Trajectory Planning of ADL Tasks for an Exoskeletal Arm Rehabilitation Robot

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Abstract

Task-orientated repetitive movements can improve motor recovery in patients after stroke. The application of a robot such as ARMin can serve to assist and support the patient during training. Audiovisual displays can be used to present movement tasks and instructions to the patient. While in the past, simple games for single joint movements have been trained, a new approach is to train more functional movements and increase participation and voluntary efforts of the patient. In order to maximally involve the patient and enhance the transfer to daily life, virtual activities of daily living (ADL) should be exercised. To train such movements a robot needs sufficient degrees of freedom (DOF). Therefore, the latest version of ARMin, was extended to seven DOF and includes a new forearm module and a hand module to support hand opening and closing as required for grasping. We identified useful ADL's and implemented them in the virtual environment. Optimal trajectories for all possible arm movements during ADL's have been investigated and a new trajectory generation method has been implemented. Seven healthy subjects performed four virtual ADL tasks with ARMin. The measured paths were compared to two common trajectory generation methods, the minimum jerk and minimum angular jerk algorithm. It could be shown that the minimum angular jerk algorithm is superior to the minimum jerk method and will be used for future ADL training with ARMin.

1 Introduction

Conventional therapy has several limitations. The training duration and intensity is usually limited by fatigue. The assistance of functional movements is restricted, because it is difficult for the therapist to support movements in all concerned joints at the same time. With robot-assisted arm training we are able to assist the patients as much as needed in all DoF. Audiovisual displays in combination with the robotic device can be used to present a virtual environment and help the patient perform different activities of daily living. To support the patient during those tasks a trajectory generation that approximates natural human arm movements and a suitable control strategy that supports the patient are needed.

Task-orientated repetitive movements can improve muscular strength and movement coordination in patients with impairments due to neurological or orthopedic problems. Thanks to neuronal plasticity, the patients can regain some of their lost abilities by relearning movement patterns with the paretic arm. Key factors for an effective rehabilitation process are training intensity and duration and highly repetitive and task-orientated movements. Besides simple games for the training of single joint movements, more functional movements, where multiple joints act together to achieve a task, should be trained to have a better transfer to daily life [1].

Many studies have been conducted to investigate human arm movements [2–5]. One subclass are the point-to-point or reaching movements, where the task is for example to reach an object and grasp it. This already covers many functional movements, which are required in everyday life. The studies of human point-to-point movements show that the curvatures of hand paths depend on where the movement is executed with respect to the body axis. Movements performed near the midsagittal plane were less curved than movements from left to right [2, 3]. The velocity profile showed to be bell shaped for almost all paths [4, 5]. However, there is always a variance in the performed trajectory between various tries and different subjects.

2 Methods

2.1 Specification of ARMin III

ARMin is an arm rehabilitation device developed at ETH Zurich, in collaboration with the University Hospital Balgrist [6]. It has an exoskeletal structure with six actuated degrees of freedom (DoF). The latest device, version III, is shown in Fig. 1. The patient is connected to the arm with cuffs on the upper arm and on the forearm. The lengths of the arm segments and the height of the device are adjustable to different patients.

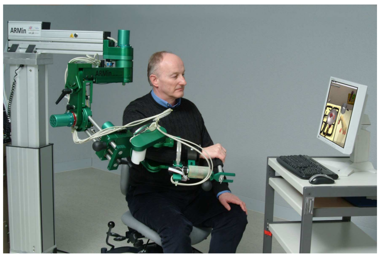

Figure 1: ARMin III

Axis	RoM	Nom. torque	Gear
Arm elevation q_1	40°...125°	10 Nm	1:100
Plane of elevation q_2	-40°...140°	10 Nm	1:100
Int./ext. shoulder rotation q_3	-90°...90°	12 Nm	1:144
Elbow flexion/extension q_4	0°...120°	10 Nm	1:100
Forearm pro./supination q_5	-90°...90°	2.5 Nm	1:28.8
Wrist flexion/extension q_6	-40°...40°	6.6 Nm	1:233
Hand open and close q_7	0°...32°	2.2 Nm	1:18

Table 1: Technical specifications of ARMin III

In most ADL tasks a hand function like precision or power grip is very important to interact with objects. For a meaningful training of those tasks it is crucial to have a module for supporting and measuring hand, respectively finger movements. For this purpose, ARMin III was extended with an additional DoF. The hand module was developed in collaboration with Hocoma AG, Volketswil, Switzerland. The range of motion (RoM) of the joints and the torques provided by the actuators are listed in Table 1. ARMin can be used for left and right arm training. Therefore, most of the joints have a symmetrical structure. Each joint has a mechanical end stop to ensure that the anatomical limits of the human arm can not be exceeded. A spring with a rope connected to the arm provides passive gravity support and is an important safety feature in case of power loss. Redundant position sensors, one analogue and one digital, are used to detect a sensor failure and to initialize position during startup. To actuate the axes, we use DC motors in combination with gears that are back-drivable, have low friction and negligible backlash. Furthermore, the maximum speed and torque of each drive was chosen from values obtained in a previous study [6]. For real time control a xPCTarget (Matlab) system is used with an update rate of $1\ \mathrm{kHz}$. ARMin is combined with a virtual environment, in which several virtual games can be played. A TCP/IP connection synchronizes the virtual world with the xPCTarget control system.

There is a broad range of activities a human can do in his daily life. To limit the number of tasks three criteria are used:

1. Important in a patient's daily live
2. Used in conventional therapy
3. Possible with RoM of ARMin

With those three criteria a limited number of ADL tasks suitable for training with ARMin has been selected. For implementing the virtual world a sophisticated game engine, GIANTS (GIANTS Software, http://www.giants-software.com), was used. State-of-the-art collision and physics algorithm allow a realistic behavior of interaction with objects in the virtual world.

2.2 Trajectory Planning

To assist and support the patient during training of ADL tasks an optimal trajectory is generated. A common method to generate a trajectory is the minimum jerk algorithm, which minimizes the cost function C_J, what leads to a straight line in task space from the starting position to the target position.

$$C_J = \frac{1}{2}\int_0^{t_f} \left((\frac{d^3x}{dt^3})^2 + (\frac{d^3y}{dt^3})^2 + (\frac{d^3z}{dt^3})^2 \right) dt \tag{1}$$

Another algorithm, the minimum angular jerk, minimizes the change of angular acceleration with the cost function C_{AJ}. This method generates a trajectory, which is a straight line in joint space and a gradually curved path in task space.

$$C_{AJ} = \frac{1}{2}\int_0^{t_f} \sum_{i=1}^{n} (\frac{d^3q_i}{dt^3})^2 dt \tag{2}$$

This second method requires inverse kinematics to determine the target position in joint space of the desired target position in task space. Because the system is overdetermined, there exist multiple solutions for the elbow position for one end-effector position. To solve this redundancy problem an additional constraint is used. If the orientation of the hand is defined for each task, then the elbow position is unique and can be calculated. The orientation of the hand ϕ_h can be defined as a function of the rotation of the upper and the lower arm [7],

$$\phi_h = f(q_3, q_5), \tag{3}$$

where, q_3 is the angle of rotation of the upper arm, which is equal to the inner/outer rotation of the shoulder and q_5 is the lower arm rotation, which corresponds to the pro/supination angle of the fore arm. Instead of a target position in space, a target pose, which includes target position and hand orientation, is defined for each task. The trajectory $\boldsymbol{p}_{ref}$ can be defined as,

$$\boldsymbol{p}_{ref} = f(p_T, p_S, \phi_{h_T}, \phi_{h_S}), \tag{4}$$

where p_T and ϕ_{h_T} are the target position in task space and the target hand orientation, respectively, p_S and ϕ_{h_S} are the start position and the start hand orientation, respectively. Both are captured at the beginning of the movement.

To evaluate these two trajectory generation methods for ARMin, an experiment with seven healthy subjects has been conducted. The subjects had to perform ADL tasks in the virtual world with ARMin. They received no support from the device and could move freely within the range of motion of ARMin. To reduce the influence of the robot, a zero interaction force control was used, where the robots gravity, spring and friction forces were calculated with a model and compensated with the motors. During the movements, the position of the hand, the joint angles q_i and the current target position were recorded.

Four tasks in two different ADL's have been investigated: Task 1 consisted of picking up food (Fig. 2(a)). In task 2 the goal was to drop the food into the pan (Fig. 2(a)). Task 3 and 4 were conducted in the bathroom scenario (Fig. 2(b)), where first the toothbrush and then the toothpaste had to be grasped. For each task, a starting position was indicated by a green sphere. Once the start position was reached another green sphere showed the target position and the recording of the movement started. Each task was repeated five times. The acquired movements were compared to the minimum jerk and minimum angular approach.

(a) Kitchen scenario (b) Bathroom scenario

Figure 2: ADL scenarios

3 Results

The mean trajectory calculated out of five records and the trajectories generated with minimal hand jerk and the minimal angular jerk algorithm, are shown in Fig. 3.

In Table 2 the mean differences between recorded trajectory and the two generated ones according to a nearest-neighbor algorithm, are listed. Although the mean and peak velocities between subjects was

Task	mean dist to min. angular jerk [cm]	mean dist to min. jerk [cm]
1	2.314 (1.832)	4.177 (2.623)
2	0.993 (0.601)	3.573 (2.598)
3	3.997 (2.706)	6.163 (3.725)
4	1.499 (0.878)	1.723 (0.817)

Table 2: Mean distances, calculated with the nearest-neighbor method, between measured and generated trajectories according to minimum jerk and minimum angular jerk

different, the velocity profile during all movements were bell shaped. The inverse kinematics method with the hand orientation as a constraint worked for all target positions used.

4 Discussion

The curvature of the performed trajectories during all ADL tasks seems to be closer to the one generated with the minimal angular jerk method than with the minimal jerk approach. Whereas in tasks one, two and four the mean distance to the minimum angular jerk trajectory is very small, in task four a larger deviation was measured. In the beginning of the experiment we observed that in task three the subjects tried to avoid

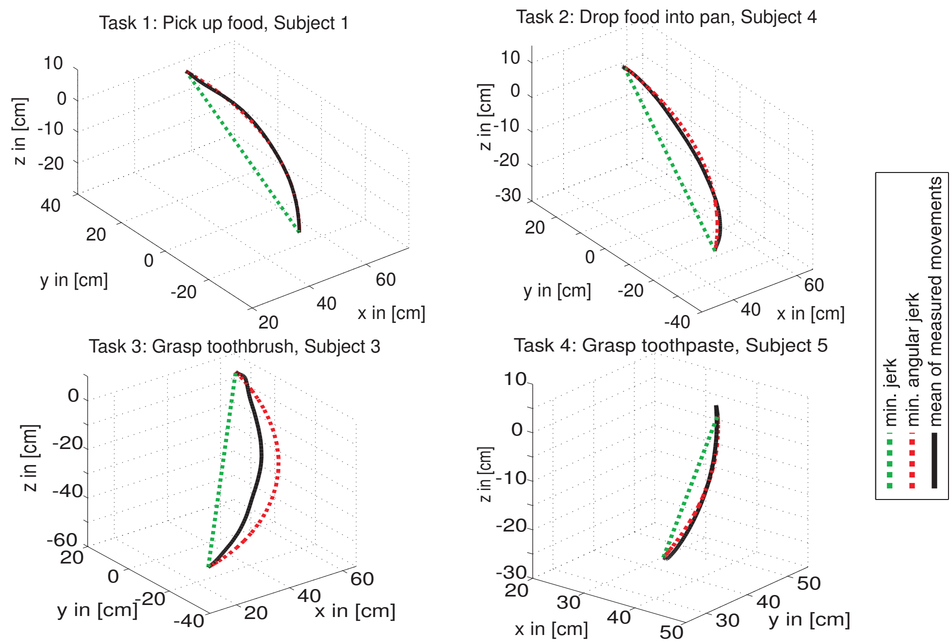

Figure 3: Recorded movements and calculated trajectories

collision with the virtual shelf. Even though, the subjects were instructed to ignore the shelf, this could be a reason for the deviation of the path. It is known that patients sometimes perform so called trick movements to achieve a task, which differ from the natural movement of a healthy human. A patient-cooperative control strategy based on this trajectory generation should consider this by giving enough freedom in the path or by deforming the trajectory to adapt it to the patient.

5 Conclusion and Outlook

The results indicate that a trajectory planner based on the minimum angular jerk approach is more suitable for point-to-point movements with ARMin III than the minimum jerk method. With the collected data, a patient-cooperative path control strategy [8], can be developed using the generated trajectory as a baseline and allowing enough freedom in the path to account for the variance between subjects and trials. The goal should be to maximize patient participation and involve voluntary efforts. In future work, trajectories for obstacle avoidance and movements, which are not reaching movements, e.g. circular movements, should be investigated.

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