Comparison of Three Control Strategies for an Upper Arm Rehabilitation Device

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Abstract. The RETRAINER S1 system is an upper limb rehabilitation device designed to be used in repetitive task-oriented training. While the device itself is intrinsically controlled by the wearer, the execution of the training exercises is automatically controlled by a finite-state machine. This contribution discusses three different control strategies tested in a clinical environment.

1 Introduction

THE impairment of the upper limb is the most common impairment among stroke survivors [1]. It is widely accepted that repetitive task training [2], the use of Functional Electrical Stimulation (FES) [3] and robot-assisted arm training [4] improve upper limb rehabilitation outcome. The RETRAINER S1 system [5] combines all these approaches. The system composes of a passive exoskeleton with lockable degrees of freedom providing weight compensation. The exoskeleton is intrinsically controlled by the wearer, who is supported by EMG-triggered FES. The system is used in task-oriented repetitive training resembling activities of daily life. The system is currently tested in a randomized control trial.

The training exercises are automatically executed based on different kinds of sensor data. Therefore the intensity and effectiveness of the training highly depend on the accumulated data and how it is used. This paper discusses three different control strategies for the automatic execution of training exercises.

2 Methods

2.1 Exercises Description

Specific repetitive, task oriented training exercises were designed to be carried out with the RETRAINER system. The exercises can be categorized by the degrees of freedom

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Research supported by European Union's Horizon 2020 research and innovation program under grant agreement No 644721.

L. Masia et al. (Eds.): ICNR 2018, BIOSYSROB 21, pp. 162–166, 2019.
https://doi.org/10.1007/978-3-030-01845-0_32

(DOF) required. Some exercises – hand-to-mouth movement and lateral elevation in the frontal plane – require a single DOF and train a specific muscle (biceps and medial deltoid, respectively). Other more complex exercises require multiple DOFs and are specifically designed to train biceps, triceps, anterior, medial and posterior deltoid. In these exercises the patient has to reach or elevate the hand over target positions placed on a desk at central, lateral internal and lateral external positions. All exercises can also be performed using objects of different size and weight to train grasping, moving and releasing of objects.

2.2 Exoskeleton

The light-weight exoskeleton provides weight compensation to upper arm and forearm by means of two adjustable spring mechanisms. The level of compensation and the lengths of the exoskeleton are highly adjustable and support patients within 5th and 95th male/female percentile. The exoskeleton has four DOFs as shown in Fig. 1. Apart from the trunk inclination, all DOFs are equipped with an angle sensor and an electromagnetic brake. The inclination angle is determined using an Inertial Measurement Unit (IMU) attached to the inclination mechanism and an orientation estimation algorithm [6]. The exoskeleton is mounted on a (wheel)chair using a clamping mechanism.

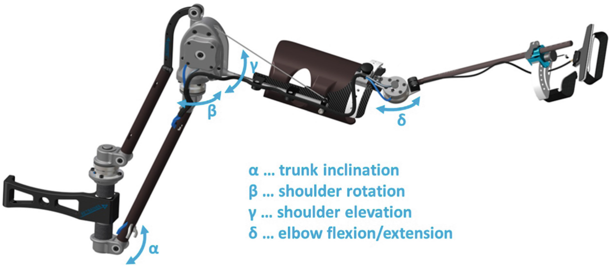

Fig. 1. Degrees of freedom of the exoskeleton

2.3 RFID Technology

The position markers and objects used during training are each equipped with passive RFID tags. An RFID reader and an external antenna are integrated into the exoskeleton. The antenna is positioned at the back of the patient's hand (see Fig. 1). The Received Signal Strength Indicator (RSSI) of the response signal of the tags is directly dependent on the distance between tag and antenna. The RSSI value can therefore be used as a measure of distance between objects/markers and the patient's hand.

2.4 Control Strategies

The execution of the exercises is controlled by a finite-state machine. Each task of an exercise is represented by a state in the state machine. Transitions between states and thus tasks are triggered whenever new sensor or RFID data is available. However, the transitions are only executed when certain task specific requirements – so called guards - are met. The three control strategies are defined by the definition of these guards and the used data:

1. *Angular Sensor Data*
   Only using angular sensor values, a guard is defined by a set of angular threshold values and corresponding comparative operators (<or>). A transition is only triggered if all thresholds are reached.
2. *RSSI Value*
   In this case a guard is defined by one RSSI threshold value and the unique ID of the corresponding RFID tag.
3. *Kinematic Model*
   Using a kinematic model, a guard is defined as a three dimensional position in space. A transition is triggered if the distance between target and current position is smaller than a movement speed-dependent tolerance radius r:

$$r = r_{\min} + (r_{\max} - r_{\min}) \cdot \frac{v_{\max} - v}{v_{\max} - v_{\min}} \tag{1}$$

   With r_{min} and r_{max} being the minimum and maximum tolerance radius and v, v_{min} and v_{max} being current, minimum and maximum movement speed.

2.5 Verification of the Kinematic Model

An eight-camera motion analysis system (Motion Analysis Corporation) was used to validate the kinematic model and the angle measurements. The data was collected at 100 Hz and processed by a motion analysis software (Cortex, Motion Analysis). The kinematic model and the angle estimation algorithm were implemented using Matlab Simulink and executed on a Beagle Bone Black with a sample frequency of 25 Hz. Angle values and the position of the exoskeleton’s tool endpoint (TEP) were recorded for 30 s. The calculated mean error and standard deviation are presented in Table 1.

Table 1. Angle and position errors

	Mean error	Standard deviation
α	−0.78°	1.0546
β	−1.76°	4.8687
γ	−0.30°	1.3629
δ	0.35°	1.1521
TEP	33.6 mm	15.5343

2.6 Patient Testing

The control strategies were tested within the framework of the clinical trial, which was approved by the Ethical Committees of the participating clinical centers. All participants of the trial were asked to sign a written informed consent.

The control strategies were tested with four patients performed a reaching exercise specifically defined for the clinical trial for at least 10 min. The guards were parameterized by moving the patients hand to each position. v_{min} and v_{max} were calculated online and $r_{min} = 20$ mm and $r_{max} = 80$ mm were chosen based on the marker radius and dimensional error. All three control strategies were tested separately and in parallel.

3 Results and Conclusion

The tests substantiated that a control strategy solely based on angle data is only feasible when a singular rotary degree of freedom is to be trained (e.g. the biceps in a hand-to-mouth movement requiring only the elbow angle). This is due to the fact that a position can be reached with different compositions of joint angles.

The RSSI-based approach has the serious weakness that electro-magnetic disturbances severely limit the accuracy. Nonetheless, the simplicity and flexibility of this approach is captivating and it should therefore be further examined (e.g. by testing a different frequency range). The strategy seems particularly interesting for exercises in which targets do not remain stationary (e.g. when moving objects).

The use of a kinematic model in combination with the speed dependent tolerance radius presented an improved precision – especially when the markers were positioned very close to each other. Although the kinematic model requires to be calibrated before each session, exploiting the full potential of this approach might further intensify the training or optimize the support: e.g. by defining three-dimensional trajectories which need to be followed or virtual walls to be surpassed.

Concluding, it has to be stated that none of the three tested strategies alone is suited for all exercises and that only an exercise-dependent combination of multiple strategies results in an optimal control structure.

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