# Synergy Analysis as a Tool to Design and Assess an Effective Stroke Rehabilitation

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*Abstract*— **The poor rehabilitation success rate, including the cases of ineffective and detrimental adaptations, make stroke a leading cause of disability. Thus, it is essential to recognize the mechanisms driving healthy motor recovery to improve such rate. Stroke alters the Synergy Architecture (SA), the modular muscle control system. So SA analysis may constitute a powerful tool to design and assess rehabilitation procedures. However, current impairment scales do not consider the patient's neuromuscular state. To gain insights into this hypothesis, we recorded multiple myoelectric signals from upper-limb muscles, in healthy subjects, while executing a set of common rehabilitation exercises. We found that SA reveals optimized motor control strategies and the positive effects of the use of visual feedback (VF) on motor control. Furthermore we demonstrate that the right and left arm's SA share the basic structure within the same subject, so we propose using the unaffected limb's SA as a reference motion pattern to be reached through rehabilitation.**

## I. INTRODUCTION

In clinical practice, stroke rehabilitation is monitored only from a functional perspective and quite subjectively: existing impairment estimation scales assess the ability for performing concrete tasks, but not the neuromuscular state itself [1, 2]. However, it has been demonstrated that during rehabilitation the affected limb develops undesired compensatory strategies [3]. Thus, it is essential to understand healthy motor-control to avoid detrimental rehabilitation and guide a correct therapy design [4].

The Central Nervous System (CNS) may simplify muscle coordination by activating a small number of predefined control-modules called synergies [5, 6]. Synergy architecture (SA) is defined as the set of synergies and corresponding activation patterns. Recent findings show that stroke affects SA mostly by altering activation patterns [7, 8] while leaving synergy structure intact except in most severe cases [9]. However, little is known about how rehabilitation impacts SA. Results suggest that rehabilitation-guided motor improvement is accompanied by slight changes in synergy structure [10]. Similarly, authors described a synergy-based impairment index that got closer to healthy values after training [11]. However, these studies are conducted at group level and do not address the nature of the changes undergone by SA or how SA could be applied in rehabilitation.

In this study, we propose to use the unaffected limb's SA as a reference pattern to be approached by the paretic limb via rehabilitation. We previously demonstrated that myoelectric signal codifies spatial information about upper-limb movements [12], suggesting a link between movement performance and the neuromuscular state. Given that the SA is also task specific [13, 14], we hypothesized the existence of a healthy SA pattern for each movement, so that restoring such pattern after stroke would avoid the development of detrimental compensatory strategies. This paper presents the preliminary tests carried out to assess the feasibility of the proposed method. First, we verify that interlimb SA of healthy subjects during common rehabilitation movements are sufficiently similar so that reestablishing the unaffected limb's SA in the paralyzed arm would represent a physiological motor state. Second, we compare the dominant and nondominant SA to investigate whether the SA shows differences due to an optimized motor control (typical of the dominant arm [15]) that should be targeted by rehabilitation.

Finally, we examine whether rehabilitation design is able to modify SA. To do so, we selected a common enforcement strategy in motor-learning processes, such as visual feedback (VF). VF is part of the sensorimotor adaptation used to correct movements during execution. However, indirect evidence suggests that synergistic organization may hinder the visuomotor adaptation [16]. To test such hypothesis, we compared the interlimb SA of common rehabilitation movements executed with and without VF.

## II. METHODS

### A. Experimental Protocol

Six neurologically intact subjects (right-handed males, age 25-35) participated in this study. Written informed consent was required for participation in the protocol, approved by the Institutional Review Board of the Institute for Bioengineering of Catalonia. Subjects performed two simple movements, involving just 1-2 degrees of freedom (DOFs), selected from standard rehabilitation routines to train elbow (extension) and shoulder (forward flexion). Given the kinematic simplicity, each movement was divided in two phases (forth and back) and repeated 30 times with each arm. The experiment was carried out in two conditions: with and without VF, consisting on a mirror placed in front of the subjects to track the execution of their own movements. At all, the analysis of each movement phase was comprised of 4 recording sets: right arm with/without VF and left arm with/without VF.

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### B. Data acquisition

EMG signals were recorded using a pair of disposable disc Ag-AgCl electrodes (1 cm in diameter, 1.5 cm inter-electrode distance; Foam electrode 50/PK – EL501, Biopac Systems Inc.) for each muscle on right and left arms according to published guidelines [17]. Registered muscles were Infraspinatus (IS), Trapezius Superior (TS), Deltoid Anterior (DA), Deltoid Medial (DM), Pectoralis Major (PM), Biceps Brachii (BB), Triceps Brachii Long Head (TBL) and Brachioradialis (BRD), plus the reference electrode placed at the corresponding wrist. Registration was done through the EMG 100C acquisition system (BIOPAC Systems, Inc.) at a sampling rate of 1000 Hz and a gain of 500. A Notch filter was used to remove 50 Hz interference.

### C. Data Preprocessing and analysis

EMG signals were manually segmented to discard fragments corresponding to resting periods. Movement segments were highpass filtered using a zero-phase Butterworth (n=6) filter, with a cutoff frequency of 50Hz, and demeaned. Linear envelopes were temporary aligned using elastic shape analysis of curves [18] and normalized to the maxima to estimate the mean envelope. Finally, a synergy model was extracted for each subject's arm, movement-phase and feedback condition, using the nonnegative matrix factorization (NMF) algorithm [19]. NMF models the activities of the recorded muscles as a linear combination of time invariant muscle synergies, each activated by a time-varying activation coefficient which can be mathematically expressed as:

$$D(t) = \sum_{i=1}^{N} C_i(t) \cdot \omega_i + \varepsilon \qquad (1)$$

where D(t) is the EMG signal at time t, N is the number of muscle synergies extracted, $\omega_i$ is the *i-th* muscle synergy, $c_i$ is the nonnegative activation vector for the *i-th* synergy and ε is any residual activity unexplained by linear combination.

### D. Synergy Architecture Analysis

To set N, we successively increased the number of synergies extracted, from one to the number of muscles recorded, and selected the minimum number of synergies required for an EMG reconstruction VAF (Variance Accounted For) of 90%. Given that the VAF of the few cases resulting in N=3 was almost 90%, N=2 models were subsequently considered to ease comparisons.

We assessed similarity between the four SA sets (right arm with/without VF and left arm with/without VF) of each movement phase. First we quantified the similarity between pairs of synergies as their scalar product. To do so, the vector norm of each synergy ($\omega_i$) was normalized to one. Each synergy in one set was matched to the synergy in the second set giving the maximum scalar product between them. Second, we evaluated the degree of similarity in muscle coordination by computing the cross-correlation coefficients of the muscle activation vectors ($c_i$). Given that activation vectors had different length we linearly interpolated the shortest vectors to equalize them before performing cross-correlation. The similarity measure reported is the mean of the maximal absolute cross-correlation coefficients between activations for each synergy. Two-way repeated measures ANOVA tests discarded significant interaction effects between variables (movement, arm, feedback). Statistical significance of the differences between synergy structures and muscle coordination was determined by the Wilcoxon signed rank-test ($p<0.05$).

## III. RESULTS

Most phases of shoulder and elbow movements were explained by two synergies regardless they were right or left arm movements or the presence of VF. There were only 2 sets from two subjects needing 3 synergies to get a VAF > 90%, however, in these cases the mean reconstruction VAF for N=2 were still very high (89.08 ±1.18 %). The VAF accounted for by the 2-synergy models was significantly greater ($p<0.05$) for right-arm movements (92.91 ± 1.00% and 92.58 ± 1.35%) than for left-arm movements (92.20 ± 1.25% and 91.96 ± 1.03%) with and without VF respectively (Fig. 1). Overall, the VAF for right-arm SA (92.75 ± 1.17%) was higher than for left-arm SA (92.08 ± 1.14%, $p < 0.01$) and so was the VAF for the SA of movements done with VF (92.55 ± 1.13%) than without VF (92.27 ± 1.19%).

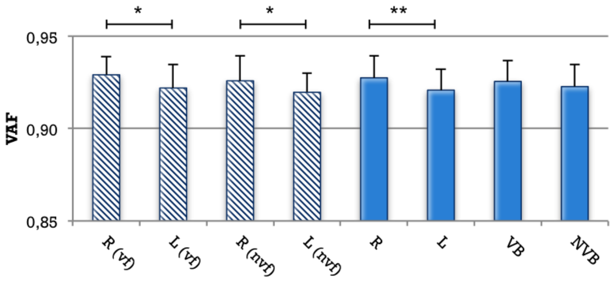

Figure 1. VAF accounted by 2-synergy models. Striped bars: right (R) and left (L) arm movements; with (vf) and without visual feedback (nvf). Solid bars are the average VAF for right (R) and left (L) arms with/without VF for both arms (VB, NVB) . Bars are mean ± SD. *$p<0.05$

Figure 2 shows the inter-subject differences in the synergy structure extracted for a representative movement (right arm shoulder exercise - back phase - no VF). At first sight one can observe that each subject has optimized a different control strategy to perform exactly the same movement. Synergy-to-synergy comparisons reveal that some subjects have very similar synergy structures (e.g. Subject 1 and 3 share the 98.2% and 95.0% of synergy 1 and 2 respectively) although the similarity degrees of others can be as low as 38.8% in the case of subjects 1 – 5, synergy 2 (Table I). Such similarity degree is consistent across subject pairs ($p<0.001$) and movements-phases,i.e., subjects sharing synergies in a movement phase are more likely to share synergies when executing other movement phases and vice versa.

The degree of intra-subject synergy similarity reveals that the amount of structure shared within the same subject for a given movement is substantially higher than between subjects. Our results suggest the VF increases the similarity between right and left arm synergy-structures (90.96 ± 4.20% vs. 85.19 ± 4.03%) (Fig. 3A). However, it seems that this effect is more evident in left-arm movements: the synergy similarity between movements done with or without feedback is greater for right arm than left arm (92.77 ± 4.65% vs. 90.08 ± 3.92%) indicating that for left-arm movements may receive a greater benefit from VF to optimize movement execution.

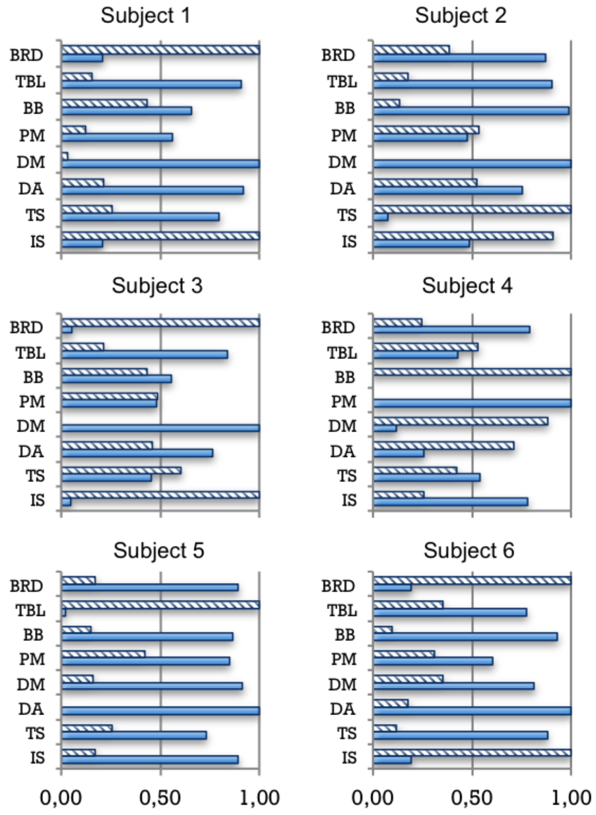

Figure 2. Synergy structure for right shoulder exercise back-phase- no visual feedback. Striped bars: synergy 1; Solid bars: synergy 2.-

TABLE I. INTER SUBJECT SYNERGY STRUCTURE SIMILARITY

| **Right shoulder exercise –back phase – no VF** | | | | | | |
|---|---|---|---|---|---|---|
| **Syn 2*** | **Synergy 1 *** | | | | | |
| | ***S1*** | ***S2*** | ***S3*** | ***S4*** | ***S5*** | ***S6*** |
| S1 | 1.000 | 0.865 | 0.982 | 0.606 | 0.812 | 0.984 |
| S2 | 0.740 | 1.000 | 0.861 | 0.637 | 0.843 | 0.852 |
| S3 | 0.950 | 0.890 | 1.000 | 0.507 | 0.740 | 0.951 |
| S4 | 0.505 | 0.496 | 0.551 | 1.000 | 0.775 | 0.594 |
| S5 | 0.388 | 0.484 | 0.485 | 0.517 | 1.000 | 0.837 |
| S6 | 0.934 | 0.703 | 0.896 | 0.484 | 0.517 | 1.000 |

* Upper diagonal are comparison between synergy 1 and lower diagonal between synergy 2

The within-subject similarity for muscle coordination was also high, but the resemblance between activation vectors (~80%) was much lower than between synergy structures (~90%). The similarity between right and left arm activation vectors slightly increased in presence of VF (82.84 ± 3.03% vs. 82.04 ± 2.60% respectively). Likewise, VF had a greater impact in the left-arm coordination showing a higher degree of similarity in the right arm (83.21± 3.22%) than in the left arm (82.01 ± 3.51%) (Fig 3B).

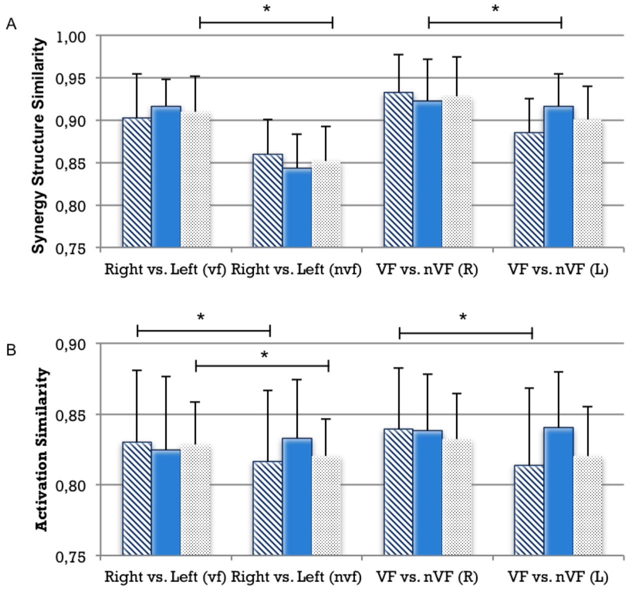

Figure 3. Synergy Model Comparison A - **Synergy structure similarity** (maximal scalar products). B- **Synergy Activations Similarity** (maximal cross-correlation). Striped bars: Synergy 1; Solid bars – Synergy 2; Dotted bars: Mean Similarity Bars are mean ± SD.

## IV. DISCUSSION

This study demonstrates that 1) given inherent inter-subject differences in muscle control, establishing a general motor control pattern of reference to asses stroke rehabilitation is not recommendable; 2) SA on right and left arms is fairly conserved within a healthy subject. These findings suggest that similarity measures between the affected and unaffected arm's SA of stroke patients may constitute a promising tool to assess rehabilitation from a neuromuscular perspective and 3) VF during movement execution improves motor control, so SA can be used to assess the effectiveness of different training strategies and design more objective rehabilitation procedures.

Results indicate that inter-subject SA differences can be substantial depending on the subject. In contrast, within-subject interlimb SA remains considerably conserved showing important structural similarities. In [7, 8, 10], authors compare stroke and healthy populations and report that the greatest SA alteration corresponds to synergy activation. Here, we show that interlimb activation patterns in healthy subjects are very similar (~80%). Hence, the synergy activation of the unaffected limb could serve as a reference neuromuscular pattern to objectively assess the improvement of the affected limb after training. Furthermore, a task-specific SA admits a certain degree of variability so that if a muscle introduces an error into the expected motor outcome, other muscles modify their contributions to minimize such error [20]. Thus, it is presumable that deviations from healthy SA may indicate compensated or abnormal movements. Accordingly, in [7], authors suggest that compensatory strategies may lead to enhanced SA alterations. However, it is sill to be proven that SA similarity between the affected and unaffected limbs indicates physiological recovery. In fact a pilot study in acute patients reports that similarity of muscle synergies between healthy and stroke patients did not increase after recovery [10], although interlimb comparisons were not considered.

Arm dominance provides advantageous control of limb-segment dynamics [15] and it has been shown that paretic limb's SA is similar to the healthy nondominant SA [21]. Our results indicate that dominant movements are less variable and characterized by a greater VAF and a more conserved SA. Thus, VAF could constitute a simple neuromuscular measure of movement control accuracy. It has to be noted that in this study, all subjects were right handed to ensure a homogeneous population similar to most stroke patients studied in literature [10]. However, results are discussed in terms of dominant and nondominant limbs, thus it is logical that the same apply to left-handed subjects but in the opposite arm.

Synergistic organization is said to possibly block visuomotor adaptation [16]. However, the SA of VF assisted movements present a higher VAF, suggesting that VF improves movement accuracy and that this improvement is reflected at a synergistic level. Furthermore, VF increases the interlimb movement similarity both in terms of synergy structure and activation probably because it enhances movement accuracy in the nondominant arm. Interestingly, the effect of VF is more apparent in the nondominant arm (the SA with and without VF differs less in right-arm movements) probably because nondominant movements are less optimized than dominant movements. Zanone described that the benefits of VF on motor performance were more apparent in children who have not yet achieved motor proficiency [22]. Thus, it is likely that the effectiveness of VF is reduced as motor control increases. Consequently, it seems that VF might be especially useful in case of substantial loss of motor control as it happens at the beginning of the rehabilitation or in severely impaired subjects.

It is remarkable that the number of synergies extracted is low compared to other studies carried out in the upper limb [7, 9, 10]. We speculate this may be due to the relative simplicity of the tested movements (involving 1 – 2 DOFs) and the selected VAF threshold.

## V. CONCLUSION

Synergy Architecture (SA) analysis may constitute an objective tool to design a suitable rehabilitation strategy and guide a physiological motor recovery since 1) within-subject interlimb SA similarity suggests that establishing the unaffected limb's SA as a reference pattern for motor recovery represents the neuromuscular fundamental-state 2) SA captures the features of control accuracy seen in the dominant arm and 3) adequate therapeutic strategies such as the use of visual feedback can effectively modify muscle control by tuning the synergy organization. However, how muscle synergies could be effectively tuned would require further analysis of these effects.

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