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Error-enhanced augmented proprioceptive feedback in stroke rehabilitation training: a pilot study.

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***Abstract*—Augmented feedback plays an essential role in stroke rehabilitation therapy. When a force is applied to the arm, an augmented sensory (proprioceptive) cue is provided. The question was to find out if stroke patients can learn reach- and retrieval movements with error-enhanced augmented sensory feedback. The movements were performed over a pre-defined path, and when deviating of the path a force is provided, as colliding to a wall of a tunnel.**

Two chronic stroke survivors (FM of 53 and 49) performed reach and retrieval movements in a virtual tunnel. When two consecutive series of 15 repetitions of the same movements were performed, there was a consistent decrease of collisions to the wall in the second series of movements. This indicates that these patients were able to learn the predefined trajectory by means of augmented proprioceptive feedback. Despite the small number of patients tested, this finding is promising for the usage of error-enhanced augmented proprioceptive feedback in rehabilitation therapy.

I. Introduction

Stroke is one of the main causes of disability in the US and Europe. In the US, the prevalence of stroke was 5.5 million (2.6% of the total population) in 2003 [1], and in Europe 1.13 million in 2003. [2] In the same year 700,000 people suffered their first stroke in the US [1], in Europe the estimated amount of people suffered their first stroke varies between 460 thousand and 1.1 million people [2]. Six months after stroke, 30 - 66 % of the patients have no proper arm-hand function [3], which limits their activities of daily life. Optimal restoration of arm and hand function is crucial to improve the patients' independency.

Rehabilitation therapy contributes to motor relearning and as a consequence to the recovery of lost functions. Literature indicates that motor relearning is influenced by several key elements; intensity [4], task-specificity [5,6], active initiation [7,8,9], motivation and feedback [10]. In past decades different innovative technologies have emerged that enlarge the possibilities to integrate these key elements in rehabilitation therapy, such as robotics and virtual reality (VR).

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Several therapeutic robots have been developed to enhance arm function (such as MIT-Manus [11], MIME [12], and ARM Guide [13]). These therapeutic robots can implement different modalities (passive, active-assisted, and active-resisted) in rehabilitation therapy. The overall effectiveness of robot-aided therapy on the upper extremity in stroke survivors is promising, as is concluded in two reviews by Prange (2006) [14] and Kwakkel (2008) [15]. In these reviews, an improvement in motor control of the paretic shoulder and elbow of stroke survivors due to robot-aided therapy was found, but no consistent influence on functional abilities was observed. [14]

It is thought that providing error-enhanced augmented proprioceptive (sensory) feedback to stroke survivors may lead to enhanced motor learning. [13,16] Stroke survivors will have more information fed back to their system than during normal movement execution, which may therefore lead to enhanced motor learning.

To demonstrate how a movement should be performed, this augmented proprioceptive feedback can be used as guidance. The guidance should only be applied when the movement deviates from the imposed trajectory (as a resistance on shoulder and elbow joint). In this manner patients are made aware of their movement patterns through augmented proprioceptive feedback.

To this end, we developed an automated system that can resist movements outside a virtual tunnel. By using this device, patients are stimulated to train their arm function actively and are made more aware of their movements.

The objective of this pilot study is to determine whether stroke survivors are able to learn reach- and retrieval movements with error-enhanced augmented proprioceptive feedback, by giving augmented force feedback to movements outside a virtual tunnel.

II. Method

A. Subjects

Two male (age 55 and 53 years) chronic stroke survivors with a Fugl-Meyer score of 53 and 49, respectively, were included in this pilot study. Inclusion criteria were: right hemiparesis, able to move the arm slightly against gravity, and first ever stroke. Exclusion criteria were: shoulder pain, and less than 6 months post stroke.

B. Experimental apparatus and recordings

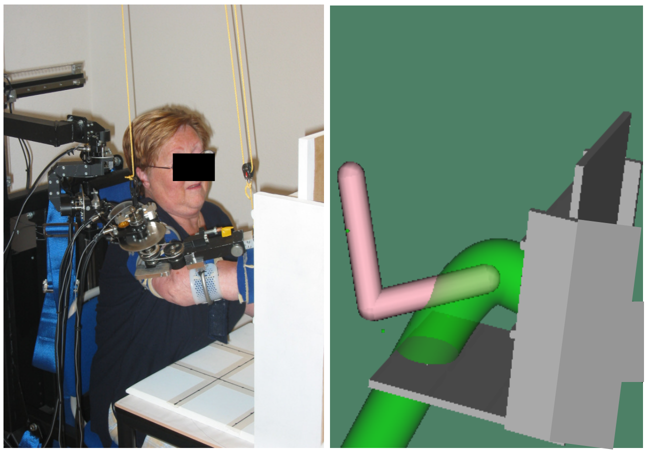
To resist movements outside the virtual tunnel, a robotic device named Dampace is used [17], see figure 1. The Dampace is an exoskeleton (two splints along the upper and lower arms with hinges at the location of the shoulder and elbow joints) which is attached to the upper and lower arm by soft straps. The length of the upper and lower arm parts of the exoskeleton can be adjusted to the subjects arm length. It has three movement axes at the shoulder (enabling ante-/retroflexion, ab-/adduction and endo-/exorotation) and one movement axis at the elbow (enabling flexion/extension).

The three axes at the shoulder and the one axis at the elbow can be resisted. Resistance torques can be individually applied to each of the four axes of the shoulder and elbow. On each axis a hydrolic disk brake is attached. Every brake is controlled by a computer via hydrolic cabling, based on the measurements of the rotation angles of the joints and/or the torques around the joint axes, measured by integrated position and force sensors.

Furthermore, the weight of the exoskeleton is compensated by a system of ideal springs located at the base of the frame, attached to the exoskeleton by wires via several pulleys overhead, not limiting movement or visibility of the arm. The weight compensation can be scaled from full compensation for the arm and the exoskeleton, to no compensation at all.

Additionally, pro-/supination of the forearm is free, but can not be resisted. The exoskeleton is attached to a rigid frame, situated behind the subject, in such a way that the shoulder can move freely, while ensuring optimal positioning of the axes of the exoskeleton with respect to the shoulder. In addition, an in height adjustable chair is attached to this frame.

The software of the Dampace has several pre-programmed profiles for resisting movements outside the virtual tunnel. Four different reach exercises are performed by using a table top, with two shelves located at 25 cm and 45 cm above the table, see figure 2.



A **B**

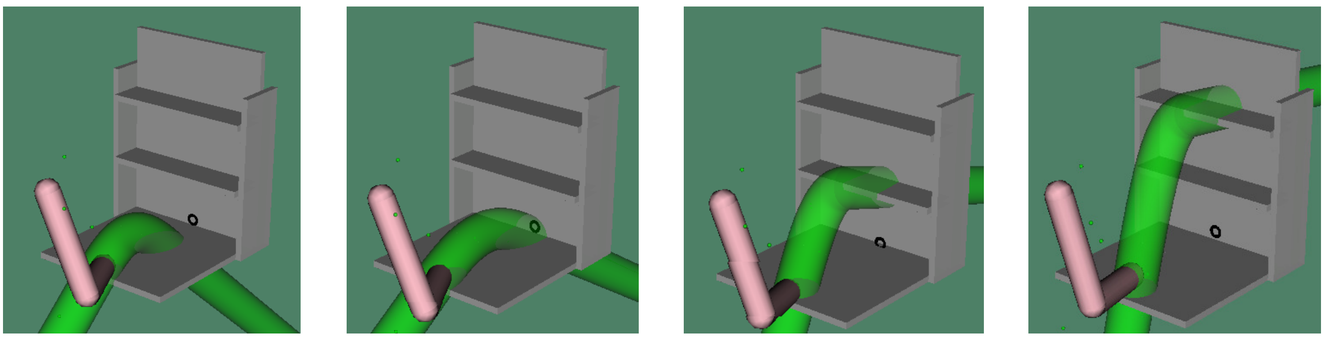
Figure 1: A: patient in de exoskeleton Dampace with the table top in front of her. B: the virtual tunnel (in green) from the first field of the table top (grey) to the first shelf (side view). The pink cylinders represent the upper and lower arm of the patient. For frontal view see figure 2.

The possible exercises consist of active reaching and grasping movements in a central position of the body. The different possible tasks and difficulty adjustments are visualized in figure 2. The different tasks are:

- Move a cup to the first field (figure 2A)
- Move a cup to the second field (figure 2B)
- Lift a cup to the first shelf (figure 2C)
- Lift a cup to the second shelf (figure 2D)

Within each of these tasks the diameter of the virtual tunnel can be decreased, and when the cup is moved to the first or second field the height of the arc of the virtual tunnel can be altered.

Kinematic data of the arm segments are recorded using integrated force and position sensors in the exoskeleton at each axis of movement. These data are translated to changes in generated torques in each movement direction of elbow and shoulder and changes in positions of arm segments and joint angles during movement.



A **B** **C** **D**

Figure 2: Representation of cup-movement exercise and corresponding table in three dimensional view. The starting point of the training task is the compartment closest to the body and right in front of the trunk. The cup is then moved to a field further from the body in the same column. The cup has to be moved to another field by making an arc. **A**) move a cup to the first field **B**) move a cup to the second field **C**) Lift a cup to the first shelf (arc height 25 cm) **D**) Lift a cup to the second shelf (arc height 45 cm)

A. Procedure

The subjects were seated in the chair of the Dampace, and their upper and lower arm were attached to the splints, see figure 1. Subjects are strapped with a four point safety belt to minimize movement of the trunk and shoulder. The initial posture of the subjects is with the upper arm aligned with the trunk (shoulder in approximately 0° of anteflexion and 0° of abduction), while the elbow is flexed approximately 90° with the forearm resting on the table in a neutral position (as if holding a cup), according to the recommendations of the International Society of Biomechanics.[18]

The movements were performed in a virtual tunnel (over a pre-defined path) and when deviating from the path a force is provided to all of the four movement axes (three of the shoulder and one of the elbow), as collapsing to the wall of the tunnel. This error-enhanced proprioceptive feedback disappears when the patient moves back into the predefined path. This error-enhanced feedback was not visible for the patient, so they could only learn from the augmented proprioceptive feedback.

Each patient performed 85 series of movement tasks. One series of a movement task consists of 15 repetitions of that particular movement. The first step to a more challenging task was the decrease of the tunnel diameter or the increase of the tunnel height. In a logbook the different tasks with their difficulty level were noted, including the amount of collisions with the wall. A collision with the wall was noted as a change of color of the virtual tunnel from green to red, independent of the time of the collision.

III. RESULTS

To determine if stroke survivors are able to learn from error-enhanced augmented proprioceptive feedback by making reach and retrieval movements in a virtual tunnel, the amount of collisions with the virtual tunnel wall are counted during a movement task with 15 repetitions. If in a sub-sequent movement task, all variables (type of task, tunnel height and tunnel diameter) were kept the same, and the collisions with the wall are decreased, a learning effect is present.

In subject 1, seven pairs (a-g) of these consecutive movement tasks were executed. From figure 3 it can be observed that in all of these consecutive movement series, in the second movement series fewer collisions to the virtual wall were made. In the first series 58 collisions (mean 8.3 per 15 repetitions) to the wall were made, compared to 20 collisions (mean 2.9 per 15 repetitions) in the second series. This indicates that the patient was able to learn to adapt his movement execution to the desired movement path.

In subject 2, five pairs (a-e) of consecutive movement tasks were executed. From figure 4 it can be observed that in all of these movement series, in the second movement series fewer collisions with the virtual tunnel wall were made. In the first series 23 collisions (mean 4.6 per 15 repetitions) to the wall were made, compared to nine collisions (mean 1.8 per 15 repetitions) in the second series. Indicating that the patient was able to learn from the collisions made with the virtual wall, and adjusts his movement to the imposed trajectory. Subject 2 made relatively fewer collisions with the wall than subject 1.

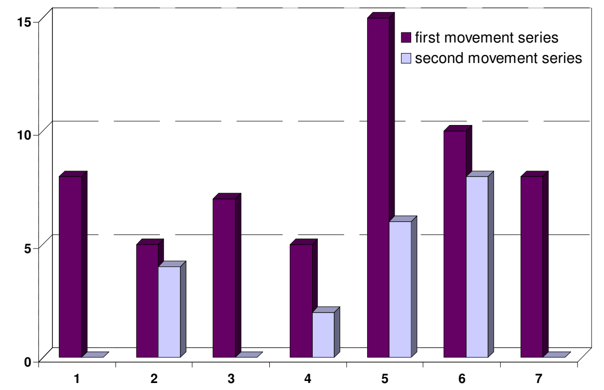


Figure 3: subject 1: amount of collisions to the virtual wall in 7 sets of consecutive movement series. Within each series 15 repetitive movements were performed. The executed movements were: 1) move a cup to second field, tunnel height 5 cm and tunnel diameter 15 cm; 2) lift a cup to the first shelf at height 25 cm and tunnel diameter 15 cm; 3) move a cup to the first field, tunnel height 8 cm, and tunnel diameter 15 cm; 4) move a cup to the second field, tunnel height 8 cm, and tunnel diameter 15 cm; e1&e2: move a cup to the first field, tunnel height 12 cm, and tunnel diameter 12.5 cm; 6) move a cup to the second field, tunnel height 12 cm, and tunnel diameter 15 cm; 7) lift a cup to the second shelf at height 45 cm and tunnel diameter 16 cm.

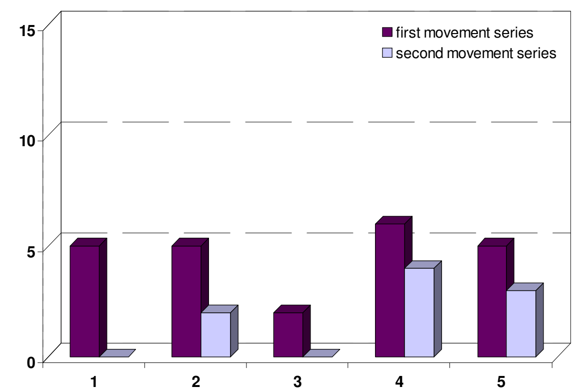


Figure 4: subject 2: amount of collisions to the virtual wall in 5 sets of consecutive movement series. Within each series 15 repetitive movements were performed. The executed movements were:1) move a cup to second field, tunnel height 6 cm and tunnel diameter 15 cm; 2) move a cup to first field, tunnel height 10 cm and tunnel diameter 15 cm; 3) lift a cup to the second shelf at height 45 cm, and tunnel diameter 15 cm; 4) lift a cup to the second shelf at height 45 cm, and tunnel diameter 15 cm; 5) lift a cup to the first shelf at height 25 cm, and tunnel diameter 12 cm.

IV. CONCLUSION AND DISCUSSION

The goal of this pilot study was to examine whether stroke survivors are able to learn reach- and retrieval movements with error-enhanced augmented proprioceptive feedback, by giving augmented force feedback to movements outside a virtual tunnel. The force feedback is applied to the shoulder and elbow when the movement deviates from the imposed trajectory, called error-enhanced proprioceptive feedback.

Two patients performed several series of movement tasks. The amount of collisions to the virtual tunnel wall were counted during subsequent series of the same movement task, each with 15 repetitions. All variables; type of task, tunnel height and tunnel diameter, were kept the same. Both chronic stroke survivors were able to learn the predefined movement task by means of the error-enhanced proprioceptive feedback. This indicates that they were able to anticipate to the applied resistance on shoulder and elbow when deviated from the virtual tunnel, and continue the movement.

An explanation for these results can be given, based on the findings with respect to internal modeling of the central nervous system as described by Kawato and Wolpert [19]. Internal models enable the central nervous system to predict the consequences of motor commands and to determine the motor commands required to perform specific tasks. [19] When during a reaching movement deviations from a desired trajectory are made, the internal model is no longer accurate and needs to be adjusted. By means of augmented sensory feedback the internal model can be gradually updated so that it eventually approximates the new dynamics of the limb. [20,21] In this manner new movements over a predefined trajectory can be learned, as observed in this pilot study.

Considerable research has been done with respect to the ability of stroke survivors to adapt their reaching movements when perturbed by a force. Most studies report that stroke survivors are able to adapt to the applied forces, and that they benefit more from error-enhanced learning than from normal learning. [16] A plausible explanation might be that sensory pathways in stroke survivors are affected, and that the motor control system needs an augmented stimulus. As a result of the triggered sensory pathways reorganization of the internal model (of motor planning and performance) may play an important role in the additional effect of sensory feedback in learning reach- and retrieval tasks. The error-enhanced augmented proprioceptive feedback as provided in this pilot study, might also trigger the sensory pathways, and as a result a specific movement task can be learned.[22]

Despite the small number of patients, this finding is promising for the usage of error-enhanced augmented proprioceptive feedback in rehabilitation therapy. In this manner augmented sensory feedback might be an effective way of training stroke survivors.

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