Kinematic and EMG Patterns Evaluation of Upper Arm Reaching Movements

G. D’Addio, M. Cesarelli, M. Romano, G. Faiella, F. Lullo, N. Pappone

Abstract—Variations in kinematic performances and muscle activations, underlying improvements in muscle function and strength, in response to upper arm training of patients with congenital or acquired brain injuries, are still poorly understood. One of the most interesting features of a robot-mediated therapy is the ability to quantify the performance of the rehabilitation tasks proposed to the patient. Although the shoulder is the most complex joint in the body, both for the range of freedom of movements and for the muscular-tendon structure, not so many commercial or research devices have been proposed to study its movements and no study have proposed a standardized, quantitative kinematic and electromyographic assessment. This study aimed to develop a quantitative assessment of kinematics and electromyographic pattern of the arm’s muscles involved in reaching robot-assisted movements by means of indices effectively describing the main pattern features in ten normal subjects. Each subject underwent a specific eight sequences motor task protocol. The system automatically classify each movement detecting its start/end times, extract main kinematic indexes plotting activation and deactivation graphs related to eight emg channels. Results showed that particularly movement smoothness indexes and timing of emg patterns may provide an effective upper arm reaching movement assessment.

I. INTRODUCTION

One of the most appealing features of a robot-mediated-therapy (RMT) consists in the possibility to quantify the performances of the rehabilitation task proposed to the patient. Robotic devices are capable of guiding or perturbing movements of a patient’s upper limb and can record motions and mechanical quantities such as position, velocity and forces applied. RMT can play a role particularly relevant in the rehabilitation of the upper limb by means of specific exercises [1-2] allowing quantitative kinematics evaluations to estimate the patient’s progress, while traditional clinical scales permit only qualitative and potentially disagreeing evaluations, since carried out by diverse therapists [3].

Changes in muscle activation, underlying improvements in muscle strength and function in response to training of patients affected by congenital or acquired brain injury, remain to date poorly understood. It is thought that the mechanisms involved may be neural or muscular in origin.

Neural changes may be quantitative, involving activation of a greater number of motor units or qualitative, involving improved co-ordination of activation between agonists, antagonists and synergists to achieve the goal of the movement [4-5].

Muscular changes may be structural, encompassing alterations in muscle mass and fibre type, or mechanical, including adaptations in muscle contractile properties that lead to modification of length–tension and force–velocity relationships [6].

Despite the shoulder is the most complex joint in our body, both in as far as to joint freedom range and to muscular-tendon structure, not so many commercial and research devices have been proposed to study its movements.

Systems currently employed have been differently applied in RMT of patients affected by congenital or acquired brain injury, but, at the best of our knowledge, no studies proposed a standardized quantitative electromyographic evaluation during robot assisted upper arm reaching movements.

This study aimed to develop a quantitative assessment of the electromyographic pattern of upper arm muscles involved in robot assisted reaching movements by means of indexes useful to implement and benchmark targeted patients oriented rehabilitative approaches. The knowledge of strategies used by muscle control system in healthy and pathological subjects may in fact to help to better plan the robot aided rehabilitation exercises.

II. MATERIALS AND METHODS

A. Shoulder Rehabilitation Device

The shoulder rehabilitation device used for this study was the Multi-Joint-System (in the following 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).

Each MJS axis is equipped with a completely independent force control and adjustment units allowing a light-G compensation mode which can totally cancel the weight of the arm making the shoulder joint completely “lightened”, experiencing a perceptive exploration at “noload” (see Fig. 1).
B. Motor Task and Training Protocol

During the exercise, subjects were asked to seat on the ergonomic robot chair with the trunk erected, neck straight fixing the central green starting point on the front monitor. 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 on a visually-guided planar reaching task. Four targets were equally spaced of 30° from a center target, in the vertical and horizontal direction, and visual feedback of both target and robot handle location were provided on a computer screen in front of the robot. The task required each subject to move from the center position to the target and then return to the center with an 8 movements sequence (Table I). We assumed the handle position right on the target if within 1 cm radius from the target circle for more than 100 ms, as indicated by an audiovisual biofeedback. To avoid onset of fatigue symptoms, each session was composed by if within 1 cm radius on more than 100 ms.

C. Experimental Setting

Experimental setting consisted in simultaneously triggered recordings of both kinematics and electromyographic signals during the above described motor tasks. Kinematic information has been derived by MJS with two signals corresponding to the vertical anterior-posterior and horizontal adduction-abduction handgrip position, with a 1°/10° degree resolution and a sampling rate of 20 Hz.

Eight EMG channels have been acquired by a wireless BTS Freemg 300 system with variable geometry mounting clip surfaces electrode, 16-bit resolution, 1 kHz sampling rate, in the 20-400 Hz frequency band, over the main muscles involved in the above described motor task and exactly: 1) sternal and 2) clavicular major pectoralis, 3) medial and 4) descending trapezius, 5) brachii triceps, 6) brachii biceps and 7) anterior and 8) medial deltoid. All surface EMG recordings have been performed according to related SENIAM recommendation [7].

D. Movement Detection Algorithm

 Movements along the two axes were automatically detected by a threshold level on the 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 as the first velocity zero crossing respectively before/after the movement detection interval.

Since also small handle jerks, causing high noise on the velocity profile, can lead to false detections, movements associated to velocity values lower than 30% of the peak velocity or narrower than 0.5 s were excluded. Depending on the signal present on each axis and on its first derivative sign, all detected movements were automatically classified as one of the expected phases of Table I (see Fig. 2).

E. Quantitative Kinematic Analysis

Quantitative kinematic analysis of the reaching movements has been described both by local morphological indexes and by global mathematical indexes.

The main series of the local morphological indexes consists on amplitude and duration of the position signal, mean and peak velocity and symmetry coefficient, 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 to this main series, movements have been

**TABLE I**

<table>
<thead>
<tr>
<th>Description of the Eight Movements Sequences</th>
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<tbody>
<tr>
<td>RH1 Horizontal 1: Horizontal abduction of the right (left) shoulder from the middle position to the outer right (left)</td>
</tr>
<tr>
<td>LH1 Horizontal 1: Horizontal abduction of the right (left) shoulder from the right external position (left) to the center</td>
</tr>
<tr>
<td>UV1 Vertical 1: Elevation of the shoulder from the middle position to the top</td>
</tr>
<tr>
<td>DV1 Vertical 1: Lower down of the shoulder towards the middle position</td>
</tr>
<tr>
<td>LH2 Horizontal 2: Horizontal abduction of the right (left) shoulder from the middle position to left (right) external one</td>
</tr>
<tr>
<td>RH2 Horizontal 2: Horizontal abduction of the right (left) shoulder from the outer left (right) position to the middle one</td>
</tr>
<tr>
<td>DV2 Vertical 2: Lower down of the shoulder from the middle position to the bottom</td>
</tr>
<tr>
<td>UV2 Vertical 2: Elevation of the shoulder from the bottom towards the middle position</td>
</tr>
</tbody>
</table>

Fig. 1. Subject under test sit at the Tecnobody MJS robot with applied telemetric EMG electrodes on the studied muscles.
described by their smoothness. This parameter is based on the minimum jerk theory stating that any movement will have maximum smoothness when the magnitude of the \( J \) parameter given by Eq. (1) is minimized over the duration of the movement.

\[
J = \int_0^1 \left| \frac{d^3 x}{dt^3} \right| dt
\]

Jerk is the rate of the change of acceleration with respect to time, (third time derivative of the position) and some studies conclude that humans by nature tend to minimize the jerk parameter over the duration of the reaching movement of the arm [8].

All these local indexes represent a synthetic morphological description of the movement depending on the onset/end movement detection times. A different way to describe each movement is to consider global mathematical indexes based on the consideration of the bell-shaped gaussian-like morphology of the velocity profile of the movement. On this basis, the signal can be described statistically like a probability density function respectively by means of k-order moments or k-order central moments of Eq. (2) and (3).

\[
M_k = \mathbb{E}[X^k]
\]

\[
M_k = \mathbb{E}[(X - M_1)^k]
\]

Of particular interest appear the third and forth order central moment, respectively named skewness and kurtosis.

The skewness coefficient describes the symmetry of the shape, with a zero value in case of symmetry, 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 zero value (normokurtosis) in case of a gaussian bell-shape flatness, a positive (leptokurtosis) or a negative (platikurtosis) value respectively in case of a shape more pointed or flatter than a gaussian bell-shape.

This approach has the advantage to not depend on the level of noise or on the movements detection threshold since their values depend only globally from the signal shape allowing to obtain indexes more standardized an comparable between different study populations.

### F. Electromyographic Pattern Analysis

Differently from commonly used methods [9], a normalized envelope for all EMG signals has been calculated by a high pass forth order Butterworth 5 Hz cutoff filtering, obtaining a good tradeoff in terms of spike removal and profile smoothness. Algorithms usually proposed [9] consider a muscle activation in case of an EMG amplitude higher than baseline resting activity plus 3 times its standard deviation for about 30 ms. However, this solution does not fit the muscular effort required to initially hold the arm in the exercise starting position, leading to a confounding identification of activation/deactivation muscle’s patterns.

To overcome the above problem, concerning the baseline activity epoch selection, two different threshold have been used as following defined:

1. activity threshold = mean (EMG) ± std (EMG)/2
2. resting threshold = mean (EMG) ± std (EMG)/2

These thresholds distinguish the EMG signals into three different areas representing different muscle activation levels: 1) a basal area, with the muscle activity inside the two thresholds, representing the basal activity necessary to maintain the initial central position of the robotic arm; 2) an active area, with the muscle activity above the activity threshold, corresponding to the muscular effort required for reaching movements; 3) a resting area, with the muscle...
activity below the resting threshold, corresponding to a muscle relaxation. To avoid confounding micro activation/deactivation detection, we identified EMG activation/deactivation in case of thresholds exceeding longer than 200 ms. Onset and end activation/deactivation times of muscle activities recorded are showed by On/Off Activation/Deactivation patterns (see Fig. 3).

III. EXPERIMENTAL RESULTS

The system has been tested on a 10 healthy subject population (males, 35±8 years old). Subjects underwent the above described motor task and training protocol on both shoulders for a total of 480 reaching movements.

For a kinematic assessment data were offline analyzed and merged in 240 horizontal right and left movements (RH1, RH2, LH1, LH2 sequences) and 240 vertical up and down movements (UV1, UV2, DV1, DV2 sequences) as shown in Tab. II.

Results showed a substantially invariance of the mean and peak velocities between horizontal and vertical movements. Different symmetry coefficient values indicated that acceleration and deceleration phases play a different contribute in horizontal rather than vertical movements, while a slightly leptokurtic shape of the velocity profile of the horizontal movements became even more pointed in the vertical movements.

However, extremely significant differences between horizontal and vertical movements are mainly marked by skewness and smoothness indexes, showing a more critical sensorimotor control patterns of vertical, adduction-abduction movements to or against gravitational force, respect than horizontal flex-extension movements.

For an electromyographic pattern analysis data were offline analyzed studying the contribution of the different muscle groups in each of the eight kinematic sequences as described below (see Fig 4 and 5 for graphs).

RH1: to make a movement so complex, capable of bringing the arm out of body axis, it is needed the joint work of almost all muscles analyzed. Particularly sternal and clavicular major pectoralis moved from baseline to the resting threshold, while brachii biceps, active in 7 and relaxed in 5 trials, showed to support the motion only if the remaining muscles are not completely able to perform the movement.

LH1: to move the arm in resting position all the muscles retain some basal activity except that the biceps, active in all patients, in some trials also supported by the medial and anterior deltoid, while medial trapezius and rarely the brachii triceps resulted relaxed.

UV1: also in this movement all muscles are active, except the pectoralis which maintained just a basal activity. No muscle is relaxing.

DV1: the biceps is the only muscle contributing to this movement, while everyone else, except pectoral, are relaxed. This behavior is due to the simple reason that the arm movement is facilitated by the presence of the gravitational force that acts in the same direction of motion. The biceps is active in 6 out of 12 tests, maintaining its basal activity in the remaining 6 trials to slow the descent.

LH2: anterior deltoid, biceps, sternal and clavicular pectoralis (both inactive in RH1) and in some trials also the medial deltoid are active. Medial and descending trapezius are relaxed (as in LH1). Particularly the triceps, is active in

<table>
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<th>Tab. II. QUANTITATIVE KINEMATIC ASSESSMENT</th>
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<tbody>
<tr>
<td>Index</td>
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<tr>
<td>-------</td>
</tr>
<tr>
<td># of movements</td>
</tr>
<tr>
<td>Mean velocity</td>
</tr>
<tr>
<td>Peak velocity</td>
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<td>Symmetry coefficient</td>
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<td>Smoothness</td>
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<td>Skewness</td>
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<td>Kurtosis</td>
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Fig. 4. EMG Activation graph of the studied subjects. Movement sequence on x axis; emg label on y axis; percentage of activation on z axis.

Fig. 5. EMG Deactivation graph of the studied subjects. Movement sequence on x axis; emg label on y axis; percentage of deactivation on z axis.
4, relaxed in 6 and in basal activity in 2 trials, with a behavior similar to the biceps in RH1.

RH2: active muscles are medial trapezius, triceps, biceps and sometimes the medial deltoid, while all the others retain their basal activity.

DV2: all muscles are relaxed except the pectoral which retains its basal activity. Biceps is active in 5, relaxed in other 5 and in basal condition in the remaining 2 trials. The behavior is similar to that in DV1, with the difference that is also relaxed in 5 trials, this is due to the fact that the resting position of DV2 is lower than the DV1 resulting in a lower effort muscle to hold the arm in that position.

UV2: all muscles are active except the pectoralis maintaining their basal activity.

IV. CONCLUSION

A deeper understanding of the kinematic and electromyographic patterns of upper arm reaching movements is fundamental to provide an innovative, flexible and quantifiable tool for the evaluation of functional recovery of the upper limb.

The understanding of the way in which the subject, healthy or pathological, makes the gesture may provide useful information concerning the rehabilitation exercise, for both developing new rehabilitation protocols for upper limb, and for the evaluation of the rehabilitation therapy as a whole.

These preliminary results indicate a sensitivity of the smoothness and skewness kinematics indexes greater than that of commonly observed amplitude/duration/velocity metrics, candidating these indexes for clinical evaluation of patients during fine movements assessment.

The recording of EMG pattern, additionally to usually evaluated kinematics indexes, may provide very useful information about timing and intensity of involved muscular groups to improve targets and effectiveness of upper arm rehabilitation protocols.

The proposed method showed to effectively describe the main pattern’s features of upper arm reaching movements in normal subjects. Future developments must be addressed to minimize the number of studied muscles focusing on kinematics and electromyographic indexes better describing patients’ rehabilitation outcomes.

ACKNOWLEDGMENT

Authors thank Mr. Gaetano Pagano, Luigi Cirillo, Feliciano Ferraro and Giuseppe Lullo for their strong support to the research development and data set recordings.

REFERENCES