Socially Assistive Robotics for Stroke and Mild TBI Rehabilitation

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Abstract. This paper describes an interdisciplinary research project aimed at developing and evaluating effective and user-friendly non-contact robot-assisted therapy, aimed at in-home use. The approach stems from the emerging field of social cognitive neuroscience that seeks to understand phenomena in terms of interactions between the social, cognitive, and neural levels of analysis. This technology-assisted therapy is designed to be safe and affordable, and relies on novel human-robot interaction methods for accelerated recovery of upper-extremity function after lesion-induced hemiparesis. The work is based on the combined expertise in the science and technology of non-contact socially assistive robotics and the clinical science of neurorehabilitation and motor learning, brought together to study how to best enhance recovery after stroke and mild traumatic brain injury. Our approach is original and promising in that it combines several ingredients that individually have been shown to be important for learning and long-term efficacy in motor neurorehabilitation: (1) intensity of task specific training and (2) engagement and self-management of goal-directed actions. These principles motivate and guide the strategies used to develop novel user activity sensing and provide the rationale for development of socially assistive robotics therapy for monitoring and coaching users toward personalized and optimal rehabilitation programs.

Keywords. Socially-Assistive Robotics (SAR), Human-robot interaction (HRI), Robot-assisted rehabilitation, Technology-assisted therapy

Socially Assistive Robotics - A New Type of Rehabilitation Tool

As a result of the confluence of enabling technological and growing societal needs, research into assistive technologies is growing rapidly. Examples of assistive domain amenable to significant technological advances include physical rehabilitation for post-operative cardiac care, post-stroke rehabilitation, traumatic brain injury, and obesity mitigation. Intense task-oriented training is known to be an effective therapy for upper

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limb neurorehabilitation from stroke, as well as unilateral brain damage from traumatic brain injury, tumors affecting arm function, and Parkinson's disease.

As the population ages and the number of sufferers of the above disabilities grows [1,2], the need for effective means of supervising and motivating rehabilitation activities is rapidly increasing. Importantly, the current standard of care cannot meet the growing needs for rehabilitation activities supervision, both in and especially outside of the clinic. The research work we propose is aimed at addressing this important problem by developing and validating non-contact robotics technology as a means to improve task-specific practice and functional outcomes. Specifically, we propose a general and affordable technology that can provide supplemental therapy, supervision, and encouragement of functional practice for individuals with imparied movement capability in an effort to significantly augment in- and out-of clinic care. *Socially Assistive Robotics* (SAR) focuses on assisting through social, not physical, interaction [3] and therefore a human-robotic therapeutic interaction can offer a possible and cost-effective method to reach our goal by maximizing the patients' motivation both during and after structured rehabilitation, such that they will continue practicing beyond the physical therapy session per se. Our long-term goal is to show that such enhancement of sustained motivation can be achieved by incorporating contact-free robotic therapy during rehabilitation. This creates a critical niche for SAR, wherein *Human-Robot Interaction* (HRI) can be used not to replace physical or occupational therapists, but to become frequently and readily available individualized rehabilitation aids. By providing the opportunity for time-extended monitoring and encouragement of rehabilitation activities in any setting (at the clinic or at home), these systems complement human care [4,5,6,7,8,9].

In this developmental/exploratory research work, we illustrate some of the key factors that impact user acceptance and practice efficacy in improving self-efficacy of paretic arm use through human-robot social interaction while optimizing functional performance and recovery. We describe a pilot study involving an autonomous assistive mobile robot that aids stroke patient rehabilitation by providing monitoring, encouragement, and reminders. We also show some preliminary results from a science and technology of non-contact robotics study that focused on the benefits of mirroring user personality in robot's behavior and user modeling for adaptive and natural assistive behaviors. All these are aimed at improving the human-robot social interaction and at the same time enhancing the user's task performance in daily activities and rehabilitation activities. Furthermore, we outline and discuss future work and factors toward the development of effective socially assistive rehabilitation robots.

1. Defining the Need and New Insights for the Hands-Off Robotic Rehabilitation

The technology described in this research features a novel, non-contact approach to robotics-based upper extremity rehabilitation. Our approach is original and promising in that it combines several ingredients that individually have been shown to be important for learning and long-term efficacy in motor neurorehabilitation: (1) intensity of task specific training and (2) engagement and self-management of goal-directed actions. These two guiding principles are incorporated into the development and testing of an engaging, user-friendly home-based robotic therapy for accelerated recovery of

upper-extremity function after stroke hemiparesis that relies on our pilot results in novel human-robot interaction [4,5].

We propose to develop and evaluate robot-assisted rehabilitation technology with general relevance to motor rehabilitation due to stroke, traumatic brain injury, tumors affecting limb use, and Parkinson's Disease. Our work is motivated by the large and growing need for providing motivation and supervision of intensive rehabilitation activities required as part of therapy in such disabilities outside of the clinic. Stroke alone is the leading cause of serious, long-term disability among American adults and the third leading cause of death in the US [1]. Each year, over 700,000 people suffer a stroke, and nearly 400,000 survive with some form of neurologic disability, placing a tremendous burden on the nation's private and public health resources [10]. The cumulative total of stroke-affected Americans is over 4 million, and the estimated annual burden from stroke related disability is $53.6 billion, of which $20.6 billion is in indirect costs due to lost productivity and income. Population-based statistics indicate that age is the strongest non-modifiable risk factor, with the incidence of stroke increasing exponentially after the age of 25, and the majority of strokes occurring in persons older than 65. It is estimated that the number of stroke survivors with disability will almost double by the year 2025 as the 'baby boom' population progressively ages, making the burden even more apparent [11]. For these reasons we propose to perform our evaluation experiments with persons post-strokes, with the understanding that the developed technology is intended well beyond the single cause for disability.

Loss of function of the upper limb is the impairment that is in most need of effective rehabilitation from stroke as well as the other conditions listed above. Statistics indicate that over 80% of first-time strokes (infarctions only) involve acute hemiparesis of the upper limb that significantly impacts the functional independence and health of the stroke survivor [12]. Stroke-related arm disabilities range from deficits in sensation and motor coordination to complete hemiparesis and loss of limb function. In addition, stroke often leaves individuals unable to perform movements with the affected limb even though the limb is not completely paralyzed. This loss of function, termed 'learned disuse,' is most obvious during the early post-injury period but can improve with rehabilitation therapy [13,14]. Yet, only limited attention has been given to upper limb rehabilitation, and functional recovery of the arm and hand has generally been resistant to the traditional approaches compared with that for the lower extremities [12,15]. Rehabilitation of the upper extremity requires more fine motor control than the lower extremity, and that rehabilitation of fine motor skills requires longer and more specific types of task-specific training than is included in the standard rehabilitation program. In addition, health insurance companies often reject requests for rehabilitation past the three to six month period following a stroke due to the belief that additional therapy would not be helpful [16]. However, clinical studies using motor training have found improvement in functional upper limb performance in patients more than 1 year post stroke and cortical reorganization and recruitment of adjacent brain areas associated with intensive use of the affected upper limb have been documented several years after the initial stroke injury [17,18,19].

The most effective known arm-focused interventions with the strongest evidence and potentially the most immediate and cost-effective appeal for the current health care environment share a common emphasis on focused task-specific training applied with an intensity higher than usual care. This, along with the findings of our recent

Extremity Constraint-Induced Therapy Evaluation (EXCITE) randomized control trial [21, 22], suggests that the potential for functional recovery goes on much longer than previously believed, and that the degree of recovery that can be anticipated involves not only the level of initial impairment but the amount, type, and intensity of practice available to the patient during the recovery process. To make significant advances in the field of motor rehabilitation, we need a better understanding of the critical factors that underlie the recovery process at the behavioral, psychological, and pathological levels, and the specific ways that therapeutic interventions modulate that recovery process across these levels. For these reasons, we propose a concerted multidisciplinary collaboration between engineering, computer and clinical sciences that will develop and evaluate cost-effective, evidence-based upper extremity rehabilitation programs aimed specifically at the promotion of engaging, motivating human-robot interaction for accelerated recovery of function.

2. Pilot Study and Preliminary Results

The today's general methodology of rehabilitation robotics involves hands-on application of forces either by the patient to a monitoring robot manipulandum, or by the robot mechanism to the patient, or a combination of the two [23,24,25,26]. Because human-robot contact involves complex issues of safety, such hands-on robotics methods remain areas of active ongoing research, with many outstanding challenges. Moreover, the existing contact robots used for upper limb rehabilitation are not portable and generally require patients to travel to a laboratory for robotic therapy, are very expensive, and expertise is necessary to program and execute trials. Risk of injury to the patient is of concern when movement of a limb with sensorimotor loss is imposed by a robot. Injuries to the upper limb from use of contact robots are of concern and have been documented [23,24]. Moreover, our recently completed clinical trial to determine the relative effectiveness of two different training protocols, delivered during the acute post-stroke period, revealed some surprising findings at the long-term follow-up, 9 months later [20]. Of particular interest, the functional-task training group, who practiced meaningful, functional tasks, demonstrated better performance than the strength-training group on a strength (isometric torque) outcome measure. One explanation for this counter-intuitive result is suggested by the post-discharge, self-maintenance literature. We believe that the functional task practice protocol provided a more favorable and meaningful context for continued arm use and associated strength gains that was mediated through meaningful activity (outside of the therapy session), than was the resistance-strength exercise training protocol. Therefore, the lack of a convenient, practical, non-technical, and safe human-robotic interaction for rehabilitation further supports the rationale of our proposed approach, which explores the contact-free robotic rehabilitation paradigm. The non-contact approach affords the client the opportunity to engage in functional therapeutic interaction conveniently and safely within the clinic or home in a user-friendly manner.

This section describes our first pilot study with a socially assistive mobile robot and the first results. The robot interacts with post-stroke patients in the process of performing rehabilitation activities such as arm movements and shelving magazines, by providing encouragement, guidance, and reminders.

Robot Test-bed

The robot used for our experiments, shown in Figure 1, consisted of an ActiveMedia Pioneer 2-DX mobile robot base, equipped with a SICK LMS200 laser rangefinder used to track and identify people in the environment by detecting reflective fiducials worn by users. A Sony pan-tilt-zoom (PTZ) camera allowed the robot to "look" at and away from the participant, shake its "head" (camera), and make other communicative actions. A speaker produced pre-recorded or synthesized speech and sound effects. The IMU-based motion capture unit provided movement data to the robot wirelessly in real time. The entire robot control software was implemented using the Player robot control system [27].

Figure 1: The Pioneer mobile robot base used in the experiments. Shown is the laser (the blue box), camera (mounted on top of the laser), and speakers (mounted on each side of the laser).

Design

This study [4,5] focused on how different robot behaviors may affect the patient's willingness to comply with the rehabilitation program. Our main goal was to test different voices, movements, and levels of patience on the part of the robot, and correlated those with participant compliance, i.e., adherence to the activities.

The robot was able to safely move about the environment without colliding with objects or people. This was achieved through the use of a laser sensor which provides high-fidelity information in real-time. Moreover, the robot was able to find and follow the patient, maneuver itself to an appropriate position for monitoring the patient, and leave when it was not wanted. This was achieved through the use of highly reflective markers worn on the leg of the patient (Figure 2), in order for the robot to reliably detect and recognize the patient.

The robot was able to monitor the movement of the stroke-affected limb. We used a light weight and low-cost inertial measurement unit (IMUs). The patient wore a maker on the wrist, which provided its 3D real-time position information to the robot through

wireless communication. The robot used the information provided by the motion sensor about the movement of the patient's limb so as to encourage the patient to continue using the limb, or use the limb more or in a different way, as appropriate based on the sensory data.
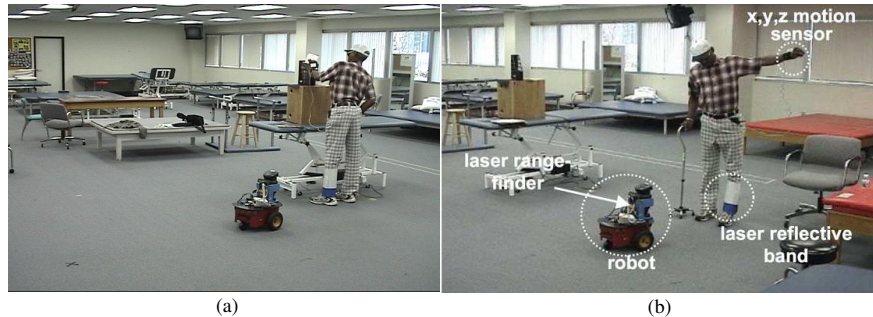
Figure 2: The two rehabilitation tasks: (a) magazine stacking and (b) free movement of the stroke-affected limb. The robot and participants during the two rehabilitation experiments: magazine stacking (left – Figure 2 (a)) and free movement exercises (right – Figure 2 (b)).

The robot was capable of using three distinct interaction modes, as follows:

I. The robot said nothing, and gave feedback only with different beeping sounds. The robot's presence also served to remind the patient of the activity. The robot kept at a distance from the patient and was not very persistent in encouraging the patient.

II. The robot used a "robotic"-sounding synthesized voice for its communication with the patient. It gave simple verbal feedback, including: "It looks like you are not using your arm", "Have you already shelved the books?", "Great, keep up the good work". It maintained a shorter distance to the patient than in the first mode and, when the patient was not reacting to the encouragement by continuing the activity, was more persistent before giving up and going away.

III. The robot used a pre-recorded friendly human voice, with humor and engagement. It stayed with the patient and followed him/her around, persistently encouraging the patient to perform the activity. It also used body movement, wiggling back and forth, side to side and turning around.

The robot was programmed to behave as follows: when activated, it started by finding the patient, approaching him/her, and maintaining a specified distance. It then gave instructions to the patient regarding the activity to be performed. During the activity, it monitored the movement of the relevant limb with the motion sensor and provided continual feedback based on the patient's behavior and its interaction mode.

Our hypothesis was as follows:
H1: More animated/engaging and persistent robot behavior will result in better patient compliance with the robot's instructions and higher patient approval of the robot.

Experiments

This system was evaluated in three short experiments at the USC Center for Health Professions on the Health Sciences Campus and in the USC Robotics Lab on the University Park Campus. Two of these were conducted with patients, and one with non-patients. Of the six stroke patients, two were women; all were middle-aged. The stroke impairment occurred on different limbs among the patients but all were sufficiently mobile to perform the activities in the experiments. All experiments were video recorded and comprised several experimental runs involving three randomly selected types of interaction for each participant. The participants were asked by the robot to perform one of the experimental tasks: shelving books/magazines or any voluntary movement of the stroke-affected limb. The robot measured arm movement as an averaged derivative of the arm angle. In the shelving task, the robot "counted" how many books the patient put on the shelf by monitoring the movement of the arm. Hence, it was possible to fool the robot by merely lifting the arm without any books; this was discovered by one of the patients. In our newly designed experiments this possibility is eliminated. The overall measure of performance the robot used was the length of time the patient persisted in the chosen activity.

At the start of the experiment, the patient was presented with a written one-page introduction to the experiment, followed by a simple questionnaire. Next, the robot was presented. The order in which the robot selected the three different modes of interaction was also randomly selected. After the patient performed both activities in all three modes (totaling six experiments per patient), a second questionnaire was presented. Finally, an exit interview solicited patient impressions and opinions and the experiment was concluded.

Results

We investigated the patients' response to the robot and to the different interaction modes. The pilot results are positive; the robot was generally well-received by the patients, and the patients expressed consistent preferences in terms of robot voices and interface technologies. Some participants continued to perform the activity beyond the end of the experiment, therefore providing further evidence of improved compliance in the robot condition well beyond any novelty effect. The design of the study emphasized the user's response to the robot's behavior. Furthermore, as expected, there were significant personality differences among the patients; some were highly compliant but appeared un-engaged by the robot, while others were highly engaged and even entertained, but got involved with playing with the robot rather than performing the prescribed exercises. All this leads toward interesting questions of how to define adaptive robot-assisted rehabilitation protocols that will serve the variety of patients as well as the time-extended and evolving needs of a single patient. Some of these questions we tried to address in the next exposed studies. Video transcripts of the experiments can be found on line [28]. The details about this study have been reported [4,5].

3. Personality-Matching Study

Our previously described experiment with a SAR system we developed, that monitored and encouraged stroke patients to perform rehabilitation activities, demonstrated that personality differences had a strong impact in the way the user's interacted with the robot. While all patients reported having enjoyed the robot, task performance ranged from strict adherence to the robot's instructions but no obvious engagement, to playful engagement and even repeated attempts to trick the robot. It is known that pre-stroke personality has a great influence on post-stroke recovery [1]; subjects classified as extroverted before the stroke mobilize their strength easier to recover than do introverted subjects [29]. Further, work in human-computer interaction (HCI) has demonstrated the similarity-attraction principle, which posits that individuals are more attracted to others manifesting the same personality as theirs [30,31,32].

Little research to date has addressed personality in human-robot social interactions and no work has yet addressed the issue of personality in the assistive human-robot interaction context.

The research question addressed in this study was as follows:
Is there any relationship between the extroversion-introversion personality spectrum and the challenge-based vs. nurturing style of patient encouragement?

Experimental Design

Figure 3: The participant is performing turning pages of a newspaper task with the robot at a social distance. The laser fiducial is on the participant's right leg, the motion capture sensor on the right arm, and a microphone is worn on standard headphones.

We [7,8] performed a series of experiments in which the simple mobile robot depicted in Figure 1, equipped with a camera and a microphone, interacted with a (healthy) user in an experimental scenario designed for post-stroke rehabilitation activities (see Figure 3). The participants were asked to perform four tasks (designed as functional activities) similar to those used during standard stroke rehabilitation: drawing up and down, or left and right on an easel; lifting and moving books from a desktop to a raised shelf; moving pencils from one bin to another; and turning pages of a newspaper. The subject pool for this experiment consisted of 19 participants (13 male, 6 female; 7 introverted and 12 extroverted). The participants completed a set of questionnaires before the experiment, which were used to assess their personality traits using the Eysenck biologically-based model [33]. The resulting personality assessment based specifically on the extroversion-introversion dimension was used to determine the robot's personality. Our behavior control architecture is based on the Bandura's model of reciprocal influences on behavior [34]. The robot expressed its personality through several means: (1) proxemics (social use of space; the extroverted personalities used smaller personal distances) [35]; (2) speed and amount of movement (the extroverted personalities moved more and faster); and (3) vocal content (the extroverted personalities talked more aggressively ("You have done only x movements, I'm sure you can do more!"), using a challenge-based style compared to a nurture-based style ("I know it's hard, but remember it's for your own good.") on the introversion end of the personality spectrum). The robot used the arm motion capture data to monitor user activity and to determine whether the activity was being performed. The experiment compared personality-matched vs. personality-mismatched (random) conditions.

Our hypotheses were as follows:

H1: A robot that challenges the user during rehabilitation therapy rather than praising her/him will be preferred by users with extroverted personalities and will be less appealing to users with introverted personalities.
H2: A robot that focuses on nurturing praise rather than on challenge-based motivation during the training program will be preferred by users with introverted personalities and will be less appealing to users with extroverted personalities.

Results

The system evaluation was performed based on user introspection (questionnaires). After each experiment, the participant completed two post-experiment questionnaires designed to evaluate impression of the robot's personality (e.g., "Did you find the robot's character unsociable?") and about the interaction with the robot (e.g., "The robot's personality is a lot like mine."). All questions were presented on a 7-point Likert scale ranging from "strongly agree" to "strongly disagree". The data obtained from the questionnaires conclusively showed that the robot's personality was fundamental in the interaction and two statistically significant results were found (ANOVA validation): (1) participants consistently performed better on the task (more pages turned, more sticks moved, etc.) when interacting with the personality-matched robot; (2) both extroverted and introverted participants reported preferring the personality-matched robot. More details about this study can be found in [7].

3. Robot Adaptation Study

Learning to adapt our daily behavior as a function of different internal and external factors it's a fundamental characteristic of humans. Creating robots capable of exhibiting similar sophisticated capabilities has proven to be a very difficult task. Therefore, providing an engaging and motivating customized protocol that is adaptable to user personality and preferences is a challenge in robotics, especially when working with vulnerable user populations and a careful consideration of the users' needs and disabilities is required. A variety of robotic learning approaches is available in the literature, but none include the user's profile, preferences, and/or personality. Socially assistive robotics presents a variety of rich opportunities for exploring learning as a tool for HRI. In this study, we [8,9] focused both on the short-term changes that represent individual differences and on the long-term changes that allow the interaction to continue to be engaging over a period of months and even years.

The research question addressed here is:

How should the behavior and encouragement of the therapist robot adapt as a function of the user's personality and task performance?

Methodology

The problem was formulated as policy gradient reinforcement learning (PGRL) and it consisted of the following steps: (a) parametrization of the robot's overall behavior (including all parametric components, listed above); (b) approximation of the gradient of the reward function in the parameter space; and (c) movement toward a local optimum. This methodology allowed us to dynamically optimize the interaction parameters: interaction distance/proxemics, speed, and vocal content (what the robot says and how it says it). Proxemics involved three zones (all beyond the minimal safety area), activity was expressed through the amount of robot movement, and vocal content varied from nurturing ("You are doing great, please keep up the good work.") to challenging ("Come on, you can do better than that.") and extroverted (higher-pitched tone and louder volume) to introverted (lower-pitched tone and lower volume), in accordance with well-established personality theories referred to earlier. These define the behavior, and thus personality, of the therapist robot, which is adaptable to the user's personality in order to improve the user's task performance. Task performance is measured as the number of movements performed and/or time-on-task, depending on the nature of the trial.

The robot incrementally adapted its behavior and thus its expressed personality as a function of the (healthy) user's extroversion-introversion level and the amount of performed activities, attempting to maximize that amount. The result was a novel stroke/TBI rehabilitation tool that has the potential to provide individualized and appropriately challenging/nurturing therapy style that may measurably improve user task performance.

Experimental Design

We designed two different experiments to test the adaptability of the robot's behavior to the participant's personality and preferences. The experimental task was a common object transfer task used in post-stroke/TBI rehabilitation and consisted of moving pencils from one bin on the left side of the participant to another bin on his/her right side. One of the bins was on an electronic scale in order to measure the user's task performance. The task was open-ended. The subject pool consisted of 12 participants (7 male and 5 female). The participants were asked to complete a pre- and post-experiment questionnaire, so as to determine the user personality (based on the Eysenck Personality Inventory (EPI) [33]), respectively the participants' preferences related to the therapy styles or robot's vocal cues, interaction distances, and robot's speed from the values used in the experiments. The learning algorithm was initialized with parameter values that were in the vicinity of what was thought to be acceptable for both extroverted and introverted individuals, based on the user-robot personality matching study described earlier.

The first experiment was designed to test the robot behavior adaptation to user personality-based therapy style. The therapy styles ranged from coach-like therapy to encouragement-based therapy for extroverted personality types and from supportive therapy to nurturing therapy for introverted personality types. The vocal content for each of these scenarios was selected in concordance with encouragement language used by professional rehabilitation therapists.

People are more influenced by certain voices and accents than others. The main goal of our second experiment was to test and validate the adaptation capability of the robot to the user preferences related to English accent and voice gender.
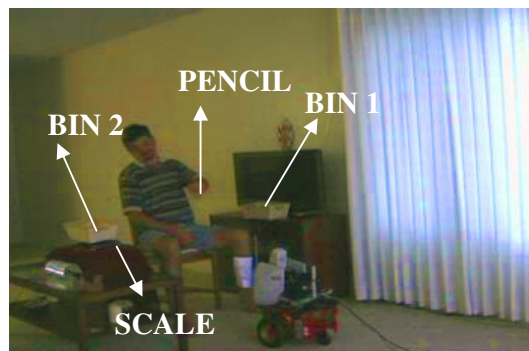

Figure 4: Participant performing the object transfer task: moving pencils from one bin to another.

Results

The experimental results provided first evidence for the effectiveness of robot behavior adaptation to user personality and performance: users (who were not stroke patients) tended to perform more or longer trials under the personality matched and therapy style

matched conditions. The latter refers to nurturing styles being correlated with the introversion side of the personality spectrum, and challenging styles correlated with the extroversion side of the spectrum. A more detailed description is given in [8].

4. Conclusions

We have presented a research program aimed at developing non-contact socially assistive robot therapists intended for monitoring, assisting, encouraging, and socially interacting with users during the motor rehabilitation process. Our first results demonstrated user acceptance of the robot. Our next round of results validated that mirroring user personality in the robot's behavior during the hands-off therapy process acts to improve task performance on rehabilitation activities. Finally, our last round of results demonstrated the robot's ability to adapt its behavior to the user's personality and preferences.

Our ongoing work is aimed at evaluating the described approach in a time-extended user study with a large group of post-stroke patients. The longitudinal study will allow us to eliminate the effects of novelty, and will also provide the robot with the opportunity for richer learning and adaptation algorithms. Our robots are designed to subordinate to the patient's desires and preferences, thereby promoting patient-centered practice and avoiding the complex issues of taking control away from patients and dehumanizing health care [36]. Our ultimate goal is to develop technology-assisted therapy methods that can augment the current standard of care in order to meet the growing need for personalized care indicated by the population demographics.

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