Enhancing patient freedom in rehabilitation robotics using gaze-based intention detection

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***Abstract*—Several design strategies for rehabilitation robotics have aimed to improve patients' experiences using motivating and engaging virtual environments. This paper presents a new design strategy: enhancing patient freedom with a complex virtual environment that intelligently detects patients' intentions and supports the intended actions. A 'virtual kitchen' scenario has been developed in which many possible actions can be performed at any time, allowing patients to experiment and giving them more freedom. Remote eye tracking is used to detect the intended action and trigger appropriate support by a rehabilitation robot. This approach requires no additional equipment attached to the patient and has a calibration time of less than a minute. The system was tested on healthy subjects using the ARMin III arm rehabilitation robot. It was found to be technically feasible and usable by healthy subjects. However, the intention detection algorithm should be improved using better sensor fusion, and clinical tests with patients are needed to evaluate the system's usability and potential therapeutic benefits.**

Keywords*— *rehabilitation robotics, upper extremities, intention detection, eye tracking, gaze-based interaction

I. Introduction

Over the last decade, a number of robots have been developed for rehabilitation of both the upper and lower limbs. These robots are frequently augmented with virtual environments (VE) that provide interesting tasks for patients. Studies have shown that exercising with a combination of robot and VE can lead to better rehabilitation outcome than exercising with a robot alone [1], that virtual reality in general can offer better rehabilitation outcome than conventional therapy [2] and that skills acquired in virtual reality can be transferred to the real world [3]. However, as emphasized by a recent Cochrane review [2], it is unclear what characteristics of virtual reality therapy are most important.

Among potentially important characteristics, psychological factors such as motivation, engagement and curiosity have repeatedly been highlighted. Especially motivation has long been suspected to play a critical role in rehabilitation [4], and VEs for rehabilitation have been shown to be more motivating than conventional therapy [5]. Several studies have therefore specifically tried to incorporate psychological factors in design strategies for rehabilitation VEs [6, 7]. Specific design strategies include automated difficulty adaptation, rich visual and audio elements, score displays and cognitive challenges to spice up the motor training.

Independently of the VE, the rehabilitation robot must be able to provide support in performing specific motions. The current state of the art includes so-called patient-cooperative or assist-as-needed robots, which maximize the patient's effort in rehabilitation by providing only the minimum amount of support necessary [8, 9]. Such robots also provide patients with a certain amount of freedom in performing a motion, as they do not impose a specific trajectory. Nonetheless, patients are limited in what actions they can perform in a VE, as robots mainly support only specific, predefined actions. For example, though the VE of Mihelj et al. [7] includes rich visual and audio stimuli as well as assist-as-needed support, in the end the robot can only support two motions: pick-and-place motion toward the left or toward the right side of the screen. In our own clinical studies and conversations with therapists, we noted that many patients enjoy themselves the most when they can experiment a little in the VE. For instance, in the cooking scenario of the ARMin arm rehabilitation robot [10], the robot provides active support only for one type of motions: placing meatballs into a frying pan. However, other types of objects in the environment can be grasped and moved around. During our previous studies [7, 10], both experimenters and attending therapists unofficially reported that patients who do not require robotic support often enjoy playing with objects and seeing the effects.

We thus believe that another factor relevant for rehabilitation may be the amount of freedom the patient has in the VE. Increased freedom could make the VE more fun and engaging by stimulating the patient's curiosity and giving a feeling of increased control. Both curiosity and control are essential components of intrinsic motivation [11]. A VE in which patients are free to try different things could therefore potentially increase motivation, but would be more difficult to develop active robotic support for. If there are many actions that the patient can perform, a rehabilitation robot needs to be able to detect the intended action in order to provide appropriate support. This could prove difficult with robots' onboard sensors, which are mainly force and position sensors and thus not necessarily reliable for intention detection in patients with motor impairments.

This work was supported by the Swiss National Science Foundation through the National Centre of Competence in Research Robotics.

978-1-4673-6024-1/13/$31.00 ©2013 IEEE

As a solution, an additional contactless sensor can be used to detect the patient's intended action: a remote video-based eye tracker. Eye tracking has already been used to provide gaze-based interaction to people with various disabilities. For instance, people with cerebral palsy, stroke or amyotrophic lateral sclerosis can communicate by selecting symbols from a screen with eye tracking [12, 13], and people with acquired brain injuries or cerebral palsy can drive a wheelchair with eye tracking [14]. Despite well-documented dysfunctions in both eye movement and spatial perception, at least part of the target population for motor rehabilitation can thus use gaze-based interaction systems.

As many VEs for upper extremity rehabilitation focus on reaching-and-grasping motions, it should be possible to detect the intended reaching motion by detecting what object the patient is looking at. The robot could then support the patient in reaching the known target using already existing algorithms. A gaze-guided robot based on electrooculography was suggested as early as 2004 by Chen and Newman [15]. Though their idea was a robotic arm that does not move the human arm, but simply moves itself to the point of gaze, the principle is similar. However, electrooculography is less suitable for rehabilitation than video-based eye tracking since gel-based electrodes must be worn on the face. More recently, Bergamasco et al. [16] demonstrated the principle of an exoskeleton that can help grasp objects the user is looking at, though that exoskeleton was not meant for rehabilitation. Most relevant for our own work, Corbett et al. [17] demonstrated the control of a HapticMaster robot using eye tracking to determine the target position and electromyography to decode the trajectory itself. Though the robot was used as a simulated neuroprosthesis, the same principle could be used for assistance in rehabilitation robotics.

Though the idea of controlling a robot via gaze is not new, our paper is the first that combines a gaze-guided robot with a VE for upper extremity rehabilitation. The VE is specifically built around gaze-based intention detection, with the goal of giving a patient more freedom in the VE during rehabilitation. Here, we describe the general idea behind the system, the implementation, and a first evaluation with healthy subjects. Based on the results, we propose an improved intention estimation algorithm. Evaluation of the intention estimation with patients is planned for a future study.

II. System Development

A. Rehabilitation robot

Our system is based on the ARMin III upper extremity rehabilitation robot [18] developed at ETH Zurich in collaboration with the University Hospital Balgrist. The ARMin III has an exoskeletal structure with six actuated degrees of freedom, including a hand module. The patient is connected to the robot with cuffs on the upper arm and the forearm. The hand is fixed into the two handles of the hand module with elastic straps. The lengths of the arm segments, the size of the hand and the height of the device are adjustable to the individual patient. Position sensors allow interaction between the human and robot to be measured at the joint level. The robot with a subject is shown in Fig. 1.

A second version of the system has been developed for the ARMin IV, a newer version of the ARMin with seven degrees of freedom and force/torque sensors, but all tests have been performed with the ARMin III.

B. Eye tracker

The eye tracker used is the SMI RED (SensoMotoric Instruments GmbH, Germany), a contactless remote eye tracker placed below the screen on which the robot's VE is shown. It tracks the patient's eyes with two infrared cameras.

The included iView software uses the known position of the eye tracking cameras as well as the measured position and orientation of the eyes to automatically calculate the gaze position on the screen. This gaze position is forwarded to the rest of the system using the C# and MATLAB software development kit provided by the manufacturer. Though the RED supports higher sampling frequencies, a frequency of 60 Hz was used to reduce computational load.

The eye tracker is calibrated at the beginning of each session by having the subject look at five points on the screen in succession. This procedure takes approximately 20 s. The tracker is relatively robust to head movement as long as the subject is seated in the ARMin and looking at the screen, though thick-rimmed glasses can degrade tracking performance. The placement of the eye tracker in front of the ARMin is shown in Fig. 1.

C. Virtual environment - Background

The selection of an appropriate VE is key to exploring patient freedom in rehabilitation. The VE must be both useful and potentially motivating, but must also be complex enough to enable patient freedom. After all, the ability to detect a patient's intended motion does not matter if there is only one motion the patient can perform. A survey of available VEs for upper extremity rehabilitation was thus conducted to find the most appropriate possibility. Such VEs can be broadly divided into activities of daily living (virtual equivalents of real-world tasks such as cooking or shopping) and game-like environments (which also incorporate motions such as reaching and grasping, but in fictional situations).

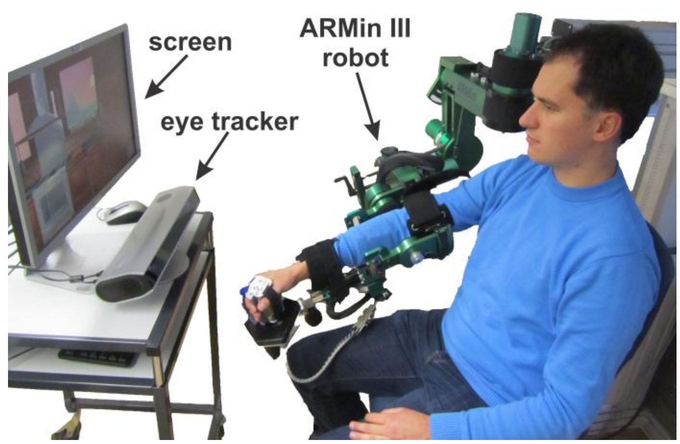

Fig. 1. A person interacting with the ARMin III robot, virtual environment and eye tracker.

Since the ARMin robot has been previously extensively used with activities of daily living [10], we chose to use such activities rather than game-like environments. A 'virtual kitchen' scenario was developed specifically for the presented system. The virtual kitchen is a popular setting that has been previously used in numerous motor rehabilitation studies [19–21]. The setting can incorporate many different arm movements and can also offer the patient some freedom. For example, the patient could select one of several possible recipes and add ingredients in any order or could simply experiment with different ingredients. Furthermore, a virtual kitchen can be made motivating. Recipes can give the patient structured goals, and simply experimenting with ingredients can be fun as new possible results are discovered. In order to gradually introduce the patient to a complex environment, successfully completing recipes could unlock new recipes or ingredients, thus providing longer-term rewards and goals.

D. Virtual environment – Our implementation

Our implementation of the virtual kitchen consists of a frontal view of a kitchen with a countertop, sink, stove, shelves, cabinets and a refrigerator (Fig. 2). The position of the ARMin's end-effector is shown as a pointer on the screen. When the pointer is touching a movable object (e.g. bottle) and the end-effector is squeezed, the object 'sticks' to the pointer and is moved around the environment as long as the end-effector is squeezed. Once the object is released, it stays on the nearest flat surface. When the pointer is over a stationary object (e.g. cabinet) and the end-effector is squeezed, the object is manipulated appropriately: a cabinet is opened or closed (Fig. 3), a button on the stove is pressed etc. In future versions of the scenario, more complex actions could be added (e.g. moving the hand out and to the side to open a cabinet, pronation/supination to turn knobs).

Structured goals are provided within the VE in the form of a recipe book containing recipes of varying difficulties (from e.g. a fried egg to tzatziki). Clicking on the book opens it and allows the patient to flip through the pages (Fig. 4). Pages can be flipped in several different ways, each of which can be enabled or disabled in a special menu: by either touching the ‘previous’ or ‘next’ buttons to the left and right of the page with the pointer, by fixing the gaze on the ‘previous’ or ‘next’ buttons for a period of time, by performing a pronation or supination movement with the ARMin, or by having the therapist press the left or right keyboard button. Once a recipe has been selected, the patient can return to the game and cook.

Each recipe involves a container (e.g. pan or pot) and several ingredients. While each recipe begins by placing the container in the appropriate spot (e.g. the frying pan must be placed on the stove), ingredients may then be added to it in any order to produce the final dish. Some ingredients, however, must first be processed. For instance, the tzatziki recipe requires grated cucumber, which is not initially available. It must be obtained by taking a cucumber and moving it to the grater, which produces the grated cucumber needed for the recipe. Once all the ingredients have been added, the dish is completed. The patient receives a congratulatory message and also receives virtual ‘money’ which acts as a game score measure. In the future, it is planned that the patient will be able to buy new recipes and ingredients with the obtained money.

The VE can sometimes be crowded with objects, which may be problematic for patients who have poor vision or lack sufficient motor control to move to a specific small object and hold it in position there. In such cases, the environment offers two optional features that can be enabled or disabled at any time. The first feature is the ‘zoom’. When the patient fixes his or her gaze on a specific sub-area of the screen for a certain amount of time (adjustable from 0 to 1 s), that sub-area becomes larger, taking up more of the screen. The effect disappears once the gaze is moved from the sub-area again. Zoomable sub-areas include each cabinet or fridge. The pointer remains the same size, allowing magnified objects to be grasped with less motor precision. The second feature is the ‘text pop-up’. When the patient moves the pointer over an object, the object’s name (e.g. “Frying pan”) appears next to the pointer, allowing the patient to quickly determine what object will be picked up if the end-effector is squeezed.

Fig. 2. The virtual kitchen.

Fig. 3. The virtual kitchen with the fridge and a cabinet open.

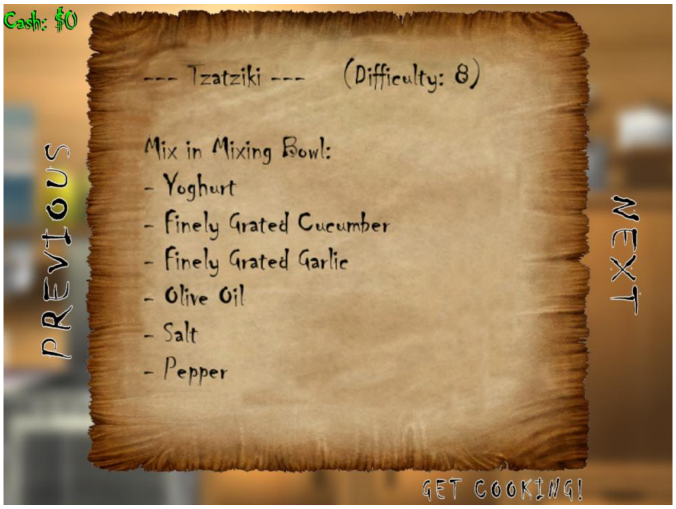

Fig. 4. The recipe book.

E. Gaze-based robotic support

The robot's task in the designed VE is to detect the intended arm motion and support it. For purposes of robotic support, we assume that patients always fixate their gaze approximately on the target of a reaching motion. The system therefore measures the current gaze position on the screen and locates the object in the VE closest to it. This object is assumed to be the desired position. For example, if the patient is looking near a bottle, the system assumes that the patient's intention is to reach for that bottle.

The robot must then intelligently help the patient move toward the desired position. This is not a trivial problem, as the robot needs to decide when to start providing support and how to provide it. First of all, the robot cannot act every time the patient fixates on a particular screen position; he/she may just be examining the environment or staring idly ahead. The challenge of knowing when to act on eye information has long been known in eye tracking literature as the 'Midas touch' problem [22]. A number of methods have been suggested to confirm the selection of a desired object: dwell time, intentional blinking, pressing a button, intentional movement, or electrophysiological measurements such as electromyography or electroencephalography. Our system utilizes a combination of dwell time and intentional movement: the patient must have been fixating on the screen position for a certain amount of time and must begin moving. The thresholds on required dwell time and movement velocity/amplitude can be adjusted on the fly by the operator.

Once the dwell time and movement conditions have been met, the robot begins assisting the desired motion. This is done using the path controller previously developed for the ARMin [10]. Essentially, a reference trajectory is generated between the current end-effector position and the desired position. This reference is based on the minimum angular jerk principle. The robot then moves the patient's arm along the reference trajectory and resists deviations too far from it. The reference trajectory can also be visualized on the screen in the form of a semitransparent tube.

III. Evaluation

At the time of writing, clinical evaluation of the system with actual patients is undergoing the ethics committee approval process. However, a first evaluation has been performed with students and staff of ETH Zurich who were not experienced with eye tracking and rehabilitation robotics. The tests were unstructured: subjects simply interacted with the system under the experimenter's supervision and provided verbal feedback about the different parts of the system (eye tracker performance, virtual environment, robotic assistance).

A. Eye tracker

The SMI RED was successfully connected to both the robot and the VE. Initially, a sampling frequency of 250 Hz was used for eye tracking, but it was reduced to 60 Hz. Since the VE is ordinarily refreshed at 60 Hz, synchronizing it to the RED at 250 Hz created unnecessary computational load. The recommended distance between the RED and the subject's eyes is 60-80 cm. In our system, however, distances below approximately 75 cm allow physical collision between the ARMin and the RED. To avoid this, the RED was placed 80-85 cm from the subject's eyes. At such a distance, we found that virtual objects on the screen needed to be at least 2 cm apart for the system to reliably determine the gaze target of a healthy subject. This is not a major constraint since the scenario should not be too crowded, but it is not yet certain whether the necessary interobject distance may be larger for patients with disabilities. In such cases, it may be necessary to use the ‘zoom’ feature or to increase the size of the objects.

The SMI RED was also accepted from a comfort viewpoint, and subjects reported no problems with obtrusiveness. One subject who performed an especially long evaluation session complained of mild eye pain toward the end of the session (after ~1 hour). This may be due to the strain of focusing on the screen, but may also be due to the infrared light emitted by the RED. As a rehabilitation session in the ARMin robot is generally not longer than 45 minutes, this should not be problematic but should nonetheless be kept in mind. Another issue that should be kept in mind is the cost of commercial eye trackers, which could represent a significant barrier to their adoption in rehabilitation. Simplified, application-specific eye trackers may present a cheaper alternative to those used for general research.

B. Virtual environment

The VE was well-received by the healthy subjects, who cooked several recipes in the environment and found it to be natural. However, people with no experience of virtual rehabilitation are likely to have a positive experience with any VE due to novelty, as we also found in our previous work [7]. The main question is whether interest in the VE decreases over multiple sessions. This cannot be easily determined with healthy subjects, who do not find movement in the VE to be difficult and thus may tire of the scenario earlier than patients who must focus on overcoming their own motor impairments.

In our evaluation, a limiting factor was found to be the number of available dishes and recipes. The current version of the VE has 10 available recipes, and once the subject has tried all of them, there is little else to do. Since a single recipe requires 30-120 seconds for a healthy subject to complete (depending on difficulty), 10 recipes should suffice for a single patient session. Over multiple sessions, the VE may be less interesting since there are no new recipes. While new items and interactions between items can be added, this increases the cost of developing the VE. This, however, is also a problem with other VEs for motor rehabilitation, which are usually less complex than ours. Nonetheless, we are currently working on implementing more recipes and providing the patient with a sense of progress by unlocking new recipes and ingredients as dishes are successfully completed.

Response to the zoom function was mixed. Some subjects found that it allowed them to select objects more easily while others found it somewhat confusing and unnatural. The biggest challenge is the already mentioned 'Midas touch' problem: subjects may simply be gazing randomly at the screen without wanting to activate the zoom. One way of addressing this would be to add requirements for the zoom (e.g. zoom activates when subject intentionally blinks), but another would be to simply make sure no object in the environment is too small. The text pop-up was better received, as it was tied to the pointer position rather than gaze position and thus immune to the Midas touch problem.

C. *Gaze-based robotic support*

Our healthy subjects did not require active robotic support, though several stated that passive support (i.e. gravity compensation) is essential to keep from tiring too quickly. Nonetheless, some subjects were asked to remain passive and only select the desired object with their gaze. This evaluation found two weaknesses. First, the robot was prone to movement when the subject was simply examining the environment, and it was not easy to manually tune the thresholds for movement and gaze duration. Second, whenever objects were close together, the robot would often move to an incorrect, nearby object due to the eye tracker's limited spatial resolution. While this is not a critical problem (since the patient would be moved to the target's general area and would only need to make a small correction), it should still be addressed. Additionally, gaze-based intention detection in patients may be harder due to different behavior (patients may, for example, look at their own hand rather than at the screen while performing movements).

We foresee two potential solutions to the weaknesses of the intention detection and support algorithms. The first possibility is adding additional visual aids. For instance, once the patient has been looking at an object for a sufficient time, the object could subtly change color in order to indicate that beginning a movement will now activate robotic support toward that object. The second possibility is a more intelligent intention estimation algorithm that would combine multiple data sources to guide the robot. As an example, the algorithm could be hierarchical (Fig. 5):

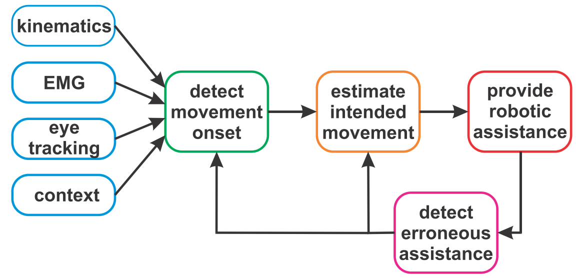

Fig. 5. Proposed hierarchical intention estimation algorithm.

- In the first stage, the algorithm would use movement velocity, the variability of the gaze position (whether the user is focusing on a point or not) and potential additional measures such as electromyography to detect that movement has begun or is about to begin.
- In the second stage, once a movement onset has been detected, the algorithm would use the movement direction and gaze position to determine the target and trigger robotic support. As an additional source of information, we could incorporate contextual task information. For instance, objects that are part of the current recipe would be weighed as more probable reaching targets. This would help e.g. separate targets that are close together and thus cannot be easily separated with eye tracking.
- In the third stage, once robotic support has been activated, the algorithm would watch for any indications that the wrong target had been selected in the second stage. For instance, active resistance by the user (measurable using e.g. interaction force sensors available in the ARMin IV) would indicate that the target needs to be re-estimated or that support needs to be deactivated entirely.

Such an algorithm could be implemented using probabilistic machine learning algorithms such as Bayesian classifiers. It would send out a ‘trigger’ signal to the robotic assistance whenever the probability of a correct decision was sufficiently high. It could even vary the amount of robotic assistance based on the probability of a correct decision by e.g. having the robot move slower when the probability is low.

IV. Conclusion

Our evaluation showed that healthy subjects can successfully use the system, though intention detection is not optimal. As a possible solution, we proposed a more complex, probabilistic algorithm to trigger robotic assistance based on sensor fusion. Once intention detection has been improved with healthy subjects, the system should be tested with patients undergoing rehabilitation. Such subjects may exhibit different gaze behavior that would be harder to analyze.

While kitchen-like virtual environments can be used for rehabilitation and patients can use eye trackers, we do not know whether gaze-based intention detection and increased freedom offer any benefits that patients would not obtain from already established virtual rehabilitation scenarios. One potential benefit is increased motivation: giving patients more freedom may engage their curiosity, immersing them into the environment and encouraging them to exercise more frequently or intensively. However, potential benefits will need to be evaluated with several patients exercising with the system for at least two sessions. It may also be necessary to include different patient populations in order to determine the effect that different pathologies (e.g. neglect) have on the performance of the system.

Aside from our own implementation, eye tracking may have a future in other aspects of rehabilitation robotics. For instance, eye tracking may not only serve to select objects on the screen, but could also make it possible to recognize undesired conditions such as stress and boredom. These have been previously detected in upper extremity rehabilitation using autonomic nervous system responses [23], which are most likely too inaccurate and obtrusive for widespread use. The main advantage of eye trackers in such applications is that they can be completely contactless and require less than a minute of calibration. This makes them suitable for rehabilitation, where any additional setup time decreases the amount of time actually spent exercising with the equipment.

Acknowledgment

The authors would like to thank Mark van Raai for extensive programming assistance, Urs Keller for ARMin support, and ETH Zurich's Consumer Behavior group for initial eye tracker assistance.

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