Distinctive physiological muscle synergy patterns define the Box and Block Task execution as revealed by electromyographic features*

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Abstract— **Stroke survivors experience muscular pattern alterations of the upper limb that decrease their ability to perform daily-living activities. The Box and Block test (BBT) is widely used to assess the unilateral manual dexterity. Although BBT provides insights into functional performance, it returns limited information about the mechanisms contributing to the impaired movement. This study aims at exploring the BBT by means of muscle synergies analysis during the execution of BBT in a sample of 12 healthy participants with their dominant and non-dominant upper limb. Results revealed that: (i) the BBT can be described by 1 or 2 synergies; the number of synergies (ii) does not differ between dominant and non-dominant sides and (iii) varies considering each phase of the task; (iv) the transfer phase requires more synergies.**

Clinical Relevance— **This preliminary study characterizes muscular synergies during the BBT task in order to establish normative patterns that could assist in understanding the neuromuscular demands and support future evaluations of stroke deficits.**

I. Introduction

Upper limb function is commonly impaired after stroke [1], [2]. Several changes in muscular activation patterns, such as abnormal muscle co-activation [3] and enlarged activity of the antagonist muscles [4], muscle weakness and spasticity, can occur leading to a complex dysfunction in the upper limb of stroke survivors [5]. Clinical tests, such as the Action Research Arm Test, the Box and Block Test (BBT) and the Jebsen-Taylor Hand Function Test, are used to assess the motor deficit, evaluate the effectiveness of a specific rehabilitative treatment and monitor the functional recovery of the upper limb over time [6]. BBT is one of the most used clinical tests to assess unilateral manual dexterity. In the BBT participants are seated facing a rectangular wooden box (53.7 cm x 25.4 cm x 8.5 cm). A 15.2-cm tall partition, placed at the middle of the box, divides the box in two compartments of 25.4 cm each. Participants are instructed to grasp one block (a wooden cube, 2.5cm side) at a time, transport the block over the partition, and release it into the opposite compartment. The number of blocks successfully transferred from one compartment to the other in one minute is defined as the BBT performance [7]. Commonly used in clinical practice because of its affordability and quickness, it presents an excellent test-retest reliability for both healthy and stroke participants [8], [9]. Although the BBT provides insights into functional performance, it returns limited information about the mechanisms contributing to the impaired movement. BBT provides, in fact, a unique performance parameter summarizing the entire motor action needed for accomplishing the task.

At the state of the art the kinematics analysis of movements and the electromyographic (EMG) technique have been explored and validated as powerful tools to assess the main features of movements of the upper limb in healthy and stroke individuals performing several complex tasks [10], [11]. Therefore, the leveraging of kinematic and EMG features may contribute to the objective characterization of the quality of the BBT movement as a whole and define quantitative indices assessing motor abilities and/or impairments in every single phase of the task. Recently the BBT was explored in its main kinematic features by means of both wearable Inertial Measurement Unit (IMU)-based systems [12] and optoelectronic systems [13]. As for the muscle patterns, in the last ten years the muscle synergy-based approach offered clinicians insight into the functional and dysfunctional execution of voluntary movements [14]. Muscle synergies are obtained by the decomposition of EMG signals collected from more muscles into two components: a vector of time-invariant weights, representing the muscle synergies, and time-varying signals, representing the neural command for the synergies [15]. Several studies have recently investigated the muscle synergies alterations after stroke, showing merging or fragmentation of the healthy muscle synergies as results of the alteration in activation and organization of muscle synergies in the stroke affected upper limb [16], [17]. Most studies explored tasks, such as reaching, reaching and grasp, point-to-point reaching executed in controlled conditions, e.g. specific force profile or movements trajectories [18], [19]. To our knowledge, muscle synergies in unconstrained tasks, such as the BBT, have not been investigated. This study aims at exploring muscle synergies in a sample of healthy participants while executing with both dominant and non-dominant upper limb the BBT task in a daily-living activity context. Establishing physiological patterns could improve our understanding of the neuromuscular demands for the task and support future evaluations of stroke deficits.

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II. Materials and Methods

A. Participants

Twelve healthy volunteers (5 males/7 females, 47.9 ± 12.4 years, 11 right-handed) with no history of neuromuscular disorders, were enrolled in the study. All participants were informed about the experimental protocol and gave their informed written consent to the study. The study was approved by the ethics board of the IRCCS Fondazione Santa Lucia, Rome, Italy (Prot. CE/PROG.752).

B. Multimodal Data Collection

Figure 1 shows the experimental setup. Electromyographic (EMG) signals and kinematic data were simultaneously collected. EMG data were acquired from 16 muscles of the upper limbs and trunk (8 per side): extensor digitorum, flexor digitorum superficialis, lateral head of the triceps, long head of the biceps brachii, anterior deltoid, lateral deltoid, pectoralis major and upper trapezius muscles. For each muscle two surface electrodes Ag/AgCl, 24 mm-diameter were placed at 24 mm inter-electrode distance on the center of the muscle belly in the direction of the muscle fibers according to the guidelines reported in [20], [21]. Data were recorded through 16 wireless sensors (Pico EMG sensors, Cometa S.r.l., Italy) and sampled at 2000 Hz by means of the Wave Plus 16 channels amplifier (Cometa S.r.l., Italy). Kinematic data were collected at 100 Hz by means 8 IMUs (MTw Awinda, Xsens Technologies, The Netherlands). The IMUs were placed by a double-sided medical tape on the following anatomical points: hand, mid forearm, mid arm of both upper limbs, over the clavicular notch and at the lumbar vertebrae level.

Fig. 1 – Experimental setup: Box and Block Test kit (rectangular box and cubes), 16 wireless sensors (in black) and 8 IMUs (in orange) for collecting EMG and kinematics data, respectively.

C. Experimental Protocol

During the experiment participants were seated in a comfortable chair (adjustable in height) with their forearms on the armrests, facing the rectangular box of the BBT kit. Participants were instructed to perform the experimental task at self-paced velocity with both upper limbs separately collected. The task was a daily-life contextualized BBT: it comprised of (i) a reaching phase from the armrest to the box containing the 150 wooden blocks (starting box), (ii) a transfer phase of each cube from the starting box to the ending box and (iii) a return phase from the ending box to the armrest. To make the task equal and feasible for stroke patients who experience difficulties in transferring each block through a 15.2 cm tall partition, a modified BBT kit (with a box-high partition) was used for the experiment. Each task was repeated twenty times (trials) for side with an inter-trial interval of 3s according to a block-design approach. An acoustic cue "GO" invited the participant to start the task. The block sequence (i.e. Right, R, or Left, L, side) was randomized inter-subjects. We set an inter-block break of 2 minutes. Before starting the experiment, we performed a reference-measurement session consisting of: (i) the Maximum Voluntary Contraction lasting 5s for each muscle of both sides, (ii) two static positions lasting 10s for the IMU systems calibration and (iii) collection of anthropometric data (participant's height and distances between the following: styloid process of radius-finger knuckles, styloid process of radius-olecranon process, olecranon process-acromion process, acromion process-clavicular notch, clavicular notch-navel, projection of the IMU placed on the clavicular notch onto the spinal cord axis-IMU placed at the lumbar vertebrae level).

D. Data analysis

In this study EMG and kinematics data were analyzed. EMG data were bandpass [10 500] Hz and notch (50 Hz) filtered. The electrocardiographic component removal was implemented by means a template matching method. EMG data were analyzed by means of a customized algorithm aiming at evaluating EMG artifacts in each trial. The trials defined as "artifactual trials" were visually inspected before being labeled definitively as artifactual and removed. To extract the envelopes, the pre-processed EMG data were rectified and low-pass filtered at 10 Hz (Butterworth filter, 7th order) [22]. The EMG envelope segmentation in trials, i.e. start and end of each trial, and in the three phases for each trial, was performed by means the biomechanical model results (IMU kinematic data). Specifically, a biomechanical model built using anthropometric measurements of the participant and fed with IMUs data was implemented. Relative linear velocity of the hand with respect of the trunk was extracted from the model. Local minima of the module of the hand velocity were used to detect phase and trial transitions. To take into account the inter-trial variability in the temporal duration of the task all EMG segmented envelopes were resampled to have the same temporal duration. Lastly, a normalization procedure was performed to allow inter-participant comparison: each muscle was normalized on the maximum value achieved for that muscle in the dataset. For each participant and side, the EMG envelopes of the muscles of the side involved in the experimental task were arranged to generate the input matrix of the synergy extraction algorithm. The non-negative matrix factorization (NMF) was applied to extract muscle synergies. The NMF decomposes the data into the product of two matrices: the time-invariant synergies (w_i) and the time-varying activation coefficients (c_i) for each synergy as in the equation (1)

$$EMG\ (t) = \sum_{i=1}^{N} c_i(t) * w_i \tag{1}$$

where N is the total number of the extracted synergies. The order of the factorization was chosen increasingly from 1 to 8 (maximum number of muscles). To avoid local minima for each order of factorization the NMF algorithm was applied 50 times. The number of synergies N was chosen as the minimum order of factorization explaining at least 80% of the data variation defines as in [23]. All analyses were performed considering both the whole task and each phase (i.e. reaching, transfer and return) of the task separately.

III. RESULTS

Table 1 shows the number of synergies extracted for each participant and side (i.e. R and L) analyzing both the whole task and each phase of the task (i.e. reaching, transfer, return) separately. As for the whole task analysis, all participants except 2 (P09 and P10) exhibited the same number of synergies while executing the BBT with their dominant and non-dominant hand (average across participants: 1.3 ± 0.5 for both R and L upper limb). As shown in Table 1, participant P09 showed one and two synergies extracted for the dominant (R) and non-dominant (L) side, respectively; whereas, the opposite was observed for participant P10. When the synergy patterns were extracted considering the 3 distinctive task phases, we found that the number of synergies for each phase and side was higher than that for the whole task analysis. The transfer phase resulted as the most demanding phase for both side with 2.8 ± 0.7 and 2.7 ± 0.8 synergies for R and L task, respectively. Reaching and return phases showed different trend in dominant and non-dominant side: reaching (return) required higher number of synergies for the left (right) than for the right (left) side. Overall, 50% of the participants presented the same number of synergies across sides, 3 participants increased the number of synergies in a specific phase (i.e. reaching in the non-dominant arm for P02 and P05, transfer in the dominant arm for P07) and the remaining participants seemed to modify the synergy recruitment from one to the other side. Figure 2 shows the time-varying activation coefficients of each synergy extracted in the whole task analysis (first column) and in the phase analysis for the task executed with the R upper limb by participant P08. The first synergy (S1) of the reaching and return phases resulted similar to the first (0-25% task) and the last (60-100% task) part of S1 in the whole task. S2 and S3 provided for reaching and transfer phases respectively further information respect to that showed in the whole task activation coefficient. Similar trends were observed for most participants.

IV. DISCUSSION AND CONCLUSION

To our knowledge, this is the first study applying a multimodal (EMG and kinematics) approach to describe the Box and Block Test task performance in healthy volunteers. The results showed the BBT task can be globally described by two synergies at most. Most right-handed participants did not exhibit differences between right and left sides. The observed higher number of synergies in the right with respect to the left side in the ambidextrous participant could be accounted by some scores of the Edinburgh Handedness Inventory [24] that reveal an almost left-handed dominance. Considering the task in its single phases showed different results (i.e. larger number of synergies) from the whole task, pointing out (i) the complexity of the transfer phase (i.e. block transported from a compartment to the other) with respect to the reaching and return phases, (ii) the need to consider the single phase in the description of the BBT task to capture abnormal synergies that occur in pathological conditions (i.e. stroke).

Further studies are undergoing to investigate the time-invariant synergies in healthy participants and to validate the proposed BBT task -based muscle synergy approach in a large stroke sample. We expect to define indices that can capture the quality of movement to ultimately support clinicians in the assessment of post-stroke motor deficit, in the evaluation of rehabilitative treatment and in the monitoring of the functional recovery of the upper limb over time.

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Table 1- Number of synergies for each participant (N=12) during the execution of the Box and Block Test task with the right (R) and left (L) upper limb. For each side muscle synergies have been extracted considering the whole task and the task in its phases: reaching, transfer and return.

Participant	**Dominant arm**	**Whole task**		**Single Phase**					
		R	L	Reaching R	Transfer R	Return R	Reaching L	Transfer L	Return L
P01	Right	1	1	1	3	2	1	3	2
P02	Right	1	1	1	3	2	2	3	2
P03	Right	2	2	2	2	3	2	2	3
P04	Right	1	1	3	2	3	3	2	3
P05	Right	2	2	3	2	2	4	2	2
P06	Right	1	1	3	2	4	2	1	3
P07	Right	1	1	2	4	1	2	3	1
P08	Right	1	1	2	3	1	2	3	1
P09	Right	1	2	2	3	2	2	3	2
P10	Ambidextrous	2	1	2	4	2	3	3	1
P11	Right	1	1	1	3	3	2	4	2
P12	Right	2	2	2	3	2	2	3	2
Average (SD)	-	1.3 (0.5)	1.3 (0.5)	2 (0.7)	2.8 (0.7)	2.3 (0.9)	2.3 (0.8)	2.7 (0.8)	2 (0.7)

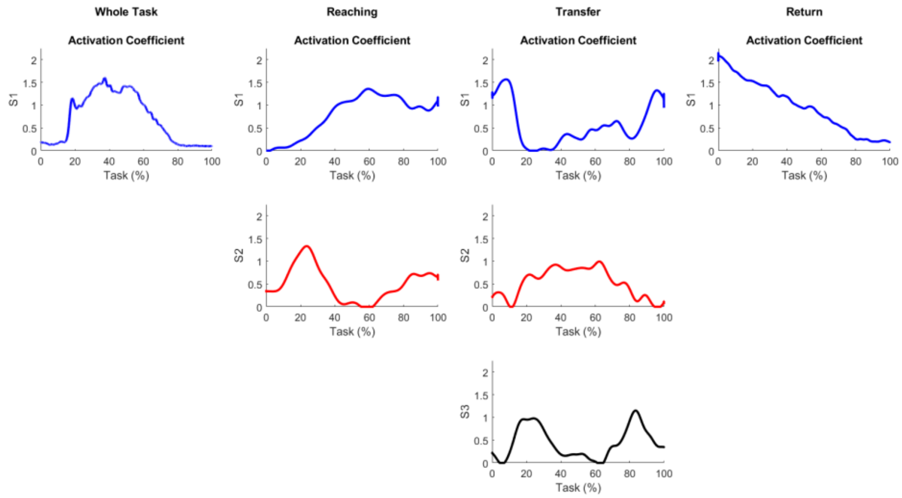

Fig. 2. Temporal activation coefficients extracted by means of the non-negative matrix factorization algorithm from the EMG data of the participant P08 during the task executed with the right side. The activation coefficient for each extracted synergy is reported for the whole *Box and Block Test* task (1 synergy) and for each phase of the Box and Block Test task, i.e. reaching, transfer and return, (2, 3 and 1 synergies, respectively).
In blue, red and black the activation coefficients of the synergies S1, S2 and S3, respectively.

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