2011 IEEE International Conference on Rehabilitation Robotics
Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 29 - July 1, 2011

Improving robotics for neurorehabilitation: enhancing engagement, performance, and learning with auditory feedback

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***Abstract*—This paper reports on an ongoing research collaboration between the University of Padua and the University of California Irvine, on the use of continuous auditory-feedback in robot-assisted neurorehabilitation of post-stroke patients. This feedback modality is mostly underexploited in current robotic rehabilitation systems, that usually implement very basic auditory feedback interfaces. The results of this research show that generating a proper sound cue during robot assisted movement training can help patients in improving engagement, performance and learning in the exercise.**

I. Introduction

Robotic devices can help automate repetitive training after stroke in a controlled fashion, and increase treatment compliance by introducing incentives to the patient [1]. Movement practice with robotic devices can promote motivation, engagement, and effort, if interactive feedback is provided [2].

Several robotic systems have been proposed in recent years for use in motor rehabilitation of stroke patients [3], [4]. A key issue is whether robotic systems can help patients learn complex natural movements involved in the Activities of Daily Living (ADLs). According to recent reviews, robot-assisted arm training is not more likely to improve ADLs with respect to standard rehabilitation treatment, however arm motor function and strength of the paretic arm may improve [1], [5], [6], [7]. One relevant research challenge concerns the role of robotic-assisted training in the acute and sub-acute phases (i.e., within three months from stroke onset) [3], [8], which may have a greater impact on the ADLs if compared to chronic phase robotic therapy [5]. One further issue is the development of home rehabilitation systems, which may help patients continue treatment after hospital discharge [3], [9].

The most fundamental problem that robotic movement therapy must address to continue to make progress is that there is still a lack of knowledge on how motor learning during neuro-rehabilitation works at a level of detail sufficient to dictate robotic therapy device design [2], although some indications in this direction have been proposed recently [4]. It's known that repetition, with active engagement by the participant, promotes re-organization [10] and that kinematic error drives motor adaptation [11]. There's also evidence that a proper sound may help individuals during the execution of a motor task [12], although the effect of sound feedback during reaching after chronic stroke may depend on the hemisphere damaged by the stroke [13]. Audio is used in many rehabilitation systems with the purpose of motivating patients in their performance, possibly using game metaphors [14], [15], [16]. Other systems use audio to reinforce the realism of the virtual reality environment [17], [18], [19]. In some cases, audio is used to give information to guide the execution of the task [20], [21]. However the potential of auditory feedback in rehabilitation systems is largely underestimated in the current literature [22].

This paper presents preliminary results from a set of experiments that use auditory feedback to augment assisted motor training exercises. In this context, the term auditory feedback denotes an audio signal, automatically generated and played back to the user in response to an action or an internal state of the system. The design of auditory feedback requires a set of sensors to capture the system state, a feedback function to map sensor signals into acoustic parameters, and a rendering engine to generate audio accordingly [23]. We hypothesize here that properly designed auditory feedback could be used to aid user motivation in performing task-oriented motor exercises; to represent temporal and spatial information that can improve the motor learning process; to substitute other feedback modalities in case of their absence.

II. Auditory feedback and engagement

The main research question addressed by our first experiments is whether and to what extent auditory feedback can increase patient engagement during robotic arm movement training after stroke [24], [25]. The working hypothesis is that auditory feedback can be used to reduce the impact of visual distraction on patient attention and effort during the execution of a robot-assisted exercises. Understanding the role of visual distraction is important, since the patient can be

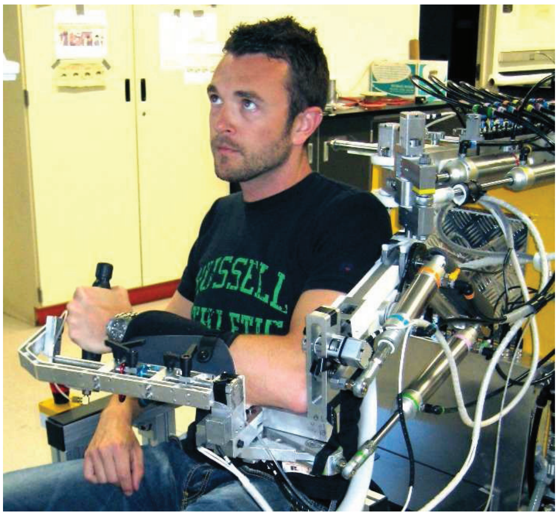

Fig. 1. Auditory feedback and engagement: experimental setup at UCI with the Pnew-WREX robotic system [26].

distracted by many external events during therapy sessions. On the other hand, one might intentionally produce distractions during the exercise to continuously challenge patient attention, in order to increase task engagement and hopefully motor learning. Since vision is the main modality usually employed to display target motions in robotic therapy, we selected a visually driven exercise. The visual distraction is expected to reduce patient performance in the execution of the exercise, while the addition of auditory feedback should counteract the effect of visual distraction, by stimulating the participant's motor system through a different sensory channel.

A. Design and protocol

The experiments used the Pneu-WREX [26] (see Fig. 1), a pneumatic exoskeleton for arm rehabilitation that evolved from the T-WREX, a passive device [27]. The non-linear force control techniques employed therein give pneumatic actuators excellent active backdrivability and position controllability. The adaptive controller uses a measurement of tracking error to build a model of the forces needed to assist the arm in moving, and includes a forgetting term that continuously attempts to reduce robotic assistance forces [28].

The tracking exercise consisted in a left to right horizontal movement of the left arm. The reference position and the hand position were shown on a black screen as a red and a green circle respectively. Participants were instructed to follow target motion as accurately as possible, assisted by the Pneu-WREX. Eight visual distractors were constructed using two geometric shapes: a filled circle and a yellow bar. By varying circle color (red/green), circle position at the bottom of the screen (left/right), and position of the bar (above/below) relative to the circle, eight different combinations were obtained. The distractors were randomly displayed during the exercise. Two parameter combinations (green-left-above and red-right-below) were chosen as *goal distractors*. Subjects were asked to click the left button of a mouse (with the hand not in the exoskeleton) each time a goal distractor appeared. This simulates a situation in which a mild distractor in the environment changes the focus of patient's attention during exercise.

Auditory feedback was provided in the form of sequences of tonal beeps (each beep at 800Hz and lasting 0.1s) and delivered through headphones. The repetition rate of the beeps was varied proportionally to the magnitude of the position tracking error, with a dead zone of 1in around the target. The beep was delivered to either the left or the right audio channel according to the sign of the error.

Each participant was asked to complete the target-tracking task in 5 different configurations:

- task A: no visual distractor, no auditory feedback;
- task B: visual distractor, no auditory feedback;
- task C: visual distractor, auditory feedback;
- task D: no visual distractor, auditory feedback;
- task E: same as A, but with the subject instructed to completely relax their affected upper extremity.

Each task consisted of 20 repetitions of a left-right-left movement cycle, performed in six seconds (total task duration: $120s$). Each subject executed all tasks in a randomly-generated sequence, after a first warm-up task of medium complexity (task B, to accommodate to the visual distractor task). The target velocity profile was chosen as a minimum jerk law [29].

We studied healthy subjects first, to characterize the normative response of the human motor system to distraction and auditory feedback, and to provide a basis for comparison with post-stroke patients[1]. A total of 10 right-handed healthy subjects (age: 20 to 42 years) [25] and thirteen individuals with chronic ($>$ 6 months) left hemiparesis as a result of a single unilateral stroke, and showing some motor recovery at the affected elbow and shoulder [24], participated to the study. The mean age of the post-stroke subjects was 56.3 ± 12.3 years, the mean Fugl-Meyer score was 25.9 ± 4.9, and the mean Ashworth score was 1.92 ± 0.8 and 0.86 ± 0.36 at the affected elbow and shoulder, respectively. The UC Irvine Institutional Review Board approved the study.

Positions, velocities, robot force, and mouse button status were sampled at a frequency of 200Hz. Position errors along the x axis (left-right) were weighted with the sign of target velocity:

$$\text{pos}_{\text{error}} = (x_{\text{subj}} - x_{\text{ref}}) \cdot \text{sign}(v_{\text{ref}}) \quad (1)$$

Lead error and *lag error* were defined as the tracking error when the subject lays ahead (positive error) or behind (negative error) target motion respectively. Errors were compared using one-way, paired t-tests with a significance level of 0.05.

B. Results with healthy subjects

Fig. 2 shows the average lead error in the different tasks, normalized to the value recorded in task E. It can be noticed that the lead error was significantly increased when the visual distractor was introduced (task B compared to task A). When

[1] Informed consent was obtained from each subject for all studies presented in this paper.

auditory feedback was added to the distractor, however, the lead error returned toward normative values (task C vs task B). Thus, visual distraction can increase tracking error while auditory feedback in presence of a visual distractor can counteract this effect. Auditory feedback had no or little effect if added to the regular task (task D vs task A).

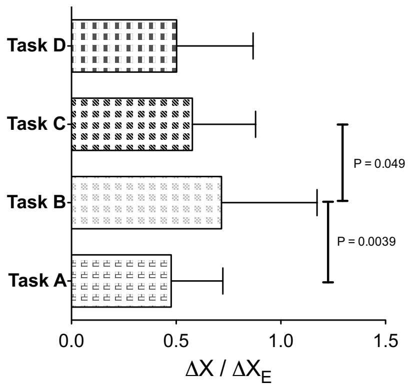

Fig. 2. Auditory feedback and engagement: average lead error of healthy subjects in tasks A (regular), B (with distractor), C (with distractor and audio), D (with audio) and E (relaxed).

C. Results with patients

Figure 3 shows the average arm support force provided by the robot during the tracking tasks. On the baseline task (A), the participants supported about 50% of their arm weight, with the robot adapting to provide the other 50% of the vertical force needed to lift the arm during the horizontal tracking task. Introduction of the distractor task caused participants to significantly reduce their effort (task B), as evidenced by an increase in the robot assistance force of approximately 25% of arm weight. The vertical position tracking error doubled, while there were no significant increases in robot assistance force or position tracking error in the left-right direction.

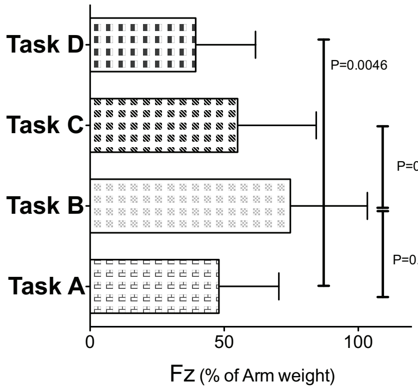

Fig. 3. Auditory feedback and engagement: arm support force provided to stroke patients by the robot in tasks A (regular), B (with distractor), C (with distractor and audio), D (with audio).

Fig. 4. Task-related auditory feedback: experimental setup at University of Padua with a pen tablet.

By introducing sound feedback of tracking error during the distractor task, the assistive force provided by the robot was significantly decreased (task B vs task C), restoring the measure close to its value during the regular tracking task (task A). The success rate for correctly clicking the mouse button when the distractor appeared was 65% for task B and 63% for task C. Thus, sound feedback helped the participants to increase their effort for lifting the arm without degrading performance on the distractor task.

Sound feedback also increased patient effort when no visual distractor was present: when comparing the tracking task with sound feedback (task D) to the default tracking task (task A), there was a significant decrease in robot force. However, no significant difference in position error was noted when comparing these two tasks.

III. TASK-RELATED AUDITORY FEEDBACK

One further research question, addressed by a second experiment, is whether continuous *task-related* auditory feedback can be more efficacious than error-related feedback in terms of patient's performance during the execution of a complex tracking task. The working hypothesis is that task-related auditory feedback can provide information that helps the subject to improve performance more than position error-related feedback.

A. Design and protocol

The experimental setup consisted of a Wacom pen as input device, a Full HD monitor and a pair of common headphones that presented audio feedback (see Fig. 4). The Wacom pen tablet was calibrated in order to match the screen size. The screen was backed by a blank wall.

As in the previous experiments, the reference position and the hand position were shown on a black screen as a red and a green circle respectively. The task was similar as well (tracking exercise consisting in a left to right movement with a minimum-jerk trajectory), in this case involving control of the pen with the right arm.

Two profiles of the target movement were envisaged:

- *fixed amplitude*, where the length of all segments was set as 60% of screen size;
- *random amplitude*, where the length of each segment varied pseudo-randomly from 20% to 90% of screen size.

Two types of auditory feedback were developed using Pure-Data (a real-time audio synthesis platform [30]), and synthesized from task and performance data:

- *task-related* feedback, simulating the sound of a rolling ball, with a gain factor proportional to the velocity of the target;
- *error-related* feedback, performing formant synthesis of voice[2], based on x (left-to-right) and y position errors.

Spatial sound information was added to both, using 3-D sound rendering based on Head Related Transfer Functions (HRTF) [31] and headphone reproduction.

Participants were asked to complete the tracking task in six different configurations:

- Task A: fixed amplitude, no auditory feedback;
- Task B: random amplitude, no auditory feedback;
- Task C: fixed amplitude, task-related feedback;
- Task D: random amplitude, task-related feedback;
- Task E: fixed amplitude, error-related feedback;
- Task F: random amplitude, error-related feedback.

Each task lasted 80 seconds and consisted of 13 repetitions of the left-right-left movement cycle. Each subject executed all tasks in a randomly-generated sequence, after a first warm-up task (without the target) to get acquainted with the tablet. During the three seconds preceding each task, a countdown was simulated through a sequence of three tonal beeps.

A total of 20 healthy subjects took part to the experiment. As before, we studied healthy participants first, to characterize the normative response of the human motor system to auditory feedback, providing a basis for comparison in future experiments with post-stroke patients.

Target and subject position and velocity were sampled at a frequency of $50Hz$. For each participant, the integral of relative velocity and the weighted position error on the x axis were measured, and afterwards averaged over all subjects. The integral of relative velocity is defined as:

$$R_{\text{vel}} = \int_{t_1}^{t_2} ||\vec{v}_r|| dt, \quad (2)$$

where $\vec{v}_r = \vec{v}_{subj} - \vec{v}_t$ is the relative velocity vector, and gives a measure of the extra total distance traveled by the subject to follow the target in the segment starting in t_1 and ending in t_2. Position error measurements were weighted with the sign of target velocity as in the previous experiment. Errors and distance traveled to follow target were compared among tasks through parametric paired t test. D'Agostino and Pearson omnibus normality test verified Gaussian distribution of data.

[2]Formant synthesis of voice is a technique of sonification which can be defined as a mapping of multidimensional datasets into an acoustic domain for the purposes of interpreting, understandings, or communicating relations in the domain under study [23]. As such, it can be thought of as the auditory equivalent of data visualization.

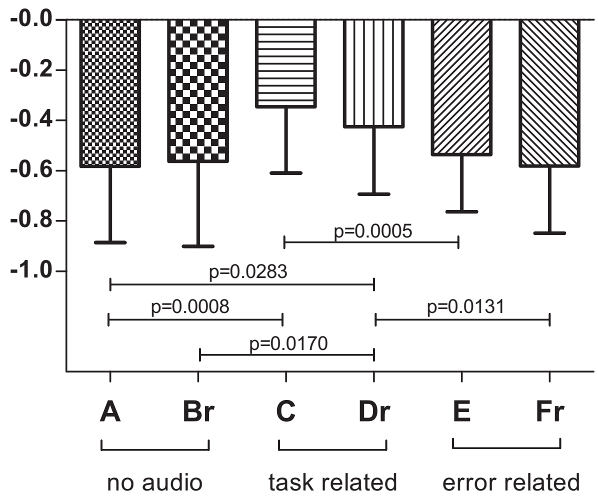

Fig. 5. Task-related auditory feedback: average weighted tracking error (normalized by target radius) in tasks A (fixed-no audio), B (random-no audio), C (fixed-task related), D (random-task related), E (fixed-error related) and F (random-error related).

B. Results

Figure 5 shows the average weighted tracking error in the different tasks, normalized to target radius. The statistical analysis showed that within the same auditory feedback modality there is no significant difference between fixed and variable length tasks. However, tasks C and D both present a significantly lower error than tasks A and B (and E and F), while in tasks E and F the presence of the error-related feedback does not significantly improve performance with respect to the case with no audio feedback (task A). These results confirm the initial hypothesis.

The statistical analysis on R_{vel} data showed that, as one may expect, the fixed-length task is always significantly better executed than the corresponding variable-length task, regardless the auditory feedback modality. On the other hand, no significant improvements come out when auditory feedback is added within the same exercise modality (fixed or variable length).

IV. Error-related auditory feedback

In the last experiment, we investigated the role of sound feedback in motor learning as sensory substitution of visual feedback during the execution of a motion task. The working hypothesis is that continuous error-related sound feedback can be used in substitution of the visual modality during motor learning in the presence of a novel dynamic or a novel visuomotor perturbation.

A. Design and protocol

The experiment was performed with an haptic 2 dof joystick (Immersion Impulse Stick) with a real-time software running at $200Hz$. As shown in Figure 6, the subjects sat on a chair with the joystick fixed in front. A white panel blacked out the hand position from the eye's prospective view. A screen in front of the subject was used to display a visual feedback and some additional information about the number of completed repetitions. The sound feedback was developed using PureData and provided to the subject by Bose QuietComfort 15 headphones.

The main task was to perform a reaching movement (back and forth, y direction, range $\pm 50mm$). The feedback modality was either visual or audio. In the first case, three colored dots were depicted on the screen (see Figure 6), two red dots corresponding to the start and the end of the reaching movement and one green dot whose coordinates represent:

- on the x axis, the current *position error* along the x axis, computed as the difference between the current joystick position and the desired reference path (either a straight line at $y = 0$ or a trapezoid, see below);
- on the y axis, the current joystick y position.

The second feedback modality consisted in a sound cue directly proportional to the x error. In both modalities, a metronome set at $33bpm$ was used to provide the rhythm of movement.

The experiment was divided into two sessions, preceded by a 30 seconds warm-up trial to let the subject understand the rhythm of the task. The first session (A) consisted of 20 repetitions (cycles) of a straight reaching task. During this session only, the subjects in the auditory feedback group received additional visual feedback (the three dots) intermittently, nearby each target position.

During the second session (B), lasting 140 cycles, a viscous force field F_x was applied after the 10th cycle and until the end of the session. The force was computed as a function of the velocity of the hand along the y axis:

$$F_{\mathrm{x}} \propto v_y \tag{3}$$

After adaptation to the force field, starting on the 61st cycle and for 40 cycles, the reference path was changed from a straight line to a trapezoid. The height of the trapezoid was an x offset of $25mm$ in the right half plane. The straight reference path was restored in the last part of session B.

Notice that the change in the reference path produced a motor perturbation. In fact, the x error was fed back to the user

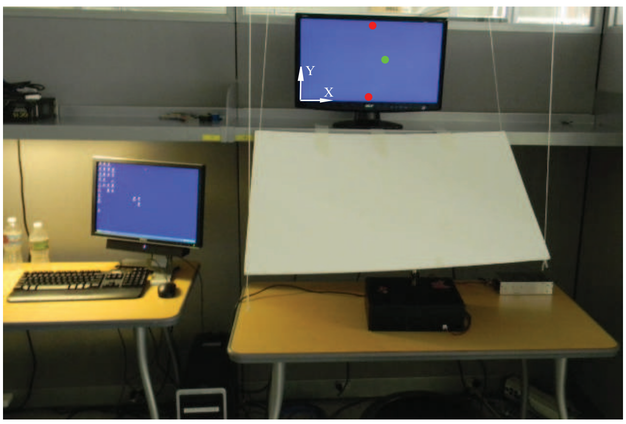

Fig. 6. Error-related auditory feedback: experimental setup at UCI with a 2-DoF force-feedback joystick.

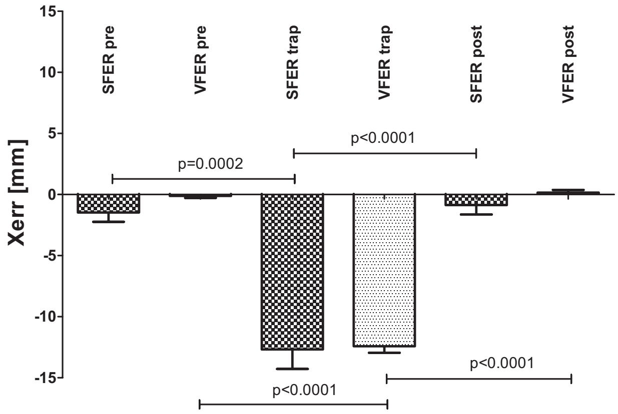

Fig. 7. Error-related feedback: mean position error in different stages (pre-trapezoid, trap., post-trap.) for video (VFER) and sound (SFER) groups.

instead of the x position, so a correct trapezoidal movement resulted either in a straight motion of the green dot (visual feedback group) or in no audio in the headphones (audio group).

Twenty healthy subjects were included in the experiment: (mean age 26.4 ± 4.0). All subjects were right handed and without hearing problems. The subjects were randomized into two groups based on the kind of feedback provided during the experiments: 10 subjects received error related sound feedback (SFER group), 10 subjects received error related visual feedback (VFER group). All subjects were instructed to move the joystick back and forth between the target positions, as straight as they could. Also, we asked them to grasp the stick on top and to hold it in the same way for the whole experiment.

B. Results

Figure 7 shows the average position error in three stages: before the trapezoid but after adaptation to the force field (*pre*), during the trapezoidal reference phase (*trap*) and after restoring the straight reference (*post*). D'Agostino and Pearson omnibus normality test verified Gaussian distribution of data. Hence, we performed paired t-test between *pre-trap* and *post-trap* in order to check whether each group felt the change of trajectory. Results show that both groups adapted to the trapezoidal trajectory, even though the mean error increased significantly due to the increased complexity of the task. Furthermore, we used unpaired t test with Welch's correction to compare the two groups in the same stages (i.e *pre-pre*, *trap-trap*, *post-post*). We found that both groups executed the whole task with comparable amounts of error, as no significant differences were found between mean errors in all stages. The fact that the pre-trapezoid error bars are small in both groups shows that subjects who received just auditory feedback adapted to the force field. These results suggests that error related auditory feedback successfully substituted error related visual feedback during motor learning in the presence of a novel dynamic and visuomotor perturbation.

V. Conclusion

The experiments presented in this paper corroborated the initial hypothesis that continuous sound feedback can be successfully employed during motor training to provide the subject with additional and/or substitutive information on task and/or error. In the first experiment, we found that introduction of a simple form of auditory feedback eliminated the slacking that arose from performing a secondary visual distractor task, increasing their effort back toward their baseline levels. Secondly, we found that rendering task-related information through sound helped subjects to increase performance during the execution of a complex and unpredictable tracking task more than providing information on position error through the same sensory channel. Finally, we showed that a visuomotor transformation can be reproduced by a consistent audiomotor transformation.

An important implication of these findings is that increased attention should be paid to incorporating effective forms of auditory feedback during robot-assisted movement training. Our impression is that auditory feedback is underutilized in most robotic therapy systems, playing a role as background music or signifying only task completion. Conversely, more complex forms of continuous sound feedback are likely to produce positive effects on patient engagement and effort during movement training, and to help them perform and hopefully re-learn complex functional movements. Future research should investigate how and to what extent auditory feedback can improve learning and motor recovery.

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