Towards Extended Virtual Presence of the Therapist in Stroke Rehabilitation

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***Abstract*—This paper considers the use of humanoid robots in residential stroke care to facilitate both direct and indirect interaction between clients and therapists. Direct interaction is realized through a humanoid-mediated teletherapy where a therapist assesses the motor function of a patient and provides therapy customized to the individual. During the teletherapy sessions, the therapist uses a simple speech interface to program therapeutic behavior and activity. Indirect interaction is implemented by the therapist-programmed artifact where a humanoid robot delivers therapeutic activities to the stroke patient in the absence of the therapist. We propose that such an approach can amplify the outcome per hour of therapist time. Outcome data from the current study indicate that the therapist can successfully provide customized therapy to individuals in residential settings and warrant further study.**

I. INTRODUCTION

Many countries are about to experience the increase of elderly population, which could lead to spiraling healthcare costs and shortages of trained professionals to address the needs to the aging population [1]. For instance, Americans who reach the age of 65 can be expected to live an additional 18.7 years and at least 80% of these people will have chronic illness that is severe enough to limit activities of daily living [2]. Many elders will choose to stay in their homes as they age [3]. This can be the highest quality and least costly option for many individuals. However, without support for activities of daily living, gradual cognitive decline, sensorimotor impairment, and/or issues related to maintaining health, otherwise independent elders may need to seek institutionalization [4]. In order to support them in residential settings, the use of humanoids in healthcare has been widely studied as a viable option [5]–[8].

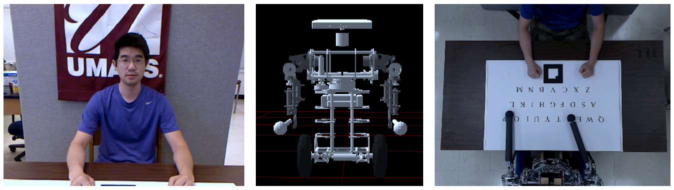
The role of humanoids is investigated in various applications of residential healthcare, including stroke rehabilitation which is the focus of the current paper. In one instance, robots are programmed to socially interact with stroke patients in order to verbally encourage the patients [9], [10]. The role of robots, in this setting, is to help the patients persist in self-driven therapeutic activities prescribed by physical therapists. In another example, a humanoid robot is programmed to physically interact with stroke patients to induce prescribed therapeutic movements [11]–[13]. In both settings, however, therapists need to assess the motor function of the patient, prescribe the therapeutic activities and instruct the technicians to program the robot's behavior that socially encourages the patients or induces the prescribed therapeutic activities. Often, however, this can be difficult in general because therapists may have to travel long distances and see fewer clients as a result.

Telerobotics offers a possible solution. A robot residing with the client in the home can serve as a spatial interface between the client and the therapist and can be teleoperated to provide many of the interactions required during therapy: the therapist can directly communicate with the patient, assess motor function, and prescribe customized therapeutic activities through the robot. In the rehabilitation community, many have investigated the feasibility of teletherapy. The employed technology, however, is mostly a telecommunication system and the use is limited to verbal consultation [14]–[17]. Accordingly, patients need to be transferred to a clinic or a hospital for further care. There exist computer-based teletherapy studies using virtual environment or a simple joystick interface [18], [19]. However, these studies rely on the pre-programmed software that limits the kinds of therapeutic activities that the therapists can employ. Also, these systems require the intervention of technicians to program the software as the therapists and the patients need new activities. In the robotics community, the use of robots to support elderly in residential settings has attracted a lot of research [20]–[22]. However, the focus of these works is on the design of robots and on user preference in possible robot-mediated applications.

In the current study, we attempt to facilitate direct interaction between a remotely located therapist and a stroke patient through a humanoid that is co-located with the patient. During this teleoperated therapy sessions, the therapist uses speech commands to program robot behavior that induces the stroke patient to perform therapeutic movements. Such teletherapy is provided by the therapist once a week. In the

(a) A therapist teleoperates the uBot-5 through a Kinect. (b) A teleoperated robot interacts with a stroke patient.

Fig. 1. Researchers demonstrating teleoperated physical therapy sessions



(a) A view from a Kinect mounted on the uBot-5 (b) A mirrored posture of a uBot-5 (c) A bird's-eye view from a web camera mounted on the ceiling

Fig. 2. The visual feedback that the therapist receives during teletherapy, which is displayed on the ROS rviz simulator.

absence of the therapist, these therapist-programmed activities are reproduced by a humanoid, which implements indirect interaction. We call this concept the *extended virtual presence* of a therapist in stroke rehabilitation. In order to validate the proposed approach, we examine whether the therapist can deliver therapy competently through the interface provided; whether the therapist can produce a customized program that induces therapeutic movements of sufficient challenges; and if the proposed therapy approach is well received by the client.

II. SYSTEM IMPLEMENTATION

A. Robot

The uBot-5 is used for the study. It is a small light-weight bimanual mobile manipulator developed at the Laboratory for Perceptual Robotics at UMass Amherst [23]. Each arm has four degrees of freedom (DOF), two for each shoulder and two for each elbow, and the torso has one DOF. We use the Robot Operating System (ROS) for the software development environment.

B. Teleoperation

In our implementation, the teleoperation mode is initiated by the verbal command "take control", which is recognized using the *PocketSphinx* package in ROS. The therapist can stop teleoperating the uBot-5 by giving the verbal command "drop control." During teleoperated therapy sessions, the posture of the therapist is detected and tracked using a Microsoft Kinect and the *OpenNI* package in ROS (Figure 1a). The joint angles of both arms and the torso of the uBot-5 are computed using the corresponding adjacent body parts of the therapist at 30 Hz. For instance, the joint angle of the uBot-5's right shoulder is computed using the angle of the torso and the right upper arm of the therapist. In order to prevent the uBot-5 from hitting the environment, e.g. a table top, a safety protocol is implemented where the uBot-5 stops moving its arm when it gets close to the environment, e.g. 2 cm from a table. The teleoperation of the corresponding arm is resumed when it moves away from the environment.

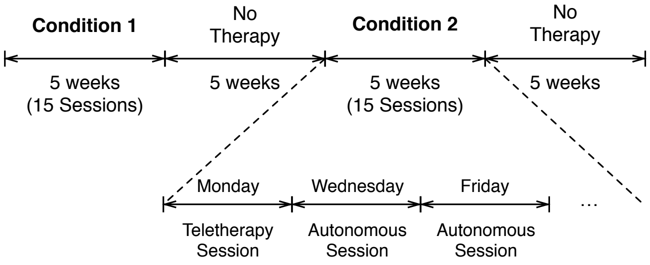


Fig. 3. The design of a single-subject case study used in this paper

C. Behavior Acquisition

In our approach, giving appropriate target positions is important in order to induce the desired therapeutic movements prescribed by the therapist during teleoperated sessions. During teletherapy, the therapist probes various target positions selecting targets based on the patient's movement abilities. During autonomous sessions, it is important that the robot presents only the selected target positions rather than imitating the complete trajectory of probing or wrong movements. Consequently, the robot behavior is determined by the target positions of the uBot-5's hands that are detected and stored by the verbal commands of the therapist: "here" or "there." Based on the sequence of target positions acquired in this manner, the robot writes controllers for both of its arms employing the control basis framework [24]. During autonomous sessions without the therapist's presence, the robot executes the acquired controllers in sequence. After presenting the last target position of the sequence, the robot starts from the first target and repeats. Note that these hand positions are Cartesian coordinate positions while the robot posture during teleoperation is determined by joint angles.

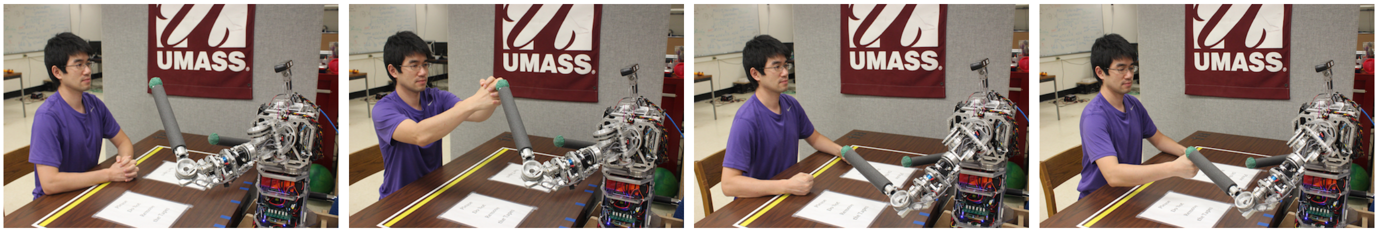
III. METHOD

A. Participant

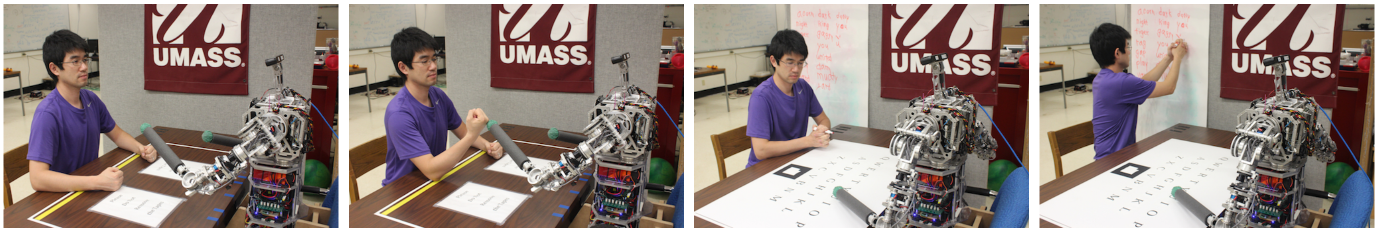
In order to be included in our study, the participant should be at least 18 years old and have had a stroke 6 months or more prior to enrollment. The assessed impairment of upper extremity motor function should be scored between 7 and 38 (out of 66) on the Fugl-Meyer Assessment (FMA). The participant in this study, who will be called Tom, was a 73-year-old male who experienced a stroke 10.5 years prior to enrollment and presented with moderate hemiparesis. He scored 32 (out of 66) on the FMA at the baseline test. Tom provided a written consent on the study procedures.

B. Study Design

Figure 3 outlines our study design. We employed a single-subject case study design which is widely used in treatment



(a) Task 1 - robot presenting a target (b) Task 1 - client reaching the target (c) Task 2 - robot presenting a target (d) Task 2 - client lifting the arm



(e) Task 3 - robot presenting a target (f) Task 3 - client rotating the forearm (g) Task 4 - robot pointing at letters (h) Task 4 - client writing words

Fig. 4. A research assistant demonstrating teleoperated physical therapy sessions

research [25]. Each condition consisted of fifteen sessions for five weeks. Sessions were performed on Mondays, Wednesdays and Fridays unless there were conflicts in schedule. Each session lasted approximately for sixty minutes. Between the two five-week treatment conditions, Tom took a five-week break and did not receive any therapies in order to minimize a carry-over effect of Condition 1 onto Condition 2. Both conditions 1 and 2 used the same following set of therapeutic tasks in order to be able to compare the task-specific competency of the therapist and performances of Tom in an equal setting (Figure 4). Tasks 1, 2, 3 were done for five minutes and Task 4 was done for ten minutes. Between the tasks, Tom took approximately five minutes of break.

1) Task 1. Tom held two hands together and stretched arms to reach for the robot's hand which was presented at various points within the Tom's reachable workspace (Figures 4a & 4b). During the exercise, the impaired arm was assisted by his own intact arm, which enabled a large range of motion.
2) Task 2. Tom lifted his impaired arm to touch the robot's hand which was presented above Tom's hand (Figures 4c & 4d). Since the task was challenging, we considered it successful even if he attained the presented target positions only lifting his forearm not his whole arm.
3) Task 3. Tom lifted and rotated the impaired forearm to touch the robot's hand which was presented above Tom's hand (Figure 4e & 4f). This may appear similar to Task 2, but the recruited muscles were different from those for Task 2.
4) Task 4. The robot pointed at the sequence of letters to spell a word. Tom held two hands together and wrote on the vertical white board the word that the robot presented. Tom came up with a word that started with the last letter of the robot's word and wrote it on the next line (Figures 4g & 4h). The robot, then, presented another word that started with the last letter of the Tom's word. This was repeated until the end of the task. This task was desiged to investigate the interaction between speech and physical therapies, extending our previous work [26]. The analysis of the cross-domain interaction is beyond the scope of this paper, and we focus on physical rehabilitation.

C. Procedure

1) Condition 1: The procedure was adapted from Jung et al. [11], [12]. Before the start of the study, Tom, the therapist and the technicians gathered along with the robot. The therapist assessed Tom's motor capability for all the tasks and determined the initial sets of target positions that were suitable to induce desired therapeutic arm movements. The therapist instructed the technicians in these initial sets and how the target positions should proceed. That is, the target positions that were successfully attained by Tom in three consecutive sessions were moved 5 cm further from Tom. When Tom was not able to attain any of the targets, they retreated 2.5 cm back toward their previous positions. Based on the instruction, the technicians programmed the robot so that the target positions were repeatedly presented in sequence for the predefined duration. During the therapy sessions, the therapist did not intervene. Tom was instructed to communicate with the technician if he wanted to advance the target positions without successes in three consecutive sessions or keep them as they were even after successes in three consecutive sessions.

2) Condition 2: Each week started with a teleoperated therapy session. In this teletherapy session, the therapist (the fifth author) interacted with Tom by teleoperating the robot and verbally programmed the appropriate target positions. The robot administered two consecutive therapy sessions using these target positions in the absence of the therapist. This sequence of three sessions was repeated five times. In this condition, Tom was instructed to express his preference and thoughts directly to the therapist during the teleoperated therapy sessions. The technician did not move target positions in the therapist's absence, even when Tom requested changes. The therapist received two hours of training in teleoperating the robot before the start of the study where she controlled the robot to move its arms in an open space as well as to manipulate a simple object placed on a table. In both conditions, to safeguard against unexpected technical malfunctions during therapy sessions, Tom sits across a table from the uBot-5 to be out of its reach throughout the study (Figure 1b).

D. Data Sources

1) Task-Specific Data: To evaluate the therapist's proficiency in teleoperating the robot and Tom's daily progress in tasks, task-specific data was collected. The target counts that were determined by the therapist during teletherapy sessions and the number of targets achieved by Tom during the teletherapy and autonomous sessions were collected. The success or failure of Tom were recorded for each task and session. In addition, the target positions in Cartesian space presented by the robot.

2) Survey: The experimenter surveyed and interviewed Tom and his spouse. Each question in the questionnaire was answered in 5-point scale (1 = negative, 5 = positive). The survey included questions about the general experience of the teletherapy sessions and that of the autonomous robot-mediated therapy sessions. The questions were adapted from those used in [13].

E. Measures

1) Therapist's Competency: In order for the proposed approach to be used effectively in practice, the therapist must be able to control the robot competently and efficiently. The competency was measured by the number of target positions that were determined by the therapist during the teletherapy sessions (sessions 1, 4, 7, 10, 13 in Condition 2) for Tasks 1, 2, and 3. This is justified by the fact that the therapist chose target positions only when both she and Tom were convinced that they could induce meaningful arm exercises. It could be understood that the more competent and efficient she became the more target positions she could determine in the same given time.

2) Therapeutic Activity Customization: One of the fundamental differences between the two conditions was the amount of direct control that the therapist had over the therapy acitivites. Hence, it is interesting to see how the therapist adjusted the level of challenge as Tom improved. This was inferred from the counts of target positions that Tom successfully and unsuccessfully attained in each task and session. They indicate the level of challenge that was bestowed upon Tom in each session and condition because he would achieve less number of targets if a more challenging set of targets was presented in the same given time. The heights/distances of the targets alone would not indicate challenge levels because multiple positions with the same height/distance would induce arm movements of different joint configurations. Hence, they are used as supplementary information.

TABLE I
THE NUMBER OF TARGET POSITIONS (TASKS 1–3) DETERMINED AND THE NUMBER OF LETTERS (TASK 4) SPELLED BY THE THERAPIST DURING THE TELETHERAPY SESSIONS IN CONDITION 2

Task	Session 1	Session 4	Session 7	Session 10	Session 13
1	21	30	32	33	42
2	20	16	17	20	29
3	18	19	24	28	36
4	12	14	20	21	20

TABLE II
THE AVERAGE COUNTS OF TOM'S SUCCESSFUL/UNSUCCESSFUL ARM MOVEMENTS ALONG WITH THE CORRESPONDING STANDARD DEVIATIONS IN AUTONOMOUS ROBOT SESSIONS

Task	Condition 1		Condition 2	
	Successful	Unsuccessful	Successful	Unsuccessful
1	47±9	0±0	44±5	0±0
2	42±9	0±0	30±7	1±2
3	28±12	3±3	37±7	1±2
Total	117±19	3±3	111±16	3 ± 4

TABLE III
THE AVERAGE NUMBER OF LETTERS THAT THE ROBOT WAS ABLE TO SPELL ALONG WITH THE CORRESPONDING STANDARD DEVIATIONS IN AUTONOMOUS ROBOT SESSIONS

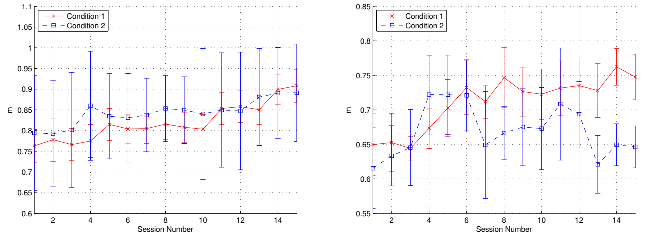
Task	Condition 1	Condition 2
4	25±5	28±6

3) Interaction Effectiveness: The proposed approach advocated the direct and indirect interaction between the therapist and Tom during the therapy. Hence, it is important that Tom understood the intention of the therapist and engaged therapeutic activities both when the therapist was present and when she was absent. We measured the effectiveness of the teletherapy system, as perceived by Tom and his wife through the survey and the interview.

IV. RESULTS

A. Therapist's Competency

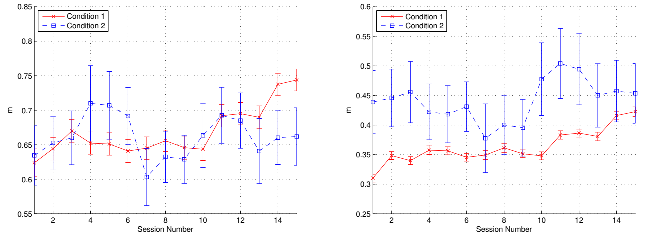
TABLE I shows the numbers of target positions presented in Tasks 1–3 and the numbers of letters spelled in Task 4 by the therapist during the teletherapy sessions. TABLE II shows the average number of target positions that Tom was able to attain successfully throughout the autonomous robot sessions. Since the attained target counts in the teletherapy sessions were governed by the competency/efficiency of the therapist rather than the motor capability of Tom, the counts from the teletherapy sessions were excluded when computing the mean and the standard deviations. In all the tasks, the counts increased as the study proceeded. The target counts for Tasks 1, 3 and 4 were almost doubled and the count for Tasks 2 increased almost 50% from Session 1 to Session 13. For Tasks 1–3, target counts in Session 13 almost equalled the average numbers of target positions successfully attained by Tom throughout the autonomous robot sessions ($Z = -0.4965, p = 0.6191$; $Z = -0.0882, p = 0.9297$; $Z = -0.1127, p = 0.9103$



(a) Task 1

(b) Task 3

Fig. 5. The average distances of the successfully-attained target positions along with the corresponding standard deviations for Tasks 1 and 3.



(a) Distance

(b) Height

Fig. 6. The average distances/heights of the successfully-attained target positions along with the corresponding standard deviations for Task 2.

respectively). On the other hand, it is difficult to conclude that the therapist was able to spell enough number of letters necessary to play the word game ($Z = -1.4350, p = 0.1513$). This indicates that the proficiency of the therapist in controlling the robot improved to the level that were able to induce therapeutic movements as many as Tom could attain for Task 1–3. However, the therapist was not able to achieve enough proficiency in object-related teleoperation (Task 4). Considering the fact that the therapist was given only two hours of prior training in controlling the robot, the therapist may practice further to develop finer control of the robot.

B. Therapeutic Activity Customization

TABLE II shows the average counts of targets that Tom was able to achieve for each task in the two conditions throughout therapy sessions. The total counts of target positions that Tom attained for Tasks 1–3 indiciate that the overall challenge level of targets determined by the therapist in Condition 2 was not significantly different from that of autonomous robot sessions in Condition 1 ($t(9) = -1.2513, p = 0.2424$). While Tom was able to attain similar number of targets for Task 1 in both conditions ($t(9) = -1.7877, p = 0.1075$), the counts for Task 2 and Task 3 were significantly different. Tom attained significantly less targets for Task 2 ($t(9) = -5.6719, p < 0.01$) while he attained significantly more targets for Task 3 ($t(9) = 3.8901, p < 0.01$) in Condition 2 than in Condition 1. A similar pattern can be found in the counts of targets Tom failed to achieve (TABLE II). In Condition 1, Tom failed to achieve the targets only in Task 3 except two unsuccessful attempts in Task 2. On the other hand, in Condition 2, Tom failed to attain similar number of targets in Task 2 and Task 3. This implies that the therapist was able to measure the physical capability of Tom and to determine the appropriate target positions that can balance the challenge level of multiple tasks better than complete autonomous robot sessions in Condition 1. Also, the therapist varied the distances of target positions within each task and session mixing close targets and far ones in Condition 2 (Fig. 5 and Fig. 6).

C. Interaction Effectiveness

Effectiveness of the proposed approach perceived by Tom and his wife were understood by the survey results. Both Tom and his spouse answered that they were able to understand what the therapist wanted Tom to achieve even though they were not able to see the actual therapist during the teletherapy (all 5 points). Both replied that Tom was able to deliver his intention and preference to the therapist and to undertand those of the therapist (all 5 points). Neither of them complained about not being able to see the actual face nor arm movements of the therapist. They also gave 5 points to the experience in autonomous robot sessions except for the fact that his wife gave 4 point to the robot's functional aspects. There was an occasion that the robot was confused noise with the speech command "take control" and imitated the abrupt torso movement of the therapist, which startled her.

V. DISCUSSION

The experiment results demonstrate that it is feasible that the therapist can measure the motor function of the patient and determine targets, balancing the challenge level of multiple tasks. Also, the survery results show that the proposed approach is well accepted by the patient and his spouse. However, the following limitations need to be addressed before making any conclusive arguments about the proposed approach in terms of therapeutic effectiveness.

First, in-person therapy can take many other forms limited only by the imagination of the therapist and the motor capability of the patients. For instance, activities may involve fine motor skills, such as object manipulation if patients are high-functioning. On the other hand, therapists may need tactile feedback with low-functioning patients in order to feel the muscle activiation during therapy. Accordingly, when treating patients with varying symptoms and disability level, the therapists will benefit from the improvements in richer online sensory feedback and more accurate/stable teleoperation that can support a variety of manipulation tasks.

Second, the proposed approach interleaves teletherapy sessions with autonomous sessions where the therapeutic activities are determined mostly based on the therapists' decisions. In the current implementation, however, the robot acts as a passive surrogate in a sense that it does not report the therapist on the targets of earlier sessions nor the correponding performance of the patient. Hence, if the robot provides the therapist with cumulative information of the therapy and the patient's performance in earlier sessions, the therapist may be able to account this when determining new tasks or targets.

In addition, a robot may play a more active role as an exeprt system where it infers and suggests the appropriate targets that may induce maximum therapeutic effects based on the cumulative information.

Lastly, the cognitive load for the therapist may need to be addressed. In the proposed approach, the therapist needs to interact with the patient as well as give speech commands to write therapy activities. Since the number of speech commands was small in this study, the therapists didn't feel overloaded. However, the full-fledged implemenation may provide a large suit of commands. Hence, it is important to investigate the speech interface that can minimize the therapist's load.

VI. CONCLUSION

In this paper, we proposed the concept *extended virtual presence* of a therapist in a remote stroke rehabilitation scenario. This approach is intended to help therapists extend their service by allowing them to treat patients living in their own homes through telerobotics. The quantitative results from our single subject case study indicate that the therapist with minimum technical background can treat the remotely-located patient in the proposed concept. This may amplify the therapeutic outcome for a fixed amount of personalized attention from the therapist. We envision that the approach may let the therapists see a larger number of patients and, consequently, reduce overall healthcare costs for stroke rehabilitation and elder care as the price of robots decreases.

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