Design and Test of Therapy Exercise for Human Arms

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Abstract. This paper presents the testing and design of several arm therapy exercises with medical device applications which use manipulators. The description of human arm motions and arm rehabilitation movements are presented together with the acquisition of the trajectories through demonstrations of arm rehabilitation exercises. A reference trajectory is generated by regression analysis for each arm rehabilitation exercise. The methodology used to obtain reference trajectories allows the implementation of learning by demonstration in medical devices.

Keywords: Arm therapy design, arm rehabilitation manipulator, reference trajectories by regression.

1 Introduction

Mechanical devices are used for guided exercises to support the process of rehabilitation therapy of the extremities. However, some devices or mechanism can only offer a limited range of trajectories which sometimes are linear or circular figures [1, 2]. Nevertheless, physical rehabilitation therapy requires more complex maneuvers [3]. The characterization and reproduction of human movements is difficult due to their complex variability. These problems have been treated in humanoid robotics through "programming by demonstration" methodology which often is referred to as "learning by demonstration" or "learning by imitation" [4]; where a robot learn skills or motions by observation of a human guidance action namely demonstration [5][6][7].

Rehabilitation robotics has used different ways to obtain reference trajectories for rehabilitation devices. In [8] reference trajectories for arm rehabilitation have been obtained using a planar biomechanical model of the arm. The model allows planning the arm trajectory to move from one point to other, including muscle tension. It is based on healthy patients and it could be applied in prosthesis and exoskeletons for postural training. However, the complex maneuvers for rehabilitation therapy requires different paths to move the arm from one point to other. In [9] reference trajectories for a rehabilitation virtual trainer have been planned using imitation techniques. A “Sarcos Sensuit” device stored the angular positions of a healthy human which are only reproduced by the virtual trainer.

In [10-11], reference trajectories have been generated for a knee rehabilitation device and an arm rehabilitation device, respectively. In both devices, the reference trajectories have been acquired from demonstrations of the exercises by using an image processing method. The trajectories have been processed and transformed to different sizes of the limbs, using anthropomorphic human dimensions. In [12] ARMIN, an arm rehabilitation device, allows remembering and reproducing the positions of a movement demonstrated by the therapist. The stored movement is reproduced using different speeds. However, in [10, 11, 12] the reference trajectories have been recorded from just a demonstration where the movements could be wrong. The variability of the human motion should be consolidated from several demonstrations [5].

In this paper a way to generate reference trajectories for arm rehabilitation is presented by using regression analysis. Several rehabilitation exercises have been processed, among which two have been used to illustrate the application of the method in this paper. The relevance of the presented approach is about the method by which references trajectories can be generated for a robot manipulator, specifically for each patient for each therapy session. The method is based on several trajectories that are performed by each patient, which are stored while the therapist guides the patient’s arm. Then a reference trajectory is generated for a robot manipulator that will guide to the patient in the next repetitions of the exercise. The process should be repeated for each patient in each therapy session so that the obtained trajectories will also consider the variations due to the health condition of each patient and are specific for the individual anthropomorphic and anthropometric dimensions. This methodology to teach trajectories to a robot manipulator is referred in the literature to as “learning by demonstration” [4]. This paper is the first stage of a project that is aimed to design an arm rehabilitation mechanism. The future work will address the design issues.

The novel contribution in the proposed method can be recognized in the procedure of generating reference trajectories for next robot guide by using the individually experiences from each patient during the rehabilitation therapy.

2 Human Arm and Motion Strokes

The arm is principally divided into three sections namely upper arm, forearm and hand, Figure 1a. The arm is connected to the body trunk through the shoulder joint; the forearm is connected to the upper arm through the elbow joint; and the hand is connected to the forearm through the wrist joint. The shoulder joint has three degrees of freedom (DOFs) moving around the axes 2, 3 (flexion-extension) and around axis 1 (abduction), Figure 1b. The elbow joint has one DOF moving around the axis 4 (flexion-extension) but the motion of the forearm around the axe

7 (pronation-supination) adds another DOF to the elbow. The wrist joint has two DOFs around the axis 5 (flexion-extension) and around the axis 6 (abduction-adduction). However, also the pronation-supination (around axe 7) adds another DOF to the wrist joint [13].

The mobility and functionality of the upper limb may be affected by injury or by neurological diseases such as polio, hemiplegia, paraplegia or sclerosis; muscle diseases such as myelitis, immobilization syndrome, muscular dystrophies, spasticity, or muscle atrophy postural alterations; joint diseases such as osteoarthritis, arthritis and periarthritis, among others [11]. Rehabilitation therapy seeks to restore the normal function of the limb, and the recovery of range of motion is one of its primary goals [14].

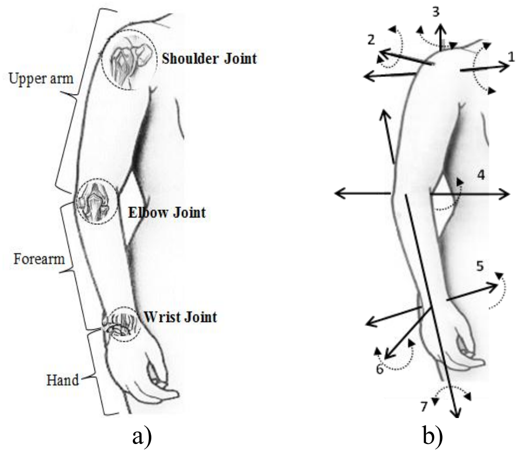


Fig. 1 A representation of a Human Arm: a) Anatomy; b) Principal parameters of motion [13].

Two types of robot structures can assist movement therapy namely exoskeletons and manipulators with specific end effector. Exoskeleton tries to imitate the natural movement of the arm and it operates directly on the movements of each joints of the arm. Manipulators with specific end-effector try to guide the patient’s hand as a therapist would do, indirectly causing the movement of the arm joints.

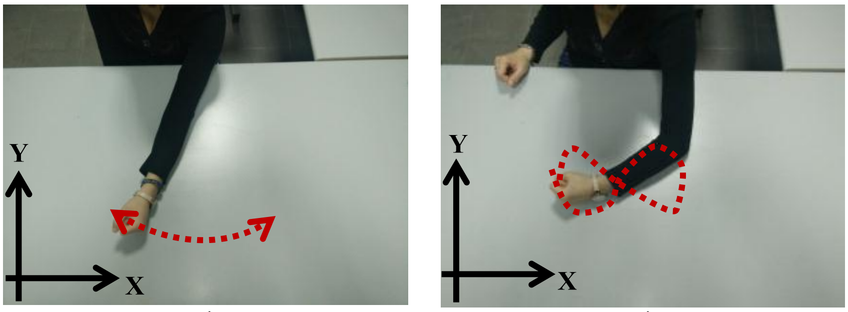
The parameters to valuate for arm motion design depend on the types of robots structures. Exoskeletons require reference trajectories from the angles generated around the rotation axes of the arm joints. Manipulators require reference trajectories from the Cartesian position of the point of the human arm where the end-effector of the mechanism will be attached during the therapy.

3 Motion Planning for Therapy Exercises

Four exercises have been recommended by Specialists of CRIQ (Integral Rehabilitation Center of Queretaro, Mexico) to treat the shoulder and the elbow. The four exercises are generally used in the rehabilitation therapy in several phases of the injury or disease in order to recover mainly capacities. The movements are followed on a horizontal plane where the reference frame is defined as X and Y as it can be seen in Figure 2. The exercises are made leaning suitably the upper limb on a table according to the procedures. The procedures have been applied for the four exercises; however only two exercises are presented as example.

Figure 2a and 2b show two rehabilitation exercises corresponding to horizontal flexion for shoulder (exercise A) and the arm motion to tracing the "figure of the number eight" (exercise B), respectively. The "figure of the number eight" involves coordinated motions of the shoulder and the elbow. The parameters of motion to evaluate in the exercises have been the displacements of a point of the hand along the axes X and Y, dotted line in Figures 1a and 1b. The Cartesian trajectories of the hand have been considered in order to generate references for a manipulator mechanism. Positions versus time have been evaluated to generate references trajectories in this stage of the work; velocities and accelerations can be considered in a later stage. However, the references trajectories can be reproduced on a device using the average of velocities and accelerations calculated by the first and second derivate of positions versus time, respectively.

The variability of patient condition is considered in the proposed method by planning update of the reference trajectory during the therapy. The reference trajectory is obtained as a statistically elaborated trajectory from several exercises that a patient will perform during different phases of the rehabilitation therapy.



Exercise A
a)

Exercise B
b)

Fig. 2 Snapshot of exercises A and B. a) Horizontal flexion for shoulder; b) Tracing "figure of number eight".

4 Acquisition and processing of trajectories for therapy use

Several tests have been carried out with examples of exercise executions using a person as demonstrator. The Cartesian components X and Y versus time have been acquired using a Microsoft Kinect device [13]. Ten demonstrations have been performed for each exercise; a demonstration is here defined as the human action to show each exercise [5, 6, 7]. The experiment consisted in carry out each exercise from start to finish, 10 times consecutive, while the Cartesian components versus time were stored using the Microsoft Kinect device [18]. The parameters can also be obtained through other acquisition methods [4].

The time of all trajectories has been normalized to allow their analysis by regression. The formula in (1) has been used for time normalization where i is the position time, N is the scale transformation, t_k is the maximum value of the vector time and t_1 is the minimum value of the vector time.

$$tn_i = \left(\left(t_i\right) * \mathrm{N}\right) / \left(t_k\right) \tag{1}$$

Figures 3 and 4 show the acquired Cartesian components X and Y versus normalized time from demonstrations of exercise A and B, respectively.

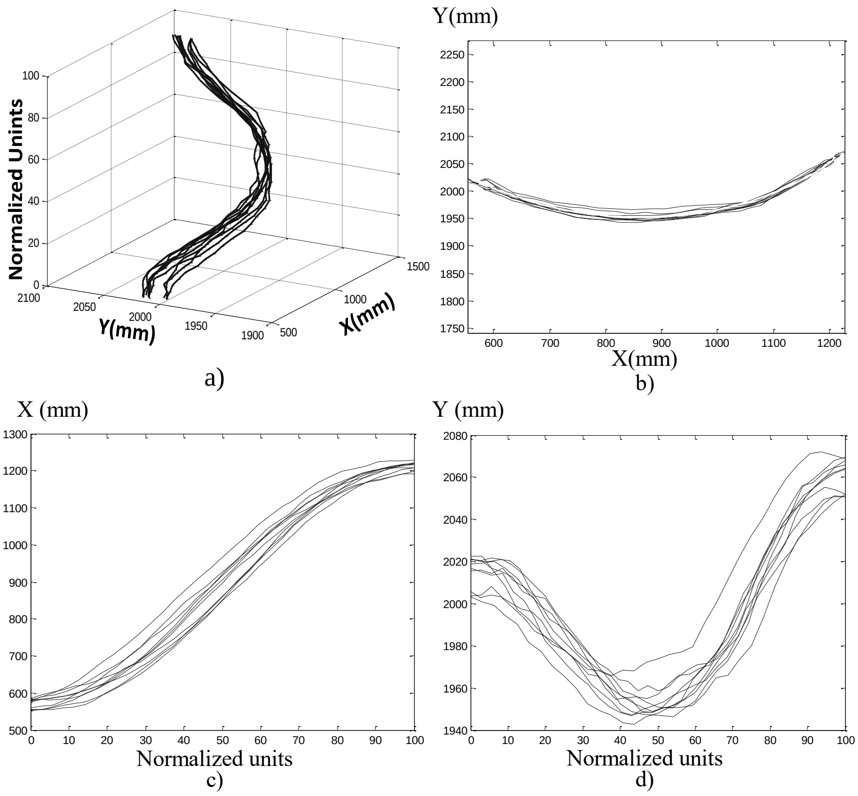


Fig. 3 Cartesian components from the demonstrations for exercise A (horizontal flexion for shoulder): a) 3D plot of X positions and Y positions versus normalized time; b) X positions versus Y positions; c) X positions versus normalized time; c) Y positions versus normalized time.

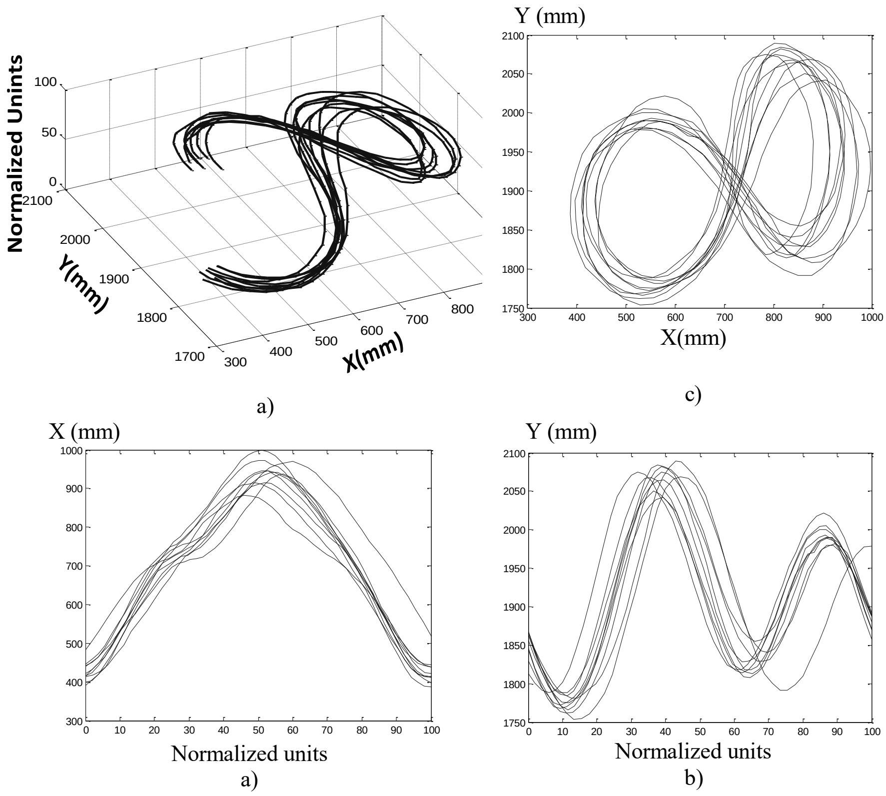


Fig. 4 Cartesian components from the demonstrations for exercise B to trace a "figure of number eight"): a) 3D plot of X positions and Y positions versus normalized time; b) X positions versus Y positions; c) X positions versus normalized time; c) Y positions versus normalized time.

Least squares regression has been implemented in order to consolidate the motion of each rehabilitation exercise; through generation of a reference curve from the set of 10 demonstrations for each exercise. The method generates the coefficients of a polynomial curve that best fit to the set of demonstrations for each exercise, under the minimum error criterion that can be expressed as:

$$\sum_{i=1}^{k}\left(\hat{p}_i - p_i\right)^2 \tag{2}$$

where $\hat{p}_i$ is the predicted value, p_i is the known value and k is the data length, p can be X or Y positions depending of the evaluated component [15, 16, 17].

The software that was used for curve fitting is a CAS (Computer Algebra System). The software allows matrix manipulations, plotting of functions and data and implementation of algorithms. Furthermore, the software has specialized tools that allow the implementation of statistical modelling as Regression analysis and other statistical methods. The curve fitting has been elaborated as off-the-shelf toolboxes using tools of CAS environment with algorisms designed by the authors.

Figure 5 shows the curves generated by regression to consolidate the demonstrations of horizontal flexion for shoulder (exercise A in Figure 2a); The generated curves for the components X and Y have been consolidated with polynomials of fourth order. The generated curves represent successfully the real shape of the exercise A as it can be seen in Figures 5a-5d. The polynomial coefficients calculated to generate the reference curves for components X and Z are in Table 1.

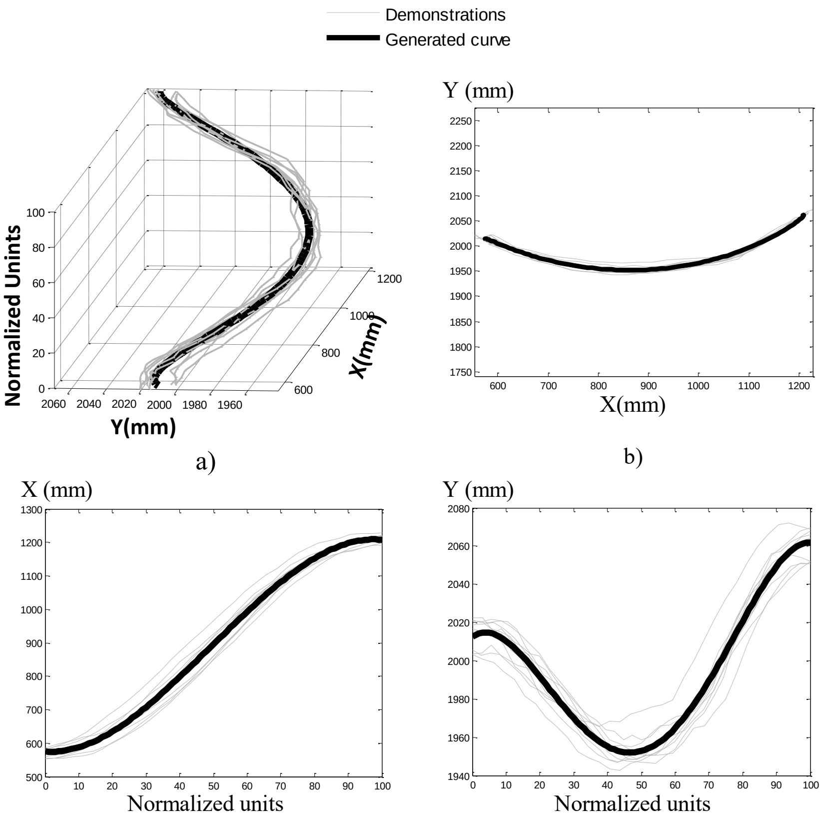


Fig. 5 Generated curves to consolidate the demonstrations of horizontal flexion for shoulder (exercise A) using 4th order polynomials: a) 3D plot of generated curves versus demonstrations; b) demonstrations and generated curve for X positions versus Y positions; c) demonstrations and generated curve for X positions versus normalized; d) demonstrations and generated curve for Y positions versus normalized.

Table 1. Polynomial coefficients- exercise A.

Components	*Calculated polynomial Coefficients by regression using 4th order polynomial.*				
X	0.0000004.657	-0.001533	0.2203	0.8394	575.2846
Z	-0.00001595	0.003198	-0.1667	1.1362	2012.6277

The fourth-order polynomial that has been used for worked out the Cartesian components X and Y of the trajectory in exercise A, has been selected by observing the error behaviour. The error has been defined as the mean square of the residuals between the curves that have been performed by the patient and the curve that has been generated by polynomials. The residuals have been calculated by using both trajectories components X and Y. A residue can be understood as the distance between a point ($\hat{X}_i, \hat{Y}_i$) and a point (X_i, Y_i). Where $\hat{X}_i$ and $\hat{Y}_i$ are Cartesian components that have been predicted by polynomials; X_i and Y_i are Cartesian components of curves that have been performed by the patient; and i identify the actual evaluated point. The distance between a point ($\hat{X}_i, \hat{Y}_i$) and a point (X_i, Y_i) can be calculated by using Pythagoras theorem.

Since the curves are fitted by using a polynomial for each Cartesian component, a curve is composed of two polynomials. Then, errors have been evaluated by using different combinations of polynomials between the pair of polynomials. The order of polynomials has been varied upwardly from 1 until 20. When polynomials with order higher than 4 have been used, the error reduction is negligible with reductions less than 0.005 %. As example, the fifth-order polynomial has presented an error reduction of 0.004 % with respect to error that is obtained with a fourth order polynomial. In addition, the changing of the shape of the curves between a fifth order and a fourth order is negligible. Therefore, polynomials with order higher than 4 are not considered useful. In addition, higher-order polynomials have disadvantages for more computing efforts and possible over-fitting. The fourth-order polynomial has had an error reduction of 5.89 % with respect to error of a third-order polynomial and an error reduction of 62.58 % with respect to error of a second-order polynomial. The fourth-order polynomial fits the shape of the curves better than a second and a third-order polynomial. First-order polynomial is not useful in this case because it can only fits straight lines. Then, fourth-order polynomial has been found convenient for the exercise A. The same procedure has been applied for the exercise B, where fifth-order polynomials have been found convenient for the Cartesian components X and Y. The selection polynomial achieved when the error reduction between polynomials is negligible as well as its effects on the shape of the curve to discard order polynomials that are not convenient.

Figure 6 shows the curves generated by regression to consolidate the demonstrations to trace a “figure of number eight” (exercise B in Figure 2b); The generated curves for the components X and Y have been consolidated with polynomials of fifth order. The generated curves represent the shape of the number eight as it can be seen in Figures 6a-6d. The polynomial coefficients calculated to generate the reference curves for components X and Z are in Table 2. The "figure of number eight" is more complex to consolidate but a fifth-order polynomial can adjust the shape. The exercises A and B have been used only as an example to apply the methodology but other exercises can be consolidated to generate reference curves for a manipulator.

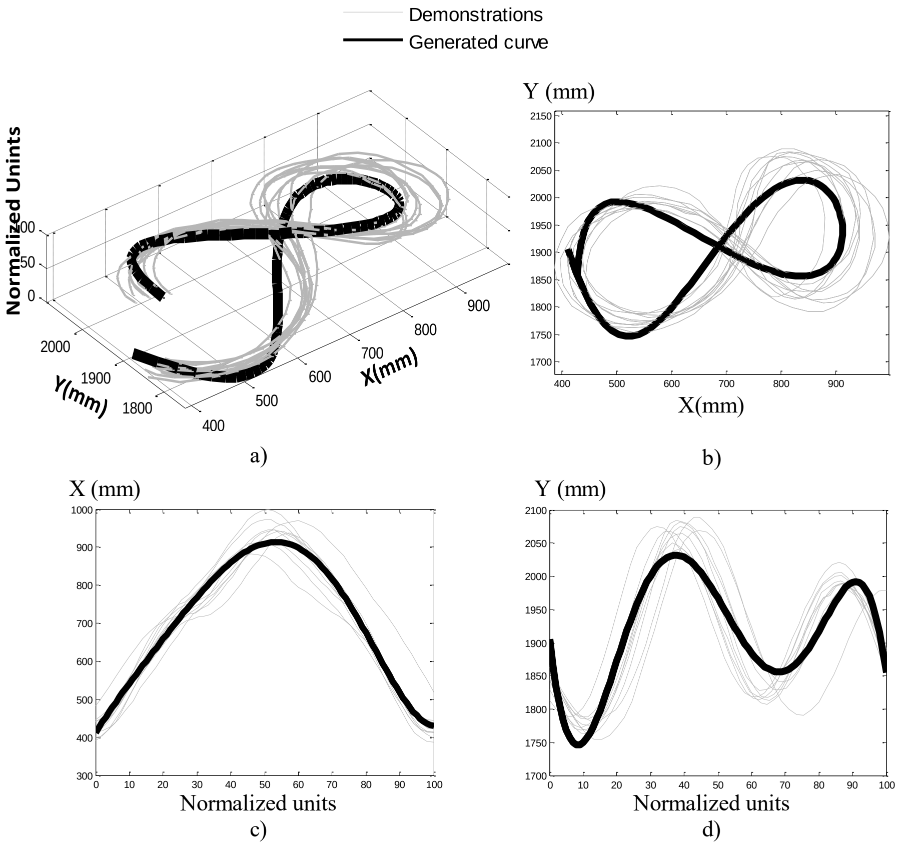


Fig. 6 Generated curves to consolidate the demonstrations to trace a "figure of number eight" (exercise D) using 5th order polynomials; a) 3D plot of generated curves versus demonstrations; b) demonstrations and generated curve for X positions versus Y positions; c) demonstrations and generated curve for X positions versus normalized; d) demonstrations and generated curve for Y positions versus normalized.

Table 4. Polynomial coefficients - exercise D.

Components	*Calculated polynomial Coefficients by regression using 5th order polynomial.*					
X	0.0000008349	-0.0001622	0.008675	-0.2230	14.4829	411.6845
Z	-0.0000004476	0.00114768	-0.1031	3.7515	-43.8987	1905.7957

The quality of the demonstrations could be improved when the trajectories are directly guided by the therapist. However, despite some demonstrations as the one of "number eight" have been difficult to repeat, the regression analysis has been able to follow an approximate shape. Furthermore, ongoing tests are being considered for error estimation of the generated curve.

The proposed method will be used to generate reference trajectories specifically for each patient, with specific dimension and shape. In practice, since each patient performs his/her own exercise, the obtained trajectory will be appropriate for his/her own physical dimensions. In addition, the exercise is guided by the therapist according to the medical diagnostic for each patient so that, a reference trajectory is obtained by using exercises that the therapist has considered as convenient for the patient.

The reference curves generated by regression to consolidate the rehabilitation exercises A and B are the trajectories that a manipulator mechanism could reproduce. Assuming the end-effector mechanism guides the patient's hand, the generated trajectories are the position inputs in the inverse kinematics. Velocities and accelerations from the demonstrations for each exercise can be considered to reproduce the position trajectories. Thresholds force should also be considered in the patient-robot interaction when the position trajectories are reproduced.

On the other hand, the generated reference trajectories for rehabilitation exercises can also be used for diagnosis; the references trajectories of healthy people can be compared with the trajectories of a patient and then the patient's health condition could be estimated.

6 Conclusions

Reference trajectories have been generated successfully by regression analysis from the demonstrations of rehabilitation exercises for the arm. The trajectories have been designed for applications to path planning of manipulators with specific end-effectors. The polynomials generated by regression to generate the reference curves have been able to fit satisfactorily the real shape of the acquired trajectories.

Cartesian positions are important for estimating the workspace and the degrees of freedom of an end-effector mechanism; the velocities and accelerations are important for the reproduction of the trajectories. The trajectories have been designed using only the Cartesian positions and future works will consider acting velocities and accelerations during the therapy.

Cartesian components of the trajectories have been stored using the Microsoft Kinect device. Other acquisition methods will be used in future developments.

The procedure described in this paper allows the implementation of learning by demonstration in rehabilitation by using an assisting robot device/manipulator, since starting from human demonstrations the device can learn trajectories to be followed in each therapeutic session.

In practice, a reference trajectory is obtained by using exercises that the therapist has considered as convenient for the patient. The reference trajectory is updated during different phases of the rehabilitation therapy. The exercise is guided by the therapist according to the medical diagnostic for each patient.

The variability of patient condition has been considered in the proposed method by planning update of the reference trajectory during the therapy. Since each patient performs his/her own exercise, the obtained trajectory will be appropriate for his/her own physical dimensions.

Finally, by using the proposed method, reference trajectories can be generated for next robot guide by using the individually experiences from each patient during the rehabilitation therapy.

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