercises. a) Initial position. b) Mid-performance. c) Sleeve Feedback. d) Progress report.

ABSTRACT

We present an intelligent user interface that allows people to perform rehabilitation exercises by themselves under the offline supervision of a therapist. Many people suffer injuries that require rehabilitation every year. Rehabilitation entails considerable time overheads since it requires people to perform specified exercises under the direct supervision of a therapist. Thus it is desirable that patients continue performing exercises outside of the clinic (for instance at home, thus without direct therapist supervision), to complement in-clinic physical therapy. However, to perform rehabilitation tasks accurately, patients need instant feedback, as otherwise provided by a physical therapist, to ensure correct execution of these unsupervised exercises. To address this problem, different approaches have been proposed using feedback mechanisms for aiding rehabilitation. Unfortunately, test subjects frequently report having trouble to completely understand the provided feedback which makes it hard to correctly execute the prescribed movements. Worse, injuries may occur due to incorrect performance of the prescribed exercises, which hinders recovery. This paper presents SleeveAR, a novel approach to provide new real-time, active feedback strategies, using multiple projection surfaces for providing effective visualizations. Empirical evaluation compared to traditional video-based feedback shows the effectiveness of our approach. Experimental results show that it is able to successfully guide a subject through an exercise prescribed (and demonstrated) by a physical therapist, with performance improvements between consecutive executions, a desirable goal to successful rehabilitation.

ACM Classification Keywords

H.5.2 Information Interfaces And Presentation: User Interfaces

Author Keywords

Rehabilitation, Augmented Reality, Projection-based Systems

INTRODUCTION

Physical therapy is of utmost importance for the rehabilitation process, but the individual effort of the patient also plays a very significant role on his own recovery. Aiming to a home rehabilitation process without the presence of a therapist, the feedback has the responsibility of guiding the patient and correcting him throughout his tasks. Because of that, the patients must be ready to learn about their condition and perform the prescribed therapeutic exercises even without professional supervision. However, it is very hard to correctly perform the exercises without help. Without any kind of feedback, the patient may end up hurting himself. Feedback that normally is given by a professional, by visual forms (the therapist demonstrating what to do), auditory (the therapist giving orders) or physical (the therapist applying physical force). Without their presence, it would be desirable for people to receive similar feedback from other sources, to maintain a targeted quality in the task execution.

Augmented Reality is a possible solution to overpass the lack of clear feedback sources whenever a physical therapist is not present. This technology has a significant potential in the rehabilitation field. Additionally, a variety of tools are already available to help on the development process of augmented reality applications that interact with the body [7]. If combined with a carefully designed form of feedback mechanism for the patient, augmented reality (AR) can be of high value on the rehabilitation process [13]. The whole idea is to give more information to a person so that he can more easily execute the assigned task. This feedback is usually given by a therapist

while enduring physical therapy. For unsupervised exercises, a different approach must be followed on the types of feedback used, making sure the therapy goals are achieved and the patient correctly performs the assigned exercises. A possible approach is to take advantage of senses by using augmented reality feedback that facilitates the way a patient gathers feedback information during exercise execution. Studies have already shown that the usage of augmented reality feedback enhances the motor learning of an individual [13].

In this work, we introduce SleeveAR, a novel approach that provides awareness feedback to aid and guide the patient during rehabilitation exercises. SleeveAR aims on providing the means for patients to precisely replicate the exercises, especially prescribed for them by a health professional. Since, the rehabilitation process relies on repetition of the exercises during the physiotherapy sessions, our approach contributes to the correct performance of the therapeutic exercises while offering reports on the patient's progress. Also, without rendering the role of the therapist obsolete, our approach builds on the notion that with proper guidance, the patients can execute rehabilitation exercises for themselves without full time supervision.

This paper reviews related work, details the SleeveAR approach and discusses its design, aided by health professionals' feedback. It also discusses technical aspects of the implementation and presents the results of the evaluation process.

RELATED WORK

Our work builds on related research involving computer-assisted rehabilitation approaches and augmented reality feedback using projection techniques. Also, we address video and augmented reality mirror approaches common in movement guidance systems.

Rehabilitation Systems

Nowadays, we can observe a wide variety of rehabilitation systems which can help improve the recovery of a patient. Many of them have different rehabilitation goals and focus on specific injuries, e.g., stroke [4, 8], or limbs rehabilitation [11, 6, 9]. The use of these systems can have a great influence in a patient's rehabilitation outside of a clinic. Not only it allows for a certain quality on the execution of exercises, but also enables the patient to exercise in a comfortable environment, his home, which makes it easier to stimulate and motivate him during the whole process [4]. The patient's rehabilitation is related to three concepts: repetition, feedback and motivation [12]. Hence, the development of a rehabilitation system should always be influenced by these three ideas and how to approach them. The repetitive nature of rehabilitation exercises can quickly become boring for a patient [10, 6, 5], therefore, there is a need for turning these exercises into something less tedious. When dealing with repetitive exercises, the main goal should be divided into several sub-goals. This way the patient keeps achieving incremental success through each repetition. Furthermore, compared to the approach where success is only achieved after finishing the whole task [12], he also increases his motivation. Gama et al. [7] developed a rehabilitation system in which the user position was tracked

using a Microsoft Kinect. In this system, the user would see himself on the screen with overlaying targets that represented the desired position. If an incorrect posture is detected (for instance, shoulders not aligned or arm not fully stretched), the user is notified in real-time with visual messages. White arrows on the screen were also used as visual cues to guide the patient's arm to the target. For each repetition, points were added to a score, depending on how well the user performed. Klein et al.[9] focused on rehabilitating stroke victims which normally end up with one of the arms extremely debilitated. His research's main focus was to motivate the patient to move his injured arm. Even with a small range of motion, it is important for the patient to move it to improve the recovery. The patient would see a virtual arm overlaying his injured arm, which would simulate a normal arm movement. The virtual arm position was calculated based on a few control points around the patients shoulder and face. The results shown an enhancement of the shoulder range of motion in all the test subjects. Also focused on stroke victims, Sadihov et al. [11] proposed a system which intended to aid in the development of rehabilitation exercises with an immersive virtual environment. Tang et al. [15] developed Physio@Home, a guidance system to help patients execute movements by following guidelines. The patient would see himself on a mirror and, on top of the reflection, visual cues that indicated the direction to which the arm should move. The exercises were pre-recorded by another person and then replicated by the patient.

Most approaches usually rely on Augmented Reality technology, enhancing our perception of the real world by adding information or manipulating our surroundings.

Augmented Reality Mirrors

Mirrors allow a person to have visual feedback of his body. It enhances the spatial awareness which is useful for motor learning activities. The concept of an augmented reality mirror does not necessarily require an actual physical mirror to be implemented. Anderson et al. [2] introduces an augmented reality approach using an actual mirror. This was achieved by creating a mirror with a partially reflective layer facing the user and a diffuse layer in the back. The reflective layer maintained a mirror natural reflection while a light-projector projected images onto the diffuse layer. The result was a mixture of the user's reflection with virtual images. Virtual mirrors could be considered an easier alternative to implement than the one used above. By allowing any screen to turn into a mirror with the use of a color camera, it is normal that this seems to be the most common approach. In a visual feedback perspective, we can generate virtual images on top of the reflection (for instance, for guiding purposes). There has been already applications that make use of augmented mirrors to guide a user, whether it be for rehabilitation [15, 16, 9] or for other types of interaction not focused on rehabilitation [1, 3].

Projection-based Augmented Reality

Using light-projectors for augmented reality has enabled the creation of very interesting applications. Through techniques of projection mapping, it became possible to turn any irregular surface into a projection screen. We can observe this technique being applied in different objects. It is regularly used for live

shows using buildings as the screen. One example could be the promotion of the movie "The Tourist" where projection mapping was applied to an entire building. But it can also be used on the human body to obtain interesting effects. By using projection mapping we can alter an object perception and create optic illusions. This kind of technique can bring great benefits to fields that rely on guiding feedback by being able to focus projection on a body part for example, just as it is necessary in rehabilitation systems. But for it to be useful, the projection mapping should be interactive and done in run-time instead of being pre-recorded like the examples above.

LightGuide [14], explored the use of projection mapping in a innovative way. The projection was made onto the user, using his body as a projection screen. Real-time visual cues were projected onto the user's hand in order to guide him through the desired movement. By projecting the information in the body part being moved, the user could keep a high level of concentration without being distracted by external factors. Different types of visual cues were developed, having in mind movements that demanded degrees of freedom over 3 dimensions. For each dimension a different design was planned so that the user could understand clearly to what direction should the hand move. To apply real-time projection mapping onto a moving body part, its position must be known at all time to make sure the light projector is illuminating the correct position. For this, motion tracking devices are used which enable to record the movement of, in this case, a person.

Information Feedback

The basic goal of feedback is, as the name says, to feed information back to the user. Our senses are constantly at work to provide us information about our surroundings. We can think about our senses as some sort of input sensor, each one designed for a specific type of information. When a patient is attending physical therapy, the therapist is constantly interacting with him. This interaction is important in order for the patient to keep doing correctly the rehabilitation. Not only does the therapist tells him what to do but also demonstrates it and, whenever necessary, physically corrects him. What we observe here is the use of three different types of feedback being given to the patient - audio, visual and haptic, each one being interpreted by hearing, sight and touch respectively. For an automated rehabilitation system to successfully work, these interactions must be simulated by other sources of feedback, in a way that the patient understands what he must do without the presence of the therapist. Visual feedback information is often used in rehabilitation systems to communicate with a user [8]. As one example of visual feedback on an augmented reality perspective, we have the overlaying of information on an interactive mirror for the user to analyze his performance in real-time [2, 15, 16, 9, 1, 3]. Since there are multiple forms of giving feedback to a user, we can see examples where more than one are used at the same time. Combining forms of feedback can provide better understanding of the tasks to a user by minimizing the amount of information given in a visual form and, instead, distribute it. But if not designed with caution, a system can end up overloading the user with too much information at the same time.

Feedback Applications

Sigrist et al. [13] suggests that different types of feedback can complement each other and enhance the user comprehension. Alhamid et al. [1] introduced an interface between a user and biofeedback sensors (sensors that are able to measure physiological functions). Even though it is not aimed for rehabilitation, his approach on user interaction can be analyzed. Through this interface, the user was able to access data about his body and health thanks to the measurements made by the biofeedback sensors. This system was prepared to interact with the user using multiple response interfaces, each one intended for specific purposes. The visual interface relied on a projector that showed important messages and results from the biofeedback measurements. In the other hand, the audio interface was responsible for playing different kinds of music through speakers. The music was selected depending on the user's current state. For example, if high levels of stress are detected, calming music would be played to help the user relax.

One of the most common approaches on visual feedback is the augmented mirror approach already discussed. Its common use is justified by the fact that even without overlaying virtual images, it enables the user to have a spatial awareness of his own body. But since a simple reflection does not provide guidance, we could observe several examples of augmented feedback being applied to the mirror. Tang et al. [15] explored two different designs for visual guidance on a mirror aimed at upper-limbs movement. Their first iteration consisted of virtual arrows that pointed at the targeted position for the user's hand. The second provided a trace of tubes placed along a path which represented the complete movement to be performed by the user's arm. In both cases it was detected some difficulty in depth perception. This kind of visual cues has proven not to be suitable for exercises where the user had to move his arm towards the camera or when he had to contract it.

Anderson et al. [2] tried to provide a more detailed visual feedback by using a full virtual skeleton placed over the user reflection. In this case the goal was to mimic the skeleton's pose and hold it for a specific time. To diminish the lack of depth perception, a second tracker was placed on the user's side. Every time the system detected a large error on the z-axis, a window would appear with a side-view of both the virtual and user's skeleton for him to be corrected. Unlike the previous approach, LightGuide [14] does not rely on interactive mirrors or screens to apply its visual feedback. By using a depth-sensor camera and a light projector, they were able to project information on the user's hand. This approach was able to guide the hand through a defined movement by projecting visual cues. All the information projected on the hand was being updated in real-time influenced by the current position given by the tracking device. The visual cues varied according to the desired direction of the movement. If the current movement only required back and forward motion, only one dimension was being used. Therefore, the visual cue would only inform the user where to move his hand in the z axis through a little arrow pointing to the correct position. Two dimensional movements would combine the first visual cue by virtually painting the remaining of the hand with a color

pattern. The portion of the hand closer to the desired position, would be painted with a different color than the remaining portion. They concluded that by using LightGuide, most of the users could better execute a certain movement than if they were following video instructions.

Our approach follows the work of Sodhi et al. [14] (Light-Guide) and Tang et al. [15] (Physio@Home), both of them addresses movement guidance. But both they lack performance review tools, feature much needed during the rehabilitation process. Also they assume that users always execute almost perfect movements, since the error feedback relies only in pointing to the direction of the pre-recorded exercise. In addition, the Physio@Home, mirror metaphor, provides for poor depth perception.

INTERACTION DESIGN

SleeveAR deals with the specific scenario of the physical recovery of an injured arm. Our approach distances itself from the mirror metaphor by augmenting with virtual guidance information on several surfaces available to the patient, full arm and floor. For the purpose of this research, we address basic physiotherapy exercises for upper arm and forearm:

Abduction-Adduction. Movements of the arm away from or towards the center of the body.

Elevation-Depression. All arm movements above or below an horizontal plane.

Flexion-Extension. Variations of the angle between the upper arm and the forearm.

Since it is required for the patients to precisely perform the prescribed exercises, our approach takes into account that physiotherapy sessions can be completed without professional supervision. Providing that, to minimise the risk of further injuries and promote the progress of recovery, SleeveAR blends movement guidance with performance reports to offer an overall awareness of the recovery progress.

Unlike LightGuide [14], our approach takes advantage of the full arm's surface and the floor. By increasing the projection area throughout the whole arm and user's surrounding environment areas, we can successfully improve an user's awareness while a movement is being executed, as depicted in Figure 2.

In addition, the movement to be performed, originates from a real health professional, so that the patient can achieve a much more realistic and useful rehabilitation process. Therefore, SleeveAR main feature is to preserve the degree of similarity between the performed exercise and the one prescribed by the therapist.

SleeveAR Workflow

Our approach consists of two main concepts. Firstly, the precise recording of the exercise being demonstrated by a personal therapist. And secondly, the ability to properly guide another person, the rehabilitation subject, during the execution of the pre-recorded exercise. Not only it provides a great range of possible exercises, but also employed the therapist's know-how to assign adequate exercises based on a patient's condition and needs. While, at the same time, provides awareness of the

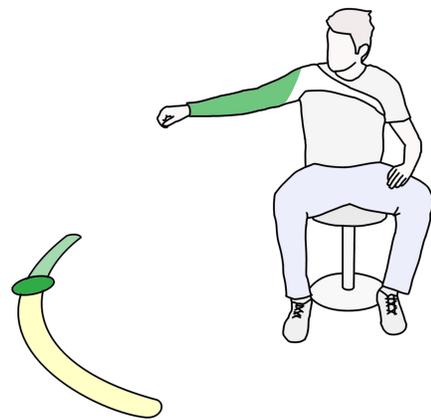


Figure 2. SleeveAR: augmented reality projections on a arm sleeve and into the floor surface provides for movement guidance and performance feedback.

rehabilitation progress to insure the correctness of the patient's movements. With SleeveAR, a therapist can demonstrate the prescribed exercises and make sure his patient performs them correctly without the requirement of his close supervision.

Therefore, the SleeveAR process can be divided into three main stages, as depicted in Figure 3. The first one, the *Recording Stage*, involves the demonstration of the by the therapist being recorded. Next, in the *Movement Guidance Stage*, which focus on guiding the patient to recreate the recorded prescribed exercise. Finally, the *Performance Review Stage* provides the patient with an overview of his performance, by comparing with the original prescribed exercise.

Recording

Usually, the patient's prescribed exercises were specifically conceived designed for the current patient's health condition. With this in mind, we wanted to maintain this relation between a therapist and a patient, by giving the therapists the power for demonstrating the prescribed exercises to the patient. Based on this demonstration, SleeveAR captures the therapist movement and store its movements for a later usage. By giving the therapist the responsibility of demonstrating the exercise, we do not need to worry about the physical limitations of the patient that would use our system to recreate it. We are assuming the recorded exercise is already customized for the patient in question. Given these assumptions, SleeveAR is able to guide a patient through those exercises as best as it can.

Movement Guidance

Our approach divides the task for guiding a patient through an exercise into two stages, reaching the first *initial position* of the exercise (see Figure 1A) and *exercise performance* (Figure 1B). These two stages constitute a simple and clear process for organizing the desired actions to be performed by



Figure 3. SleeveAR Interaction Workflow

SleeveAR while interacting with a patient. To successfully recreate an exercise, we considered the user must first reach the exercise initial position, i.e., the first arm position from the recorded demonstration. For accomplishing this first task, a patient must follow SleeveAR’s feedback to achieve the correct arm position. After the initial position has been reached, as determined by SleeveAR, the system starts guiding the user through the remaining exercise. It could be an almost impossible task for a patient to exactly recreate the original demonstration of the exercise. With this in mind, SleeveAR needs to rely on thresholds for specific values of tolerance. By doing so, if it were required of a patient to achieve, for example, a 90 degree arm flexion, he would not need to actually achieve it, being only enough for him to get close to that degree of flexion according to the specified tolerance. Finally at the end of each exercise, SleeveAR should provide an overview of the patient’s performance in comparison with the original. This helps the patient understand what he might have done wrong and in which parts of the exercise he could still perform better. To successfully guide a patient through his exercises while informing him of his performance, we need to plan how SleeveAR interacts with its users. Next section describes our planned designs for providing real-time and interactive feedback aimed at the user.

Performance Review

Whenever an exercise is finished, SleeveAR must provide users with a review of their performance, as shown in Figure 1D. By reviewing their exercise, a patient is able to understand how close he was from the original exercise.

Patients are informed about their performance by two different designs. First, and perhaps most importantly, the original exercise trajectory is drawn on the floor, followed by the user’s recently executed attempt. These trajectories will help to visualize what fractions of the exercise that can be improved. Second, a score is calculated, based on similarity between both movements, and also projected on the floor. With this “gamification” feature, users feel motivated to improve their score and, consequently, improve their overall performance.

In Figure 4, we depict the feedback provided after the user’s performance. The orange and green line represents the original trajectory and the user’s attempt, which are drawn on the floor. The calculated score is shown with a horizontal bar, which shows the percentage of similarity between the performed movement and the recorded movement.

Real-time Feedback

Our approach employs visual feedback projected both on the user’s arm and onto the floor area inside his field-of-view. It also provides audio notifications to inform the user about the end of its movement and important transitions. The motivation of our approach is to provide the user detailed movement guidance information on the floor, while taking advantage of

his peripheral vision and hearing for important notifications regarding body stance errors and cues to start/stop the exercise.

Visual Feedback

Providing useful and minimalist design was our goal when designing our visual feedback. There were some key points we wanted to address when designing it. First of all, the visual information had to provide the user with a representation of his *current* position, while also showing the target position. These representations had to be done in a way the user would easily comprehend what to do in order to achieve the same target position. To provide suitable feedback regarding the full arm we first applied different design for each of the regions. Next we present our planned visual feedback designs.

Fore Arm. Before creating the fore arm visual feedback it was important to understand what type of movement could be executed with this arm region. The fore arm is connected to the upper arm by the elbow joint and its range of motion could be summarized in extension and flexing of the arm. When extending or flexing the arm, we basically are changing the elbow angle, given by the angle between the upper and fore arm. To represent the current state, we use the black bar, as depicted in Figure 5A. Whenever the user moves his fore arm, this bar moves accordingly. On the other hand, the desired fore arm state is represented by the green bar. For the user to achieve this state, it is required of him to move his fore arm in order for the black bar to reach the green bar. To extend the user’s awareness we added two additional features specifically to this design. Depending on the distance between both bars, the circle color would fade between red, too far, and green, close enough. Also, if the black bar gets too far from the desired position, rotating arrows appear to warn the user he is currently not correctly positioned.

Upper Arm. As for the upper arm region, the type of movement allowed can be represented by the direction it is pointing to, which is obtained by a direction vector from the shoulder to the elbow. Once again, it is necessary for the design, as shown in Figure 5B to both show the current and desired state. To represent the upper arm current direction, a dotted circumference was chosen. By moving the upper arm vertically or horizontally, the dotted circumference should move, respectively, vertically and horizontally.

Full Arm. Each one of the previously presented designs are able to guide each arm region individually. In order to guide a user to a full arm position, we combined both of them as depicted in Figure 5C. By replacing the grey circle, used on the upper arm’s design, with the elbow angle circle from the fore arm’s design, we are able to use both of them simultaneously. All these designs are able to guide the user to a specific, but static, position. For us to be able to guide a user throughout a movement, there need to be some changes on it.

Additionally to the floor-projected feedback, we also present information on the user’s arm. The projection gives feedback to the user by representing the correctness of the current state of his arm by colors (red/green), see Figure 5.

Augmented Floor. During an arm movement, we can not assume that both the upper and fore arm remain the same.

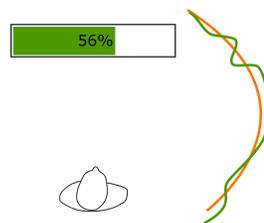


Figure 4. Top view of the projected performance report.

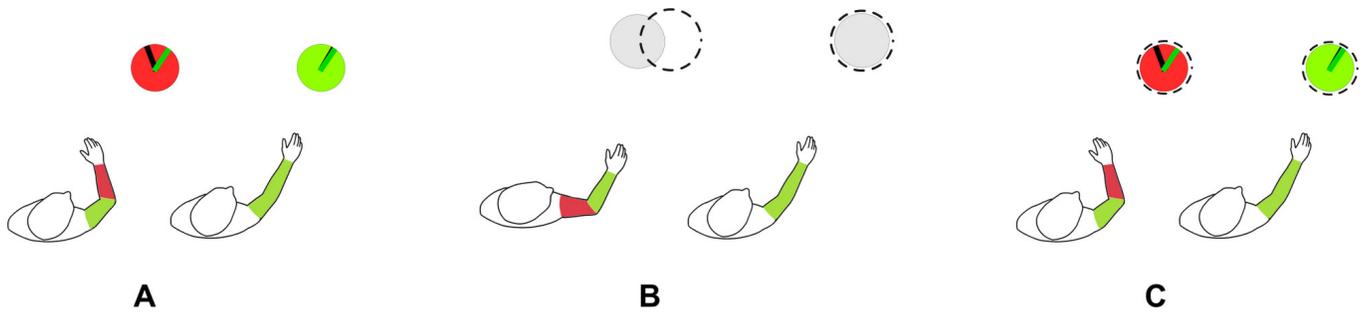


Figure 5. SleeveAR projected visual feedback. a) Forearm flexion feedback. b) Full arm positioning feedback c) Combined Full arm positioning and forearm flexion feedback.

We can have an example where the arm remains fully extended throughout the movement or where the fore arm varies during the movement. In this case there's an elbow angle variation which mean the fore arm desired state is continuously changing. With this in mind, our planned feedback must then change its desired state during the movement. As for the upper arm, to help the user know to where he must move it, a path is drawn showing the direction to where he must go. If we look closely at the previously presented design, we can observe it actually focus around the circle. The fore arm changes the circle itself, while the upper arm controls the dotted circumference that must cover also the circle. With this in mind, if we move this same circle through the movement path, we are able to continuously inform the user about the desired direction while also updating what specific elbow angle he should have. In Figure 6 we can observe an example where the user is already midpoint in the exercise.

Audio Feedback

Audio feedback plays an important role in timing and user notification contexts. Hence, we planned the usage of audio for notifying our users about specific events in SleeveAR. In the Recording phase, SleeveAR had to provide a notification when it actually starts recording. In this case, a countdown audio clip was used to briefly prepare the user, so he could position himself in the desired exercise initial position, before the actual recording began. Another notification sound is also played when the recording has stopped. As for the Movement Guidance phase, SleeveAR notified the user whenever an exer-

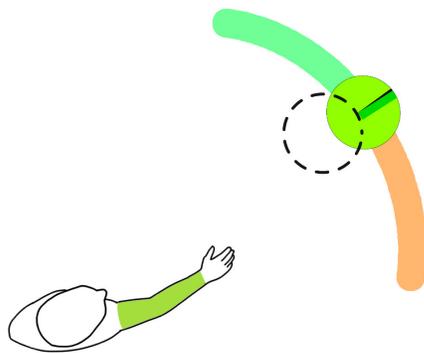


Figure 6. Movement guidance feedback

cise attempt started. From there, the main source of feedback is provided in visual form.

IMPLEMENTATION

We built a prototype in order to prove our assumptions that realtime feedback using projection-based augmented reality originates better results than previous mirror-like video approaches in a real physical therapy scenario. The developed environment is comprised of input devices to track peoples' arm movements, while providing visual and audio cues to perform complex rehabilitation exercises, including progress report. We chose the Optitrack as our tracking system to implement SleeveAR's approach. This tracking system relies on body markers to capture movement.

The Sleeve

We designed a custom sleeve, as shown in Figure 7, made out of wool material. We employed a white colored cloth to better render light projections. To solve positioning problems, we maintain the sleeve in place using a kind of "belt" around the user's torso which greatly increased its stability. Each of the rigid bodies were still attached to a bracelet, but in this case the bracelets were stitched to the sleeve. This improves significantly the rigid bodies attachment due to the bracelets never leaving the sleeve, while also enabling us to still squeeze them more or less depending on the user's arm thickness. Another advantage of using our custom sleeve is providing a better surface to project information, due to it being white. This enable us to have a smoother and more neutral surface to project color for example. With this in mind, for our work, we required three different rigid bodies. Each one should be attached to a different arm location, in this case, shoulder, elbow and wrist. Having an easy way to attach and hard to move method of holding our rigid bodies was vital for our work. Rigid bodies moving out of place during a movement could result in unwanted and unexpected results. Therefore, we created a better attachment method, by using a custom designed sleeve.

Given the real-time tracking information, the SleeveAR prototype then generates user feedback according to the specific exercise the user is attempting to execute. Such feedback is provided by controlling speakers to deliver audio notifications and, most importantly, by making usage of a light projector to project information both on the user's arm and floor.

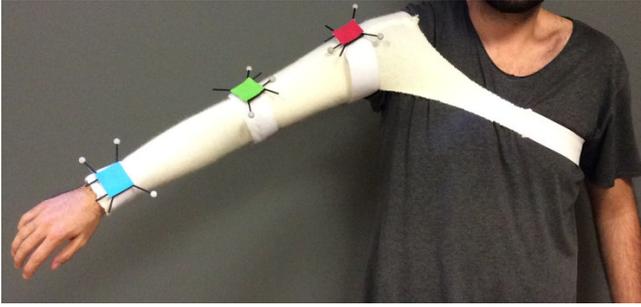


Figure 7. The Sleeve

Setup

Aiming for an environment favourable for the performance of rehabilitation exercises, we build our main setup in laboratory space comprised with the optimal area for tracking and to render projections. The SleeveAR setup is depicted in Figure 8. Multiple infrared motion cameras were installed in the ceiling for position input. Also in the ceiling, we use a commodity short-throw projector, facing downwards, to cover the maximum area surrounding the interaction space. Additionally, two audio speakers were installed as depicted in Figure 8. Our prototype handles essentially two main components:

Tracker Server. The tracker module provides the position data from the user’s arm captured from ten infrared motion cameras. Also, the tracker server transmits a UDP data stream of data over a local network.

SleeveAR Module. This module deals with the position input data from the tracker server, while processing it to determine the correct response, visual or audio feedback. In addition, the SleeveAR module utilizes the positional vector between the projector and the sleeve’s position to determine where to project the arm’s feedback techniques. Since, by calculating where the arm’s shadow is cast, our prototype is able so superimpose projections on top of the sleeve’s surface.

EVALUATION

To evaluate SleeveAR, we intended to observe how well a subject recreates simple arm movements just by following the feedback at his disposal.

To assess performance we exercised the system using simple arm movements, five different exercises were created for this evaluation. Each exercises was simultaneously captured both using video and using the SleeveAR’s Learning component. In this way, we ensure that the same movement is recorded both in video and in our system.

In this section we present a detailed account of the experimental evaluation. We address the experimental methodology employed for assessing our prototype with test subjects, the type of tests performed, the collected sensor information and the metrics used. We then present the experimental results and their critical analysis. All the results are discussed in depth to achieve a better understanding about our prototype functionality and performance. Finally, the chapter reports on a qualitative assessment produced by a professional physical therapist after using our system.

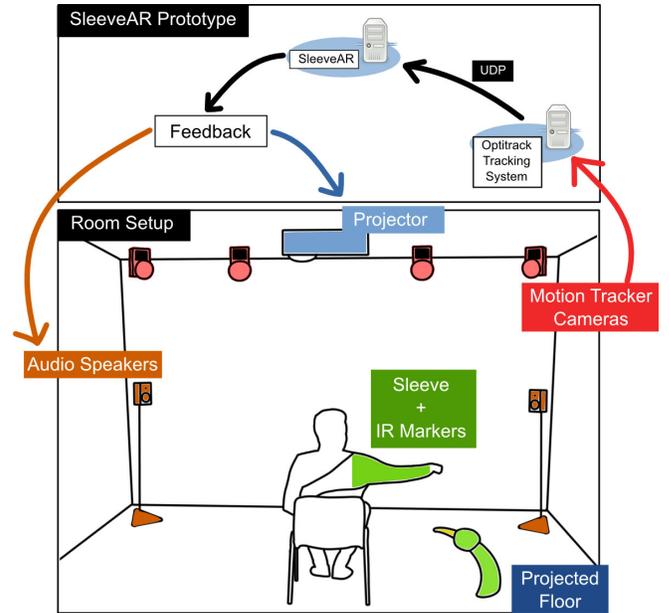


Figure 8. SleeveAR prototype’s architecture and room apparatus.

Methodology

We conducted an experimental evaluation with 18 subjects. Participants were mostly computer science graduate students from our lab and School, whose ages ranged from 19 to 51. Each trial sessions lasted roughly thirty minutes, starting with a brief introduction and a brief explanation regarding the main goal of our prototype.

Next, each participants was asked to replicate five different rehabilitation exercises in two distinct stages: *Video approach*, where the participant watches a video intended exercise at least two times and then, while following the video playing, the participant executes the same movement based on the video observation; and *SleeveAR approach*, the exactly same previously recorded exercises, now with real-time feedback.

Regarding these two approaches, half of the participants started with the former while other half with the latter.

Last, a questionnaire was filled by each participant, concerning the user preferences between the SleeveAR and the video sessions. The questionnaire was comprised of basic user profile questions, followed by nine questions in a form of a Likert scale of six values, evidenced in Table 2.

Performed Tasks

Participants were asked to execute five different exercises which consisted of rather simple combinations of possible anatomic arm movements, described previously. Each exercise

Exercises	Abduction/Adduction	Elevation/Depression	Flexion/Extension
1	✓		
2	✓	✓	
3	✓		✓
4		✓	
5	✓	✓	✓

Table 1. Tasks performed during the evaluation sessions.

consisted of different movement combinations which can be seen in table 1. These same five exercises were executed for both the above mentioned second and third stages. To store the original exercise we first had to capture it, hence, each exercise was simultaneously recorded with a video camera and with motion tracking devices. Under these circumstances, we made sure that the content being stored in video format directly represented the data being stored on SleeveAR's prototype.

While in the SleeveAR phase, the users would first be presented with a small tutorial which introduced interactively each of the feedback components individually. More specifically, the fore arm feedback, followed by the upper arm feedback and finishing with its combination. After the tutorial, both the SleeveAR and Video phases had the same methodology. The user had three attempts for each exercise, being the first two more aimed at practicing the exercise.

Participants

The participants in this trial were invited randomly and consisted mainly on students attending our educational institution. Thereby, the set of test users was comprised of 18 participants, 14 males and 4 females, and all with a college degree. In regard to their age, we had an average age of approximately 26 years old. All participants declared not having any physical impairment at the moment of the test. It should be noted one of our participants was a professional physical therapist.

Results and Discussion

The data gathered consists of user preferences and task performance. The main objective was to address the correctness of the executed exercises. Experiments with test subjects were performed for a baseline scenario, consisting of exercise execution through video observation, and for a patient assisted scenario consisting of real-time feedback provided the proposed prototype. Furthermore, this evaluation provides a formal study of our feedback techniques. Therefore, the analysis of the results is divided into a *User Preferences Overview* and *Task Performance Overview*.

User Preferences Overview:

Results from the questionnaire, as shown in Table 2, suggest that there are no statistically relevant differences between the two tested approaches. Evidencing that, regarding user preferences, test subjects were convinced that they were capable of executing successfully all five exercises.

However, we observed users were more interested in using SleeveAr because it provided a new and interactive experience. Furthermore, due to the gamification provided during the performance review, the majority of users were challenging themselves to improve their score on each exercise. Hence, they were completely focused on exercises execution, trying to make the best usage of our prototype

Participants were also free to share any personal thoughts regarding every visual feedback presented during the tests. In general, our feedback had a positive approval rate. Participants seemed to understand the purpose of each feedback projected on the floor and reacted accordingly to it. On the other hand, the arm projection, even though being considered a very useful

It was easy to...	Median (IQR)	
	Video	SleeveAR
...perform the first exercise?	6 (0)	6(1)
...perform the second exercise?	6 (1)	5.5(1)
...perform the third exercise?	5.5 (1)	5(2)
...perform the fourth exercise?	5.5 (1)	5(2)
...perform the fifth exercise?	5 (2)	4(1.75)
...follow the guidance information?	5 (1)	5(1)
...see if the arm was in the right position?	5 (2)	5.5(1.75)
...see if the arm was in the wrong position?	6 (2)	6(1)
...see when the exercise ended?	6 (1)	5(1)

Table 2. User preferences resultant from the questionnaire. Table values show the median and the inter-quartile range for each questionnaire question (in the form of a Likert scale of six values).

idea, received a few improvement suggestions regarding our implementation. Some participants stated some difficulty following both the arm and floor feedback at the same time, even though they are placed in the same field of view. As for the floor feedback, some participants complained about their arm occluding their vision when looking down at the projections. This could be solved by positioning the floor feedback further away from the user.

Task Performance Overview:

The performance metrics were given by the degree of similarity between the participants' arm trajectories and the original trajectories demonstrated by the therapist. It was measured using the *Dynamic Time Warping* algorithm (DTW), which is appropriate for measuring a degree of similarity between two temporal sequences which may vary in time or speed. With the application of this algorithm in mind, the recorded movements can be reformulated as a sequence of positions. One can then compare the performance values for both the proposed solution and the baseline scenario.

Since an arm movement is divided by the upper and fore arm sections, the DTW was applied to each section individually, thus providing a more detailed set of values. This separation enables to observe if there were significant performance differences between each arm region.

The final DTW values of each exercise are the result of adding both arm regions' DTW values. It is important to highlight that DTW values closer to zero directly represent movements more similar to those of the original demonstration.

Figure 9 shows the average DTW values of each exercise for both approaches. Experimental results show that, in terms of task performance, participants using the SleeveAR approach obtained better values closer to the pre-recorded rehabilitation exercises. Suggesting that, even though test subjects thought that they were almost equally successfully using both approaches, SleeveAR do provide a performance more equal to the one prescribed by the therapist.

INTERVIEW WITH A PHYSICAL THERAPIST

A professional physical therapist, besides the test subjects, also tested the SleeveAR prototype, performing the same exercises as the evaluation ones performed by the test subjects. This expert feedback was afterwards gathered in an interview as a qualitative evaluation of the proposed solution.

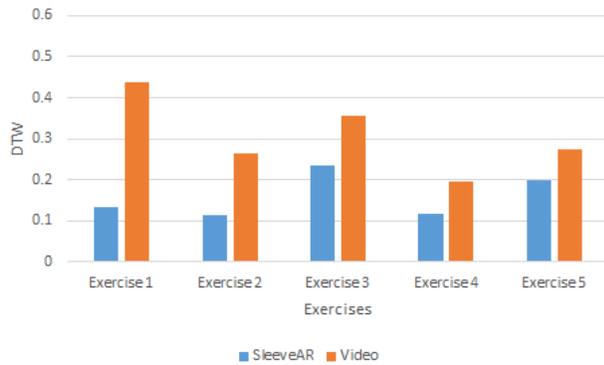


Figure 9. Average results of the Dynamic Time Warping algorithm of each exercise for both approaches.

First of all, this prototype main vision was to prove we were able to guide subjects through pre-recorded exercises in order for them to be as close as possible of the original exercise. With this in mind, we wanted to know in what way would this kind of tool be useful in a regular physical therapy work environment. We also wanted to understand what would be missing to make SleeveAR a more complete tool for a common use along this field of rehabilitation.

We now present the most significant feedback, stressing both the positive and negative aspects of the proposed solution.

Missing feedback from one of the three axis. For SleeveAR feedback to be fully complete, it would need to take into account the missing axis of movement in its real-time feedback. Since this prototype focused on guiding the arm through relatively simple movements, we did not detect this problem. But, consequently, in the evaluation tests, we realized that it might have helped to take this into account. Without verifying the upper arm's rotation, SleeveAR considers both arm poses to be the same. This happens because both the upper arm direction and angle between the upper and fore arm remain the same.

Arm obstructs visibility. Occasionally, the right arm might obstruct the user's vision, making it difficult to observe the feedback being projected onto the floor. This issue could be solved by projecting all the visual feedback further away from the subject

Increase number of tracking points in shoulder area. In physical therapy, a lot of arm movements also focus on the shoulder area. With this in mind, it would be necessary for our sleeve to contain more tracking points around the shoulder instead of only having a tracking point for the shoulder, elbow and wrist.

Potential useful tool for patient reports. Some physical therapists follow a group of standard arm movements to initially evaluate a patient's condition. With this tool, they could receive full reports with necessary data that otherwise they would have to measure physically. It could be possible to extend SleeveAR to return several additional information about a patient's range of movement after executing a group of exercises. This would allow a physical therapist to have access to

information much faster and, possibly, more precise about the patient.

Also, with the possibility of recording movements and later replaying them, SleeveAR could offer a great way of demonstrating the patient, in a visual form, how much he has improved over the course of his rehabilitation, by replaying the recordings of his movements.

A great tool to help a physical therapist when multi-tasking. While working in a physical therapy gymnasium, therapists often have to look after several patients at the same time. Tools like SleeveAR could help the therapist by lowering the amount of times they have to correct a patient and, therefore, focus on another patient that might need more priority help.

Provides a great motivation with the feedback received. The Knowledge of Performance and Results demonstrated in SleeveAR is very satisfactory and could really help in motivating a patient while showing his evolution as he keeps repeating the exercises. Being able to show how the patient performed by drawing his trajectory over the original exercises helps understanding which parts need improvement. Also, the real-time feedback does a great job at instantaneously showing the patient what to correct on his exercise.

CONCLUSION AND FUTURE WORK

Augmented reality with visual feedback for rehabilitation is expected to provide a patient with improved sources and correction when executing exercises outside of a clinic. This would be preferred, as opposed to exercising with no feedback where there is no way of correcting the execution. The state of the art presents several solutions to provide guidance during movement's execution. However, there is still room for improvement, and much research is needed to determine the optimal combination of different feedback sources. Projecting light on top of the limbs to guide a subject through a movement had some promising results, still it is difficult for patients to accurately replicate the rehabilitation exercise prescribed.

We have introduced SleeveAR, which brings augmented reality feedback and movement guidance to therapeutic and rehabilitation exercises. Not only to precisely guide people in how to perform, but also, to provide simple and clear awareness of the exactitude or the incorrectness of the required actions, using visual and audio cues. With SleeveAR, patients are able to formally assess feedback combinations suitable for movement guidance while solving some of the perception problems and also contribute with different feedback techniques in addition to the ones observed in the state of the art. Furthermore, results from user tests suggests that people can replicate previously pre-recorded movements by following our proposed feedback approaches.

Despite that, we consider that it is both possible and interesting, as future work, to add multitude of projected surfaces (walls, furniture, or even the ceiling) to determine their impact on the people performance and awareness during a rehabilitation session.

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