Smoothness evaluation of horizontal reaching movements during robotic rehabilitation

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***Abstract*—Several studies have showed the importance of a clear understanding of arm movements. It is been proved that when a subject was instructed merely to move his hand from one visual target to another, his hand usually moved along a roughly straight path with a bell-shaped speed profile. Moreover, natural and coordinated movements, at least in absence of any other overriding concerns, are performed in order to be as smooth as possible. Although in the past have been explored kinematic characteristics of reaching movements recorded with actigrafi or goniometric systems and potentiometers, few studies have evaluated the kinematic characteristics of these movements obtained with the new rehabilitative technologies, such as robot mediated therapy. In this paper we tested the applicability of the minimum-jerk model proposed to one join goal directed horizontal reaching movements performed by healthy subjects with a robotic shoulder rehabilitation device. Results show a good qualitative and quantitative agreement between the measured trajectories and the predicted ones by the model. The smoothness index is minimized overall the entire kinematic task in according to the theory of minimum jerk.**

***Keywords*— kinematic, smoothness, reaching movements, upper limb.**

I. Introduction

MANY studies agreed that it is of extreme importance a clear understanding of how the human arm moves in order to define the algorithms used by the central nervous system to plan movements. It was been demonstrated [1-3] that when humans are asked to reach a stationary target, despite the infinite number of possible trajectories that can be chosen, they show stereotypical patterns in arm movements. Particularly subjects tend to move their hand along a straight path with a single-peaked, bell-shaped velocity profile and these features are independent of the hand's initial and final position within the workspace. This finding and the tendency of natural movements to be characteristically smooth and graceful, led Hogan [4] to suggest that the motor coordination can be mathematically modelled by postulating that voluntary movements are made to be as smooth as possible.

In order to address the optimization of smoothness, the authors adopted a quantitative measure of this property. It, named "jerk", was defined as the derivative of acceleration and was demonstrated that healthy subjects tend to minimize it during the movement execution. This theory, called "minimum-jerk model", is very appealing due to its simplicity and ability to predict the global features of reaching movements. Moreover movement smoothness has been used as a measure of motor performance of both healthy subjects and persons with stroke [5;6].

Kinematic assessment of reaching movements is considered as "a strategy level assessment" for upper arm function and permits to carefully analyze the influence of impairment on reach movement [7]. Recent studies have focused on the development of mechatronic and robotic systems for rehabilitation which make able the patient to perform repetitive and goal-oriented movements. These systems permit to make a safe and intensive training that can be done in combination with other kinds of rehabilitative treatments. Kinematic analysis allows to record quantitative data about movement patterns that can help clinicians to better address the rehabilitation protocols, providing information not captured using clinical measures, and usable as reliable outcome measures in upper limb rehabilitative clinical settings[8;9].

In this paper we described our implementation of the minimum jerk model with for point-to-point horizontal reaching movements in healthy subjects performed during robot mediated therapy (RMT), compared with the ones computed by the theoretic model. Then, we quantified the smoothness of movements made by healthy subjects.

II. Materials and Methods

A. Shoulder Rehabilitation Device

The shoulder rehabilitation device used in this study was the Multi-Joint-System (in the following MJS) of the Tecnobody (Fig.1). Its mechanical arm is provided with four "freedom" ranges, giving the patient freedom of joint movement in the three fundamental axes of movement (Anterior-Posterior, Adduction-Abduction, Internal rotation-External rotation).

B. Motor Tasks and Training Protocol

For this study, 10 healthy subjects (35±8 year old, males) were enrolled. Each subject underwent to 5 trial, each of them consisting of two horizontal reaching tasks. Each task was executed at target amplitude of 30° with at least intervals of three seconds of resting time between each task and one minute of resting time between each trial. During the session, subjects were asked to seat on the ergonomic chair of the robot with the trunk erected, neck straight fixing the central green starting point on the front monitor (green circle with letter "H" in Fig.2). The arm under test holding the robot grip by the hand in a position parallel to the floor at 90° with the trunk, the arm not under test on side handle close to the seat. Kinematic task consists of a visually-guided planar reaching task. Two targets ("T" in Fig. 2) were equally spaced of 30°

(really the arm reaches each new position covering a 30° angle) around a center target (Fig.2) and visual feedback of both target and robot handle location were provided on a computer screen in front of the sujcet. The task required each subject to move from the center position to the target and then return to the center with a sequence of four movements (Table I). Subjects underwent the above described motor task and training protocol on dominant shoulder for a total of 20 reaching movements.

C. *Movement Detection Algorithm*

Spatial coordinates of the handle position along x and y axes were analogically recorded with a 1/10° degree resolution and sampled at a sampling rate of 20 Hz.
Quantitative kinematic analysis of the reaching movements has carried out considering their velocity profile by means of a moving average derivative filter with trade-off features between a low-pass filtering and theoretical derivative high-pass transfer function. Movement's onset/end times were calculated considering the angular excursion between two successive zero crossing on the velocity profile. In order to avoid to consider false positives due to noise, only the zero crossings with an interval distance equal to the set angular excursion of the target were accepted [13]

D. *Quantitative Kinematic Analysis*

The quality and accuracy of the movements have been described [10-12] by smoothness index. It was been demonstrated that in order to produce a maximum smoothness movement, one must minimize the jerk cost functional defined as

$$J = \int_0^d \left|\frac{d^3x(t)}{dt^3}\right|^2 dt$$

where x is the angular displacement. To test the hypothesis that movements to different targets and/or of different duration were simply scaled replicas of a standard movement, normalized smoothness is considered. Different ways to normalize jerk-based measures have been used. In this study, we have tested the hypothesis that the trajectories of human movements are consistent with the fifth-order minimum jerk model and it has been considered the following normalized kinematic index [5]

$$J = \frac{d^5}{A^2}\int_0^d \left|\frac{d^3x(t)}{dt^3}\right|^2 dt$$

where A is the movement amplitude. The mathematical model described above was implemented in Matlab.

E. *Statistical Analysis*

Comparison between measured and simulated velocities profiles was performed and the agreement between the two curves was evaluated considering the sum of squares of the differences between the measured and simulated velocity profile, normalized by the sum of squares of the measured velocities (Mean Squared Error, MSE).

III. RESULTS AND DISCUSSION

In Fig 3-4 the mean velocity profiles of the simulated and measured movements for the subjects under experiment during the execution of the basic movements are marked by red and blue lines, respectively. The high agreement between the two curves was confirmed on the basis of formal statistical tests described above and was used as a numerical estimate of the degree of fit between the two profiles. The mean value of these errors, evaluated on all velocity profiles, was 0,018 ± 0,007 (mean ± sd). Jerk, described above as the time-derivative of acceleration, has been used as an empirical measure of smoothness and quality of movement. In Fig.5 are reported the distribution of smoothness indexes and, as you can see, they are minimized overall the entire kinematic task and there are not difference(*p<0.05) between simulated and measured values in according to the theory of minimum jerk that the reaching movements in healthy subjects are substantially regular. Future steps are related to extend this analysis to the pathological subjects and study the changes of smoothness during disease recovery.

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Fig.1. A picture of the MJS produced by Tecnobody and used in the lab. The picture shows a subject sit on the ergonomic chair of the robot in making his exercise.

Fig.2 The visually-guided planar reaching task.

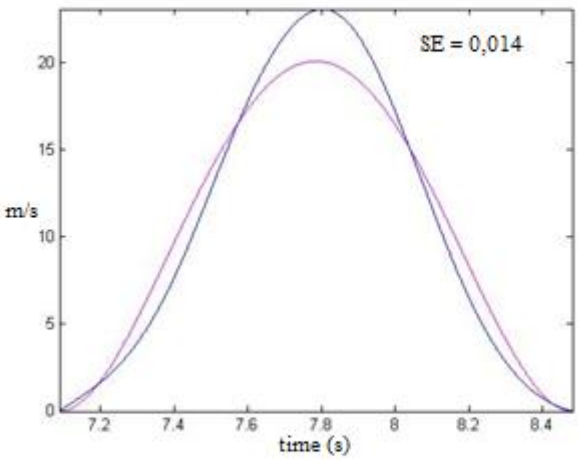

Fig.3.Representative example of the comparison between measured (blue line) and simulated (red line) movements related to horizontal abduction at 30° of target (EH1)

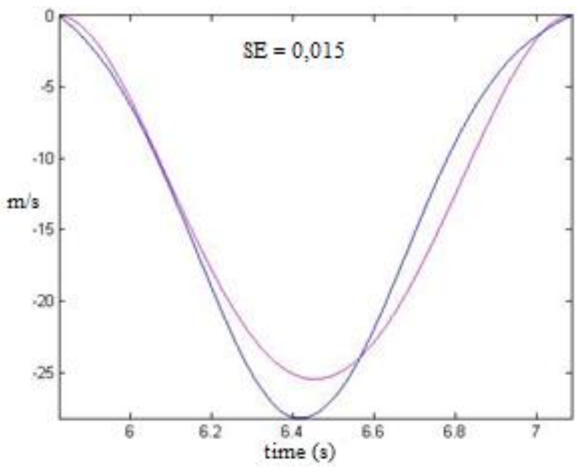

Fig.4 Representative example of the comparison between measured (blue line) and simulated (red line) movements related to horizontal adduction at 30° of target (IH1).

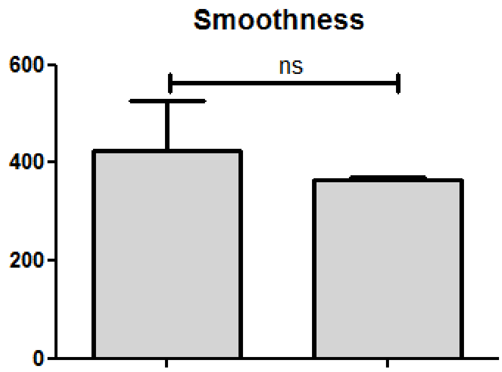

Fig.5. Comparison of the smoothness index between measured and simulated velocitiy profiles (*p<0.05).

Table I Description of the four movements sequence in horizontal reaching task.

Task	Acronym	Meaning	Description
External	EH1	External Horizontal 1	Horizontal abduction of the right (left) shoulder from the middle position to the outer right (left)
	IH1	Internal Horizontal 1	Horizontal abduction of the right (left) shoulder from the right external position (left) to the middle one
Internal	IH2	Internal Horizontal 2	Horizontal abduction of the right (left) shoulder from the middle position to left (right) external one
	EH2	External Horizontal 2	Horizontal abduction of the right (left) shoulder from the outer left (right) position to the middle one