ARMin – Exoskeleton for Arm Therapy in Stroke Patients

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Abstract—Task-oriented repetitive movement can improve movement performance in patients with neurological lesions. The application of robotics can serve to assist, enhance, evaluate and document rehabilitation of movements. ARMin is a robot for arm therapy applicable to the arm training in clinics. It has an exoskeleton structure and is equipped with position and force sensors. Our latest version ARMin II has six degrees of freedom. The mechanical structure, the actuators, and the sensors of the robot are optimized for patient-cooperative control strategies based on impedance and admittance architectures.

The device can work in three therapy modes: passive mobilization, game therapy, and task-oriented training. This paper presents the technical components of the new version ARMin II, the therapy modes, the control strategy for a new example of a game therapy, and clinical results of a pilot study with 11 chronic stroke patients and of single case studies conducted with three chronic stroke patients.

I. INTRODUCTION

RECENT studies estimate that stroke affects more than 700,000 people in the U.S. each year [1]. Of these individuals, 60-70% will be alive one year after the insult, resulting in a prevalence of 3 million stroke patients [2]. The major symptom of stroke is acute sensory hemiparesis [3]. With the available rehabilitation techniques, motor recovery of the lower extremities is usually faster and more pronounced than motor recovery of the upper extremities [4]. Regarding stroke patients with severe upper extremity paresis, only 18% regain full arm function [5]. However, arm function is essential to cope with tasks of daily living.

Several studies prove that sensorimotor arm therapy has positive effects on the rehabilitation progress of stroke patients (see [6] for review). The goal of this therapy is to induce long-term brain plasticity and to improve functional outcomes. Critical factors are that the therapy is intensive [7,8], of long duration [9,10,11], highly repetitive [12], and task-oriented [13].

Regarding these criteria, one-to-one manually-assisted training has several limitations. The training is labor-intensive and therefore expensive. The disadvantageous consequence is that rehabilitation, i.e., the training sessions, are often shorter than required to gain an optimal therapeutic outcome. Finally, manually-assisted training lacks repeatability and objective measures of patient performance and progress.

By the implementation of robotic devices, in contrast, training sessions can be automated and duration and number of training sessions can be increased. By the use of patient-cooperative controllers that support the patient only when necessary and by the use of appropriate audiovisual displays to motivate the patient, we hypothesize that the training will be more intensive than traditional manual arm therapy [14-17].

Many groups have therefore developed and evaluated arm therapy robots (see [18] and [19] for review), for example the MIT-Manus [20], Assisted Rehabilitation and Measurement (ARM) Guide [21], Mirror Image Motion Enabler (MIME) [22], Bi-Manu-Track [23], GENTLE’s [24], Neurorehabilitation Robot (NeReBot) [25], REHAROB [26], and Arm Coordination Training 3-D (ACT3D) [27]. These devices are so called endeffector-based robots, meaning that the endeffector of the robot is connected to a distal part of human limb, i.e. the hand. Depending on the available degrees of freedom of the robot, the human hand can be positioned and oriented in space.

In contrast, the structure of exoskeleton robots resembles the human arm anatomy. The rotation axes of the robot must correspond to the rotation axes of the human skeleton and, therefore, the arm can be connected to the exoskeleton at several points. As the arm segments are individually actuated, single-joint torques can be applied. Rosen et al. [28] is using an exoskeleton robot with seven degrees of freedom (DoF) (shoulder: 3DoF, elbow: 1DoF, lower arm: 1DoF and wrist: 2DoF) allowing to control the most important joints of the human arm. With this design, the shoulder complex is reduced to a spherical joint, composed of 3 individual axes, intersecting at the center of the glenohumeral joint. The exoskeleton robot developed by Craig et al. [29] uses five motors to actuate the shoulder complex in order to get a more ergonomic shoulder movement.

While many clinical studies (see [19] for review) have been conducted with endeffector-based robots with limited possibilities to control position and orientation of the human arm in the three dimensional space, not much clinical evidence has been reported from work with actuated arm-exoskeleton robots.

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Sanches et al. [30] performed a controlled clinical trial with a passive exoskeleton device that allowed to measure arm position and to compensate for gravity forces. Another passive exoskeleton is under development by Stienen et al [31].

II. METHODS

A. Specifications of ARMin

To perform task-oriented [13] training, the robot must be able to move the shoulder, the elbow, as well as some distal joints. The range of motion (RoM) of the arm must correspond to the RoM of the human arm. For good performance of model-based patient-cooperative control strategies [32], the robot must have low inertia, low friction, and negligible backlash. Furthermore, the motor/gear combination needs to be back-drivable. The required velocities and accelerations have been determined by measuring the movements of a healthy subject during two tasks (eating soup and manipulation of a coffee cup) and are summarized in Table 1. Safety of the patient and the therapist must be guaranteed at any time.

<table>
<thead>
<tr>
<th>Axis</th>
<th>ROM</th>
<th>Velocity</th>
<th>Acceleration</th>
<th>Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axis 1: Vertical shoulder rotation</td>
<td>-60°…60°</td>
<td>71°/s</td>
<td>103°/s²</td>
<td>20Nm</td>
</tr>
<tr>
<td>Axis 2: Horizontal shoulder rotation</td>
<td>-45°…135°</td>
<td>60°/s</td>
<td>116°/s²</td>
<td>20Nm</td>
</tr>
<tr>
<td>Axis 3: Internal/external shoulder rotation</td>
<td>-50°…95°</td>
<td>150°/s</td>
<td>245°/s²</td>
<td>10Nm</td>
</tr>
<tr>
<td>Axis 4: Elbow flexion/extension</td>
<td>-5°…95°</td>
<td>91°/s</td>
<td>116°/s²</td>
<td>20Nm</td>
</tr>
<tr>
<td>Axis 5: Pro/supination of the lower arm</td>
<td>-90°…90°</td>
<td>62°/s</td>
<td>58°/s²</td>
<td>8Nm</td>
</tr>
<tr>
<td>Axis 6: Wrist flexion/extension</td>
<td>-50°…90°</td>
<td>55°/s</td>
<td>43°/s²</td>
<td>5Nm</td>
</tr>
</tbody>
</table>

Axis 2 and 4 are driven by a dc motor with a Harmonic Drive gear unit (Harmonic Drive Inc., Japan) with a reduction of 1:100. This motor/gear combination is characterized by low backlash (transmission accuracy α<0.04°) and good back-drivability (no-load back driving torque T= 2.8 Nm). Axis 3 is also driven by a dc motor with a Harmonic Drive gear unit with a reduction of 1:30. The output shaft of the gear box is connected to a tooth belt that is fixed to the two ends of a curved rail (Fig. 2).

Axis 5 for pronation and supination of the lower arm is realized by a cable-driven half cylinder rotary module. Wrist flexion/extension (Axis 6) is implemented with a dc motor connected to a ball spindle.

Axis 1 is actuated by a linear module with a ball spindle incorporated. This ball spindle is driven by a dc motor and moves the point A (Fig. 1) in vertical direction. The linear displacement results in a rotation of the upper arm around the y-axis and in a vertical rotation of the upper arm around the point S. Considering S as immobile in space would simplify the kinematic design, because this assumption would reduce the shoulder complex to a spherical joint composed of 3 individual axes intersecting at the center of the glenohumeral joint [28].

The human shoulder complex has at least 5 DoF, and the vertical position of the glenohumeral joint depends on the elevation angle of the upper arm [33]. Therefore, the height of S should also change with the elevation angle in order to get an ergonomic shoulder movement and to avoid misalignment between the robotic rotation axis and the human rotation axis.

A linkage system that connects the slide of the linear drive (axis 1) with a ball spindle allows changing the height of point S depending on the arm elevation angle. More details about this mechanism is described in [34]. For a rotation of 80°, the vertical movement of S is around 80 mm.

The actual position of each axis is measured with a digital

B. Kinematics, Actuation and Sensors

An exoskeleton structure was selected for the mechanical structure of the robot (Fig. 1). The patient is sitting in a wheelchair, while his arm is placed inside an orthotic shell.

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Fig. 2. Axis 3: Internal/external shoulder rotation. The dc motor (M2) drives the Harmonic Drive gear unit with the output shaft connected to a toothed wheel driving the tooth belt.
encoder as well as a potentiometer-based sensor. The encoder allows high resolution (0.0009°) position sensing and the additional potentiometer provides initial absolute position information and serves as redundant sensor to detect malfunction of a position sensor. A six degree of freedom force/torque sensor (JR3 inc., USA) measures the interaction force between the human and the robot (Fig. 1). In addition, motor current measurement is used for torque estimation.

The overall setup is shown in Figure 3. A computer monitor is used for visual feedback and two loudspeakers are used for acoustic feedback.

A counterweight of 14.5 kg, positioned behind the robot, is connected via a nylon cord with the linear slider of axis 1 (point A in fig. 1) and the friction of axis 3 (static part: 2.8 Nm) prevents the robot from collapsing in case of power interruption and the therapist or the patient can still move the robot with some additional force as the motor/gear units are back-drivable.

C. Three Therapy Modes

ARMin allows three different therapy modes. The goal of the passive movement therapy is to prevent joint degeneration and to preserve joint mobility. In this mode, the robot moves the patient’s arm while the patient remains passive. As the RoM of the patient’s arm depends on the pathology, and differs from patient to patient, a teach-and-repeat protocol has been implemented. Thus, the therapist can first move the human arm and the robot while the position data is recorded. During the teaching, the robot is actively weight and friction-compensated, so that the therapist just feels the resistance of the human arm and not the one of the robot. By feeling the resistance of the human arm the therapist can select an appropriate RoM. Once recorded, the trajectories are smoothed and then repeated. During the repeat sequence, the robot is position-controlled. In order to help the patient to know the position and orientation of his arm, an avatar doing the same movement is presented on the graphical display (Fig. 4).

The purpose of the game therapy is to motivate the patient with simple games presented on the audiovisual display. One example of a game is the ball game presented in Figure 4. This game scenario includes a ball rolling down an inclined table and a hand connected to a handle. The ball is reflected by the walls and the patient’s task is to catch the ball with the handle. Whenever the patient is able to catch the ball, he doesn’t get any support by the robot. Only in case when he cannot catch the ball he gets support from the robot [35]. The color of the handle changes depending on the patient’s performance. Another example for a game therapy is the labyrinth game, with the control strategy described in the next section.

In the task-oriented training mode, the patient is asked to grasp an object by approaching it with the virtual hand and to put it onto a table (Fig. 4). The control strategy for these kind of tasks is based on the minimal intervention principle, which allows an efficient exploitation of task space redundancies and results in user driven movement trajectories and is described in [36,37].

D. Control Strategy for the Labyrinth Game

A labyrinth with the dimension $n \times m$ is displayed to the patient (Fig. 5). The actual position of the robot in joint angle coordinate system is given by:

$$\tilde{q} = (q_1, q_2, q_3, q_4, q_5, q_6)^T$$  (1)

with $q_k$ being the actual joint angle of axis $k$. A red sphere with the radius $r$ on the display indicates the actual hand position $\tilde{h}$ derived from the actual position of axis $i$ and axis $j$:

$$\tilde{h} = \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} d - \frac{q_i - q_{i\min}}{q_{i\max} - q_{i\min}} n \\ d - \frac{q_j - q_{j\min}}{q_{j\max} - q_{j\min}} m \end{bmatrix} (1 \leq i \leq 6, 1 \leq j \leq 6, i \neq j)$$  (2)
All axis combinations are possible, but \( i = 2 \) or \( i = 4 \) and \( j = 1 \) are the most intuitive ones. The range of motion can be adjusted to the patient’s needs by selecting appropriate maximum and minimum values. The factors \( d_i \) and \( d_j \) are either equal to 1 or -1 and define the direction of the movement on the screen. The four axes that are not involved are position controlled and kept in a static position (Fig. 6).

The labyrinth topology is randomly calculated in such way that there is always a path (path width = 1) between the start point \( \bar{h}_{\text{start}} \) and the endpoint \( \bar{h}_{\text{end}} \). The matrix \( M \), given by

\[
M = \begin{pmatrix}
    a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{n,1} & a_{n,2} & \cdots & a_{n,n}
\end{pmatrix}
\]

with

\[ a_{i,j} = \begin{cases} 
    1 & \text{if field}(i,j) \text{ occupied} \\
    0 & \text{if field}(i,j) \text{ free}
\end{cases} \]

reflects the topology of the labyrinth. Axes \( i \) and \( j \) are first position controlled and guide the patient’s arm to the start point \( \bar{h}_{\text{start}} \). Once there, the robot control is changed to force control (Fig. 6). The reference force has been selected as a linear function depending on the overlap of the sphere with the wall and for non-boundary positions \( (1 < x < n, 1 < y < m) \) the force is given by:

\[
\begin{align*}
    F_x &= \begin{cases} 
        a_{x,y} \left(1 - x + x_{y}\right) k / r & \text{if } x < r + x_{y} \\
        a_{x,y} \left(-x + r + x_{y}\right) k / r & \text{if } x > r + x_{y} \text{ and } (x \leq x_{y} + 1 - r) \\
        0 & \text{otherwise}
    \end{cases} \\
    F_y &= \begin{cases} 
        a_{x,y} \left(y - y_{x}\right) k / r & \text{if } y < r + y_{x} \\
        a_{x,y} \left(-y + r + y_{x}\right) k / r & \text{if } y > r + y_{x} \text{ and } (y \leq y_{x} + 1 - r) \\
        0 & \text{otherwise}
    \end{cases}
\end{align*}
\]

(4)

with

\[ x_0 = \text{floor}(x) \quad \text{and} \quad y_0 = \text{floor}(y) \]  

(5)

Boundary positions need to be treated separately. The factors \( k_x \) and \( k_y \) are positive numbers that scale the force and there selection depends on the patient’s performance. A patient with poor ability to control the position of his hand will need a lot of guidance and, therefore, high factors \( k_x \) and \( k_y \). A healthy person would be able to pass the labyrinth without touching the walls and \( k_x \) and \( k_y \) could therefore be set to zero. The game is over when the patient either reaches the end position or when he enters into an occupied field. Therefore, if

\[ a_{x_0,y_0} = 1 \]  

(6)

a nasty sound is produced to indicate that the game is over and the game starts again. If the patient reaches the end point, then he will be awarded by a nice sound, a new labyrinth is generated, and the game starts again.

Fig. 5: Labyrinth game scenario. The red circle indicates the actual position of the human arm. The walls are indicated with white cubes and the yellow path is the trajectory where the patient can pass without feeling resistance. The patient can collect points by catching the yellow/black spheres.

Fig. 6: Labyrinth control schema with friction and gravity compensation, position control for the fixed axes, position or force control (depending on the state machine) for the active axes 1 and 2.
E. Clinical Evaluation

Most of the clinical evaluation has been performed with the earlier version of ARMin [16]. This simpler version has only axis 1-4 implemented and the shoulder complex is simplified to a three DoF ball and socket joint, what means that there was no link between axis 1 and point S (Fig. 1). Actuators, sensors and software are similar.

A pilot study was carried out to validate the patient comfort and handling, i.e. whether the robot is adjustable to different patient sizes, whether the cuffs are comfortable for the patients, and whether the patients are able to perform the movement tasks. Furthermore, the patient acceptance was interrogated. This pilot study included 11 patients with a cumulative training duration of more then 76 hours.

A possible benefit on the motor performance was not assessed in the pilot study, but in the subsequent single case studies with three chronic stroke patients (14-40 months post-stroke). Thereby, after a baseline phase, the three patients trained their impaired upper extremity with ARMin three or five times a week during eight weeks. A single training session consisted of 20 minutes of mobilization and 40 minutes of ball game training. The cumulative training duration was 88 hours. Active range of motion, isometric muscle strength and the score in the ball game were measured with ARMin and the Fugl-Meyer score [38] was assessed by an experienced therapist.

III. RESULTS

A. Control Strategies

The force field of the labyrinth with the topology presented in Figure 5 is shown in Figure 7. By exerting enough force, the user can pass through a wall and can enter into an occupied field. This case is detected and treated as a “game over” with immediate restart. A good patient would pass the labyrinth without touching the walls (Fig. 8) while a patient with poor control touches the walls several times. The work that the force field exercises onto the patient is calculated by integrating the interaction force over time and serves as performance measure to evaluate the patient. In addition to that, whenever the patient touches the wall, a nasty sound is produced.

B. Clinical Evaluation

The pilot study showed that the teach-and-repeat method enables the therapist to select an appropriated movement for the mobilization of the patient. Figure 9 shows typical trajectories for passive mobilization. It was possible to adjust the robot to patients with body sizes varying from 155cm to 192cm. But taller subjects are possible (maximum estimated: 210cm). It took 5 minutes to position a patient in the robot and additional 10 minutes to change the robot’s kinematics from the left arm to the right arm and vice-versa.

The patient acceptance was assessed on a questionnaire and the patient rated the robot with 5.5 point out of a scale from 1 to 6. All patients wanted to continue the robot-supported therapy. The three patients participating in the single case study, where highly motivated for the ARMin therapy and not a single therapy session was canceled.

The investigation of the effects showed that intensive training with this device can induce improvements in
coordination of arm movements, isometric muscle strength, active range of motion, and functional tasks. However, the single patients did not improve in all parameters, and the ones in which they improved differed. Thus, the effects of ARMin training seem to be quite individual. The improvements in the Fugl-Meyer Assessment (17 (+3), 33 (+3), 21 (+4.2)) are in a similar range as in other studies with robotic devices [20,22]. These improvements in Fugl-Meyer score are remarkable in chronic stroke subjects. Nevertheless, we observed that the carry-over into activities of daily living (Barthel index) was rather small. This means that the subjects regained movement abilities but did not change their way how to cope with activities of daily living. Therefore, future work will focus on the training of activities of daily living.

IV. CONCLUSION AND OUTLOOK

The ARMin robot was built with four active DoF in the first prototype and has then been extended with two additional DoF for the forearm in order to allow training of task-oriented movements and an additional coupled-DoF to accommodate the vertical movement of the center of rotation of the shoulder joint. The modular design of the ARMin robot that allows various combinations of proximal and distal arm training modes will also serve as platform for the search of the best arm rehabilitation practice. The functionality has been proven during the pilot study, and the results of the three single case studies suggest that this sort of therapy has positive effects on the movement performance of chronic stroke patients. For the future, a controlled clinical study with a larger amount of patients is in preparation.

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