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Kinematic evaluation of horizontal reaching movements in rotator cuff disease during robotic rehabilitation

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***Abstract* – Upper limb reaching movements (RM) are the most used motor task in robotic rehabilitation treatments of several disorders of the arm and the shoulder. Robotic rehabilitation allow to record quantitative data about movement patterns that can help clinicians to better address the rehabilitation protocols providing information not captured using clinical measures, but the biomechanical parameters proposed until today, to evaluate the quality of the movement, are related to the specific robot used and to the type of exercise performed and are not yet standardized. In this paper a quantitative kinematic assessment of robot assisted upper arm free reaching movements is proposed. Particularly, the effect of rotator cuff tendinopathy on kinematic patterns during horizontal movements has been evaluated.**

INTRODUCTION

When humans make point-to-point movements in free space can choose, in principle, among infinite possible trajectories. However, it was been demonstrated [1-3] that when humans are asked to reach a stationary target, so performing a *reaching movement* (RM), despite the infinite number of possible trajectories, they follow stereotypical patterns and tend to choose trajectories with specific features, defined *invariant kinematics* [4-8]. 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 [9-13]. In the last few years, the RM derive their growing importance not only by the contribution they give to the understanding of the movement's physiology, but also to their diffusion in rehabilitative field. Upper limb RM are in fact the most used motor task in rehabilitation treatments of several disorders of the arm and the shoulder of various central and peripheral etiology [14]. Moreover kinematic assessment in reaching movements is considered as "a strategy level assessment" for upper arm function [15] and permits to carefully analyze the influence of impairment on reaching movement [16].

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 allow 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 clinical upper limb rehabilitative settings [17;18]. Currently, different systems for robot-aided neuro-rehabilitation developed for upper limb rehabilitation there exist, like in particular 1) the MIT-Manus; 2) the mirror image motion enabler (MIME) robots, developed for unrestricted unilateral or bilateral 2D shoulder and elbow movement; 3) the ARM guide assisting 1D reaching in a straight-line trajectory; 4) the Bi-Manu-Track, enabling the bilateral passive and active practice of forearm and wrist movement; and 5) the Gentle/s system [19], which can provide robot mediated motor tasks in a three-dimensional space. Although all these systems have been differently applied in the robot mediated therapy (RMT) of patients affected by different congenital or acquired brain injury, none of the previously performed studies addressed a standardized quantitative kinetic evaluation of robot assisted upper arm free reaching movements. The biomechanical parameters proposed until today in the scientific literature, to evaluate the quality of the movement, are related to the specific robot used and to the type of exercise performed and are still far to be considered as viable alternatives to the clinical scales. Despite to the motors benefits achieved thanks to RMT, another limit of this technique is the lack of information that show improvements on "activity of daily living" (measures ADL) [20].

This study aimed to develop a quantitative kinematic assessment of robot assisted upper arm free reaching movements, by means of evaluation metrics supplied by

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the robot device, taking advantage by the speed profile shape that is the kinematic invariant of all point-to-point RM, using relatively simple indexes typical of a Gaussian profile. In particular, we report a case study concerning the comparison between kinematic patterns of a subject affected by rotator cuff tendinopathy and a healthy subject.

Table 1. Description of the movements sequence in horizontal reaching tasks.

Task	Symbol	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 adduction 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 adduction of the right (left) shoulder from the outer left (right) position to the middle one

MATERIALS AND METHODS

A. Motor task and training protocols

For this study, 1 healthy subject (HS) and 1 pathological subject (PS) (males, 45 years old) have been enrolled. Informed consent was obtained from each of them prior to their participation in the study.

Each subject has been underwent to 2 sessions, with at least intervals of 15‘ of resting time between them. Each session consists of 7 trial composed by 2 horizontal reaching tasks (external and internal, as defined in table 1), with at least intervals of 1’ of resting time between two trials. Each trial has been executed at a fixed target amplitude (of 30°).

Kinematic task consists on a visually-guided planar reaching task. Two targets are away from a central point of 30° (really the arm reaches each new position covering a 30° angle) and visual feedback of both target and robot handle location are provided on a computer screen in front of the robot (Fig. 1). Hence, the task required each subject to move the hand from the center position to the target and then return to the center with a sequence of 2 single-joint movements (table 1).

Figure 2. The visually-guided planar reaching task.

Before measurements recording, subjects executed 3 trials as training.

Vertical RM were not considered since the pathological subject was not able to perform them.

The shoulder rehabilitation device used has been the Multi-Joint-System (MJS) of the Tecnobody.

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.

During the session, subjects have been 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. 1). The arm under test holding the robot grip by the hand in a position parallel to the floor at 90° with the trunk (anatomic position), the arm not under test on side handle close to the seat (Fig. 2).

Fig. 2. 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.

B. Signal processing

Spatial coordinates of the handle position along x and y axes were analogically recorded with a 1/10° resolution and sampled at a sampling rate of 20 Hz. Quantitative kinematic analysis of the reaching movements has carried out estimating 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 [21].

C. Quantitative kinematic analysis

Quantitative kinematic analysis of the reaching movements has been described both by morphological indexes and by statistical indexes. Morphological indexes here considered are amplitude and duration of the position signal, mean and symmetry coefficient of the velocity signal. Mean velocity is here named m.velocity and the symmetry coefficient is calculated as the ratio between the time interval from the peak of the velocity to the end of the movement (deceleration time) and from the onset to the peak of the velocity (acceleration time). In addition the quality of the movements have been described 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:

$$J = \int_0^d \left|\frac{d^3x(t)}{dt^3}\right|^2 dt \quad (1)$$

where x is the angular displacement. Movement smoothness has been used as a measure of motor performance of both healthy subjects [22] and persons with stroke [23].

In order to avoid the dependence on amplitude and duration of movements, the normalized smoothness is considered and among the different ways to normalize jerk-based measures proposed in literature [24-29], we have chosen the following dimensionless jerk measure (Eq. 2):

$$J = \frac{D^5}{A^2}\int_{t_0}^{t_f} \left|\frac{d^3\theta}{dt^3}\right|^2 \quad (2)$$

As previously proposed [30], a different way to describe each movement is to consider indexes based on the consideration that velocity profile of the movements have a bell-shaped gaussian-like morphology [1]. On this basis, the signal can be described statistically like a probability density function respectively by means of k-order moments or k-orders central moments of Eq. (3) and (4).

$$M_k = E\left[X^k\right] \quad (3)$$

$$M_k = E\left[\left(X - M_1\right)^k\right] \quad (4)$$

Of particular interest appear the third and fourth order central moment, respectively named skewness and kurtosis. The skewness coefficient describes the simmetry of the shape, with a zero value in case of simmetry, a positive or a negative value respectively in case of a right or left asymmetry. The kurtosis coefficient describes the flatness of the shape, with a three value (normokurtosis) in case of a gaussian bell-shape flatness. Distributions with negative or positive excess kurtosis are called platykurtic distributions or leptokurtic distributions respectively.

D. Statistical Analysis

In order to test if differences obtained in indexes' values are due to chance or to the type of movement a Mann Whitney test has been used.

RESULTS AND DISCUSSION

A total of 56 RM was recorded for each subject.

In Fig.3 we reported the signal position recorded for both healthy and pathological subject for a complete task.

In Fig.4-5 are shown the position, velocity, acceleration and jerk profile related to EH1 movement for bth HS and PS. As was to be expected, the movement of the pathological subject is more fragmented and less continuous. It is notable that the complete movement had a highly asymmetric speed, acceleration and jerk profile, quite unlike normal human movement. Particularly, it can possible to note several peaks in the velocity profile, typical situation in pathological movement (e.g. stroke disease), according to literature [31].

This behavior is also confirmed by the statistical analysis, whose results are shown in table I. It is possible to observe that the kinematic indexes for PS are significantly different from the those evaluated for HS. The value of symmetry coefficient resulted different from one in PS, indicating that the phases of acceleration and deceleration contribute differently in their movement. Skewness index also showed significant p values between HS and PS. Particularly interesting is the behavior of the smoothness index which is about ten times higher compared to one of the HS. Finally the kurtosys resulted different from the theoretic value of 3and differences are not significant, indicating that signals, even if symmetric (HS), are more flat than Gaussian curves.

Interesting is the behavior of the mean velocity value that appears to be similar in PS compared to HS. This could be an indicator of a good performance of the task carried out by the PS, although studying the *cinematic quality* of the movement through the above indices there is a significant *deviation* from ideal behavior.

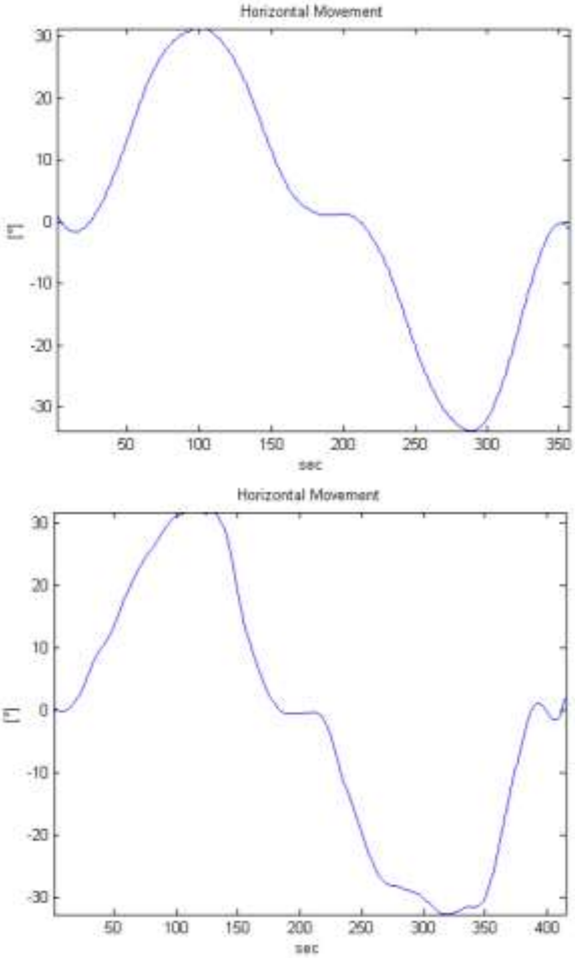

Fig.3. Example of signal position recorded during a complete task for both for healthy (above) and pathological subjects .

Table 1. Statistical Analysis of kinematic indexes (for p<005 and *** if p<0.001 ns=not significant).*

Index	HS	PS	p-value
Simmetry	1.00±0.1	1.71±1.00	0,0158*
Skewness	0.00±0.1	0.21±0.3	0,0287*
Kurtosys	2.3±0.08	2.4±0.4	ns
Smoothnes	118±35	1125±1101	***
m. velocity	7.55±0.8	8.00±2	ns

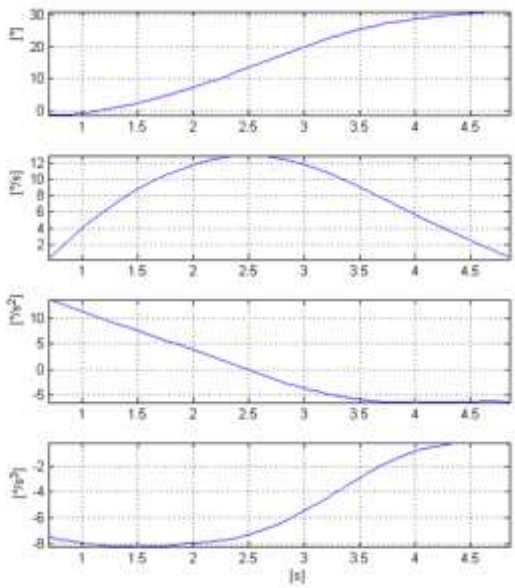

Fig.4. Example of position, velocity, acceleration and jerk profile for one EH1 movement of HS.

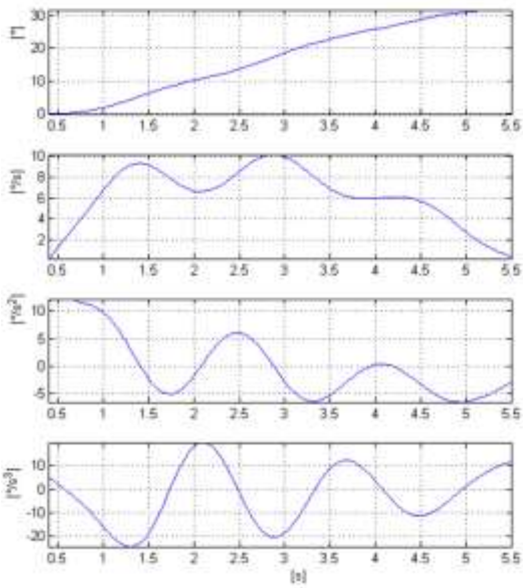

Fig.5. Example of position, velocity, acceleration and jerk profile for one EH1 movement of PS.

These preliminary results indicate a sensitivity of the kinematic indexes proposed greater than that of commonly observed, such as for example velocity metrics, hence these indexes could be useful in deeper clinical evaluation of patients during fine movements assessment. A better and quantitative measure of impairment would improve the accuracy and strengthen the predictive ability of models of recovery. This in turn would lead to more effective therapy and, presumably, faster and more complete recovery from the disease.

REFERENCES

[1]E. Morasso P., “Spatial control of arm movements”, Experimental Brain Research, 1981,42, Issue 2, pp 223-227.

[2]Abend W, Bizzi E, Morasso P,”Human arm trajectory formation”,1982, Brain 105:331-348.

[3]Flash T, Hogan N., “The coordination of arm movements: an experimentally confirmed mathematical model”,J.Neurosci. 1985;5(7):1688-703.

[4]Corcos DM, Gottlieb GL, Agarwal GC., “Organizing principles for single-joint movements. II. A speed-sensitive strategy”, J Neurophysiol, 1989;62(2):358-68.

[5]Berardelli A , M Hallett , Rothwell JC , Agostino R , Manfredi M , Thompson PD , Marsden CD ., “Single-joint rapid arm movements in normal subjects and in patients with motor disorders”, Brain. 1996;119 (Pt 2):661-74.

[6]Uno Y, Kawato M, Suzuki R., “Formation and control of optimal trajectory in human multijoint arm movement. Minimum torque-change model”, Biol Cybern. 1989;61(2):89-101.

[7]Goodman SR, Gottlieb GL., “Analysis of kinematic invariances of multijoint reaching movement”, Biol Cybern. 1995;73(4):311-22.

[8]Hogan N., "The mechanics of multi-joint posture and movement control”, Biol Cybern. 1985;52(5):315-31.

[9]Morasso P., “Spatial control of arm movements”, Experimental Brain Research, 1981,42, Issue 2, pp 223-227.

[10]Polit A, Bizzi E., “Characteristics of motor programs underlying arm movements in monkeys”, J Neurophysiol. 1979;42(1 Pt 1):183-94.

[11] Abend W, Bizzi E, Morasso P., “Human arm trajectory formation”, Brain. 1982;105(Pt 2):331-48.

[12] Hollerbach, J.M., ``Planning of arm movements," in: Visual Cognition and Action: An Invitation to Cognitive Science, Volume 2, D. Osherson, S.M. Kosslyn, and J.M. Hollerbach, eds., MIT Press, Cambridge, Mass., 1990, pp. 183-211.

[13]Atkeson CG , Hollerbach JM ., “Kinematic features of unrestrained vertical arm movements”, J Neurosci. 1985 Sep;5(9):2318-30.

[14]Marchal-Crespo L., Reinkensmeyer D., “Review of control strategies for robotic movement training after neurologic injury”, J Neuroeng Rehabil. 2009; 6: 20.

[15]Duff SV, Shumway-Cook A, Woollacott MH. (2011). Clinical management of reach, grasp and manipulation disorders. In Shumway-Cook A, Woollacott MH (Eds.), Motor Control: Theory and Practical Applications, 4th ed. Baltimore: Lippincott Williams & Wilkins.

[16]L.Fetters, “Measurement and treatment in cerebral palsy: an argument for a new approach”, Phys. Ther., 71:244-247,1991.

[17]Masiero S, Celia A, Rosati G, Armani M., “Robotic-assisted rehabilitation of the upper limb after acute stroke”, Arch Phys Med Rehabil. 2007;88(2):142-9.

[18]Zollo L, Rossini L, Bravi M, Magrone G, Sterzi S, Guglielmelli E., “Quantitative evaluation of upper-limb motor control in robot-aided rehabilitation”, Med Biol Eng Comput. 2011; 49(10):1131-44. doi: 10.1007/s11517-011-0808-1. Epub 2011 Jul 27.

[19]Krebs HI, Hogan N, Aisen ML, Volpe BT: Robot-aided neurorehabilitation. IEEE Trans Rehabil Eng 1998, 6:75-87.

[20]Prange GB, Jannink MJ, Groothuis-Oudshoorn CG, Hermens HJ, Ijzerman MJ., “Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke”, J Rehabil Res Dev. 2006 Mar-Apr;43(2):171-84.

[21] Iuppariello L., Romano M., D'Addio, Bifulco P., Pappone, Cesarelli, M. (2014, June). Comparison of Measured and Predicted reaching movements with a robotic rehabilitation device. Accepted by Medical Measurements and Applications (MeMeA), 2014 IEEE International Symposium.

[22]T Platz, P Denzler, B Kaden, and K-H Mauritz. Motor learning after recovery from hemiparesis. Neuropsychologia, 32(10):1209–1223, 1994.

[23]Catherine A. Trombly. Observations of improvement of reaching in five subjects with left hemiparesis. Journal of Neurology, Neurosurgery, and Psychiatry, 56:40–45, 1993.

[24]D’Addio, G., Iuppariello, L., Romano, M., Lullo, F., Pappone, N., & Cesarelli, M. (2014, January). Kinematic Indexes’ Reproducibility of Horizontal Reaching Movements. In XIII Mediterranean Conference on Medical and Biological Engineering and Computing 2013 (pp. 81-84). Springer International Publishing.

[25]D'Addio, G., Lullo, F., Pappone, N., Romano, M., Iuppariello, L., Cesarelli, M., & Bifulco, P. (2013, May). Relationships of kinematics indexes with amplitude and velocity of upper arm reaching movement. Medical Measurements and Applications Proceedings (MeMeA), 2013 IEEE International Symposium on(pp. 120-123).

[26]D’Addio G., Cesarelli M., Romano M., Faiella G., Lullo F.,Pappone N.. Kinematic and EMG Patterns Evaluation of Upper Arm Reaching Movements in Robot Assisted Therapy. IEEE Proceedings of The Fourth IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics 2012,ISBN: 978-1-4577-1199-2, pp 1383- 1387.

[27]D’Addio G., Cesarelli M., Romano M., De Nunzio A., Lullo F. and Pappone N.. EMG Patterns in Robot Assisted Reaching Movements of Upper Arm. 5th European Conference of the International Federation for Medical and Biological Engineering IFMBE Proceedings Volume 37, 2012, pp 749-75.
[28]Cesarelli M, D'Addio G, Romano M, De Nunzio, A.M, Pappone N. (2011).Kinematics patterns of upper arm reaching movement in robot-mediated therapy. Proceedings of IEEE International Workshop on Medical Measurements and Applications Proceedings, ISBN: 978-1-4244-9336-4, pp 465 – 468.
[29]Iuppariello L., Romano M., D’Addio G.., Faiella G., Bifulco P., Cesarelli M. Smoothness evaluation of horizontal reaching movements during robotic rehabilitation. Accepted by GNB2014, 25th-27th June, Pavia, 2014.
[30]Hogan, N., Sternad, D. “Sensitivity of smoothness measures to movement duration, amplitude, and arrests (2009) Journal of Motor Behavior, 41 (6), pp. 529-534. Cited 36 times.
[31] Linda Fetters and James Todd. Quantitative assessment of infant reaching movements. Journal of Motor Behavior, 19(2):147–166, 1987.