

Hands-off Assistive Robotics for Post-Stroke Arm Rehabilitation

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Abstract—This paper describes an autonomous assistive mobile robot that aids stroke patient rehabilitation by providing monitoring, encouragement, and reminders. The robot navigates autonomously, monitors the patient’s arm activity, and helps the patient remember to follow a rehabilitation program. Our experiments show that patients post-stroke are positive about this approach and that increasingly active and animated robot behavior is positively received by stroke survivors.

I. INTRODUCTION

This project aimed to develop an autonomous assistive mobile robot that could aid persons post-stroke with arm disabilities during their rehabilitation. By encouraging the patient to use the disabled arm, and by monitoring progress, the robot would provide support and motivation when regular physical therapy is not suitable or available. Thus, the robot may increase the rate and amount of recovery as well as the general well-being of stroke survivors. This work is part of our ongoing effort toward the development of novel human-robot interaction techniques for non-contact (hands-off) mobile robots, which is being incrementally evaluated and improved through experiments with patients.

Stroke is a major cause of neurological disability. Most of those affected are left with some movement disability. Through concerted use and training of the affected limb during the critical post-stroke period, such disability can be significantly reduced [1]. The rate and amount of recovery greatly depends on the amount of focused training. Evidence shows that the intensity and frequency of focused therapy can improve functional outcomes [2]. However, since such rehabilitation normally requires supervision of trained professionals, lack of resources limits the amount of time available for supervised rehabilitation. As a result, the quality of life of stroke patients is permanently reduced, and medical costs and lost productivity continue to be incurred.

In this work, we propose the use of an assistive mobile robot (Figure 1) as a complement to conventional physical therapy and rehabilitation, as a means of addressing the above challenges of intensive rehabilitation. The approach involves the development of a safe, user-friendly, and affordable mobile robot that is capable of following the patient in the home or hospital environment. The robot monitors the patient’s use of the stroke-affected limb, provides

encouragement, guidance, and reminders. It also logs the patient’s movement of the affected limb and keeps track of rehabilitation progress for reporting to the physical therapist. The patient’s arm movement is registered with a light-weight inertial measurement unit (IMU) worn on the forearm much like a wristwatch. The robot behaves in response to the sensed movements of the affected limb. For instance, it provides gentle reminders to the patient if the affected arm has not been active for some period, and praise and encouragement if it has. The robot is also able to report performance data in analytical form to the rehabilitation staff, who can then use it to fine-tune the robot-assisted therapy.

Our approach to robot-assisted hands-off rehabilitation is based on an already validated post-stroke therapy method, which constrains the patient’s use of the healthy limb in order to encourage the use and thus recovery of function in the stroke-affected one [3]. This process of exercising toward regaining lost movement is cumbersome and can be very frustrating for the patient. The robot’s task is to, in part, provide monitoring and reminding, but also in part to serve as a friendly companion during a difficult time. While the robot tracks and follows the patient by default, it leaves when asked to; it is designed to be welcomed by the patient, not to be annoying, ignored, and shut off. Our work so far has been in validating patients’ acceptance of a robot with a few simple behaviors; our ongoing work continues to improve the robot’s capabilities of engaging the patient.

II. RELATED WORK

Because of the growing elderly population and thus the predicted rise in stroke [4], much effort has been made during the past decade to improve post-stroke rehabilitation. A robot-assisted arm therapy workstation has been developed for training upper limbs and evaluating limb performance [5]. A number of similar devices employing hands-on rehabilitation robotics technology have been developed [6] and investigated [7], [8]. In general, such mechanical devices are worn by the patient during exercises, and use built-in sensors to measure generated limb forces and movement. Results suggest that using such mechanical assistive guides seems to be sufficient for enhancing movement recovery but not that it is necessary. It appears that the purposeful,

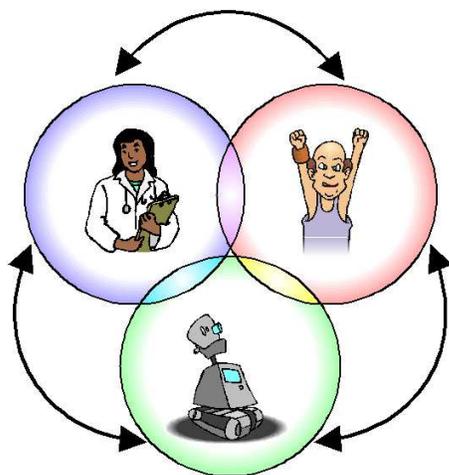


Fig. 1. An illustration of the interaction among the physical therapist, patient, and robot in the context of robot-assisted stroke rehabilitation. The robot does not attempt to take the role of the trained professional; instead it helps the patient by providing time-extended and individualized attention.

meaningful functional task practice is the primary stimulus for arm movement recovery.

The above devices all depend on physical contact between the patient and the robot, raising issues of safety, affordability, and feasibility for in-home use. A non-contact approach of the type we propose raises fewer of those concerns. Furthermore, by focusing on regular activities and tasks performed in daily life rather than constrained repetitive exercises, the patients can be more easily motivated to perform time-extended rehabilitation activities, potentially resulting in improved overall recovery outcomes.

Research shows that pet ownership increases health and emotional well-being of elderly [9]. Moreover, it has been demonstrated that people often attribute animal or human characteristics to even simple robot pets [10]. These inherently human tendencies provide a grounding for the hands-off assistive robot rehabilitation methods we describe, which are aimed at having a positive effect on both patient recovery and perceived quality of life.

III. DESIGN

The robot uses a standard Pioneer2 DX mobile robot base. A SICK LMS200 scanning laser range finder enables it to find and track the patient's legs. For obstacle avoidance, the laser was used together with the on-board ultrasound array. A Sony pan-tilt-zoom (PTZ) camera enabled the robot to "look" at the patient and away, shake its "head" (camera), and make other communicative actions. The camera could also be used to find and track a patient wearing colored markers (as was done in an earlier set of experiments we performed). A speaker produced pre-recorded or synthesized speech and sound effects. To monitor arm movement, the patient wore a sensor based on an inertial measurement unit (IMU), which sent data wirelessly to the robot in real time.



Fig. 2. The robot and a stroke patient during an experiment, where the desired activity is to shelve books. The arm sensor is visible on the patient's right forearm; the patient also wears laser fiducials on her leg to make it easier for the robot to recognize and follow her.

We used a behavior-based system [11], [12] for control. Behavior pre- and postconditions [13] were designed to properly coordinate behavior execution in response to real-time feedback from the sensors. The software was implemented using the Player robot device server [14].

IV. EVALUATION

While our goal is eventual unmonitored use, the experiments described here used a prototype system that was tested in a controlled environment. We focused on the study of how different robot behaviors affect the patients' willingness to comply with the rehabilitation program. Specifically, we tested different voices, movements, and levels of patience on the part of the robot and correlated those with patient compliance. Exit interviews and questionnaires were also administered to all the patients in the study.

A. Experiments

The system was evaluated in three sessions, each of which featured two subjects. The first session was performed with a non-patient user, while the other two were conducted with stroke survivors. All sessions took place in rehabilitation research labs at the USC Health Sciences Campus. The stroke patients were middle-aged, and their disabled limbs were sufficiently mobile to perform the activities in the experiments. Of the six subjects, two were women. The experiments lasted about one hour per person. Every evaluation session comprised six experimental runs. Thus, a total of 36 experiments were performed.

1) *Activities:* In all experiments, the robot asked the patient to perform one of two activities. The first activity was to shelve books; its difficulty could easily be adjusted by using books with different weights and varying the height of the bookshelf (Figure 2). The robot used the arm motion data to determine whether the activity was performed properly. As

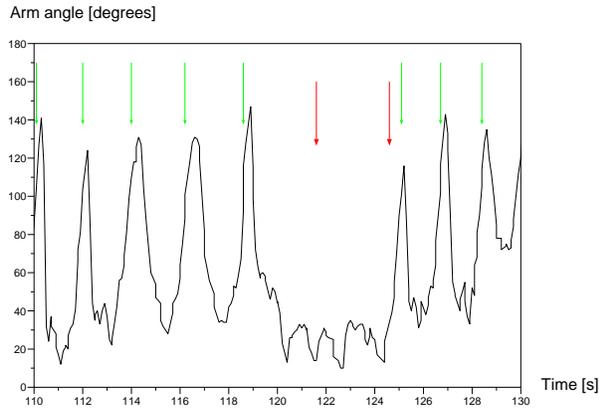


Fig. 3. A patient’s arm activity during an experiment. The thin arrows show when a reaching motion is detected. The thicker arrows show when arm inactivity triggers the robot to encourage the patient.

it was thus possible to fool the robot by just raising the arm without carrying the load of a book (as one patient quickly discovered), the number of books put in the shelf was used as a final validation.

The second activity consisted of any voluntary activity that involved the movement of the affected arm. Here, the robot measured arm movement as an averaged derivative of the arm angle. The compliance measure was the total time the patient performed the activity.

2) *Interaction Modes*: As noted above, three experiments were performed by each patient and activity. In each of these, a different interaction mode was chosen randomly and used in response to the patient’s arm movement. The interaction modes can be thought of as different robot personalities. Our hypothesis was that a more animated/engaging robot behavior would result in better patient compliance and higher patient approval of the robot. The modes included:

- 1) The robot gives feedback only through sound effects.
- 2) The robot uses a synthesized voice and is not persistent.
- 3) The robot uses a pre-recorded human voice, body movement, and is persistent.

B. Results

The robot was generally well-received by both patients and physical therapists. According to the questionnaires, the patients enjoyed the robot’s presence and interactions with it. Furthermore, they preferred the use of recorded human voices to synthesized ones. More enthusiastic interaction modes received higher approval scores.

One prominent feature of the robot personality was the voice it used. The robot used pre-recorded as well as synthesized male and female voices. In our small sample, male patients generally preferred the female voices, and vice versa.

The robot recognized patient arm movements sufficiently reliably, as shown in Figure 3. To do so it employed a simple model based on the angle between the arm and the normal to the floor as an indicator of reaching. The same figure shows

when reaching was detected and when encouragement was triggered in its absence.

We found that patient compliance with the rehabilitation routine was much higher during the experiments with the robot than under normal (non-robot) conditions. Because the experiments were quite long in duration, not all of this compliance can be attributed to the novelty of the situation. Furthermore, many of the experiments needed to be terminated before the patient had stopped doing the activity, thus preventing collection of reliable compliance data and possibly further underestimating the compliance boost.

V. DISCUSSION

Although more than thirty experiments were performed, only six subjects and of those only four patients post-stroke participated. Thus we look forward to continuing and expanding trials for further evaluating this methodology. However, even with the limited amount of evaluation to date, the patients’ and physical therapists’ reception and acceptance of the robot was surprisingly enthusiastically positive. Some of the patients immediately started to attribute human or animal intentions and emotions to the robot, talking to it as if to a dog or child. We are strongly encouraged by this high level of engagement with a simple system, as it bodes well for our continuing research. People naturally engage with physically embodied creatures, which is critical for time-extended interaction as required post-stroke.

Since only basic processing of the arm orientation data was performed, the patient could trick the robot into thinking that the requested activity was performed. However, tricking still required motion, so the patient was performing a type of exercise in any case. We are currently exploring ways of setting up competitive game-like scenarios as another means for the robot to motivate patients.

We discovered that the movement monitoring algorithm needed to be adapted to individual patients, as each was affected in a unique way. This leaves additional room for adaptive capabilities and learning in the context of robot assisted rehabilitation.

As mentioned above, it was difficult to assess the robot’s impact on patient compliance. During the experiments, a great improvement in compliance was observed, but the role of novelty is a confounding factor. Furthermore, the presence of other observers (the physical therapist and the robotics researcher) no doubt also had an affect on compliance.

Finally, we noted that some robot personalities inspired the subjects to explore and deviate from prescribed behavior. Some versions of the robot were perceived as boring while others were received with interest (and even joy). In one case, a happy pre-recorded voice and encouraging movement made the patient interested and inspired to perform the activity well. A less spirited voice and encouragement level was perceived as boring, and, as a consequence, the patient did not comply with given instructions. However, this led the patient to explore the robot’s capabilities instead and to continue to move about the room, leading the robot along. 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.

VI. CONCLUSIONS AND FUTURE WORK

We have described a hands-off mobile robot designed for assisting in stroke rehabilitation. The first results have provided guiding insights and motivation for much work left to do. Stroke survivors seemed to welcome the robot and be genuinely interested in technology that may improve their health. Although we need more experimental data to verify that the robot actually can make a difference in rehabilitation, the response we received from patients and physical therapists was strongly encouraging.

Immediate improvements of the system under development include:

- Better interpretation of the patient's arm movement. This will be done by transforming and classifying the movement data into movement primitives [15].
- Recognition of patient intentions and emotions. This will be done through the use of affect detection in speech and gesture.
- Dynamic adaptation of the interaction modes in response to patient's behavior (and mood) and learning models of the user.
- The use of the robot sensor data in combination with clinical measures of impairment (Fugl-Meyer motor) and function (Box & Block; TEMPA; Action research arm test).

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REFERENCES

- [1] C. Winstein, D. K. Rose, S. M. Tan, R. Lewthwaite, H. C. Chui, and S. P. Azen, "A randomized controlled comparison of upper extremity rehabilitation strategies in acute stroke: a pilot study of immediate and long-term outcomes.," *Archives of Physical Medicine and Rehabilitation*, vol. 85, pp. 620–628, 2004.
- [2] R. Teasell and L. Kalra, "What's new in stroke rehabilitation: Back to basics," *Stroke*, vol. 36, pp. 215–217, 2005.
- [3] S. Wolf, S. Blanton, H. Baer, J. Breshears, and A. J. Butler, "Repetitive task practice: a critical review of constraint induced therapy in stroke," *The Neurologist*, vol. 8, pp. 325–338, 2002.
- [4] J. Broderick, T. Brott, R. Kothari, R. Miller, J. Khoury, A. Pancioli, J. Gebel, D. Mills, L. Minneci, and R. Shukla, "The greater cincinnati / northern kentucky stroke study: Preliminary first-ever and total incidence rates of stroke among blacks," *Stroke*, vol. 29, no. 2, pp. 415–21, 1998.
- [5] C. G. Bugar, P. S. Lum, P. C. Shor, and M. Van der Loos, "Development of robots for rehabilitation therapy: The palo alto va/stanford experience," *Journal of Rehabilitation Research and Development*, vol. 37, no. 6, pp. 663–674, 2000.
- [6] H. I. Krebs, B. T. Volpe, M. L. Aisena, and N. Hogan, "Increasing productivity and quality of care: Robot-aided neuro-rehabilitation," *Journal of Rehabilitation Research and Development*, vol. 37, no. 6, pp. 639–652, 2000.
- [7] D. J. Reinkensmeyer, L. E. Kahn, M. Averbuch, A. McKenna-Cole, B. D. Schmit, and W. Z. Rymer, "Understanding and treating arm movement impairment after chronic brain injury: Progress with the arm guide," *Journal of Rehabilitation Research and Development*, vol. 37, no. 6, pp. 653–662, 2000.
- [8] D. J. Reinkensmeyer, C. T. Pang, J. A. Nessler, and C. C. Painter, "Web-based telerehabilitation for the upper extremity after stroke," *IEEE transactions on neural systems and rehabilitation engineering*, vol. 10, no. 2, pp. 102–108, 2002.
- [9] A. Beck and A. Katcher, *Between Pets and People: The Importance of Animal Companionship*, Purdue University Press, 1996.
- [10] P. H. Kahn Jr., B. Friedman, and J. Hagman, "I care about him as a pal: Conceptions of robotic pets in online aibo discussion forums," in *Extended Abstracts of the Conference on Human Factors in Computing Systems CHI 2002*, Minneapolis, Minnesota, USA, 2002, pp. 632–633.
- [11] R. C. Arkin, *Behavior-Based Robotics*, MIT Press, 1998.
- [12] M. Mataric, "Behavior-based control: Examples from navigation, learning, and group behavior," *Journal of Experimental and Theoretical Artificial Intelligence*, vol. 9, no. 2-3, pp. 323–336, 1997.
- [13] M. N. Nicolescu and M. J. Mataric, "A hierarchical architecture for behavior-based robots," in *Proceedings of the First International Joint Conference on Autonomous Agents and Multi-Agent Systems*, Bologna, Italy, 2002, pp. 227–233.
- [14] B. P. Gerkey, R. T. Vaughan, and A. Howard, "The player/stage project: Tools for multi-robot and distributed sensor systems," in *Proceedings of the 11th International Conference on Advanced Robotics*, Coimbra, Portugal, 2003, pp. 317–323.
- [15] E. Drumwright, O. C. Jenkins, and M. J. Mataric, "Exemplar-based primitives for humanoid movement classification and control," in *IEEE International Conference on Robotics and Automation*, New Orleans, USA, Apr 2004, pp. 140–145.