2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

# Angular Velocity Profiles of Upper Limb Joint Synergies in Reaching Movements: a pilot study*

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*Abstract*— **The spatiotemporal kinematic synergy, a coupling of multiple degrees of freedom (DoF), runs through human activities of daily living (ADL). And it is an entry point for exploring the central nervous system's (CNS) control process of musculoskeletal system by analyzing the time-varying kinematic synergy. The aim of this study was to find more physiological properties from the angular velocity profiles of synergy. Ten healthy right-handed subjects were asked to reach target button at different locations. During reaching movement, the motion data of five right upper limb joints were recorded, and the synergistic patterns were extracted by PCA algorithm. Our results showed that the combinations of the first four synergies were sufficient to explain raw data. As far as possible to exclude the effects of individual and information differences, we found shoulder flexion/extension and elbow flexion/extension made distinct contribution in a period of time to the control procedure performed by CNS after targets were confirmed. Our preliminary results implied that reaching movements required comparatively constant scheduling of shoulder horizontal abduction/adduction, shoulder internal/external rotation and wrist ulnar/radial deviation by CNS, while scheduling of SFE and EFE depends on the objectives.**

*Clinical relevance*— **The findings of this paper may provide a novel dynamic control evidence based on CNS for realizing near-natural control of assistive devices in motor rehabilitation area.**

## I. INTRODUCTION

The synergy stems from the coordination of neurons between limbs, is also a manifestation of simplifying the control strategies of the CNS during movements [1]. For example, the human arm, a sophisticated musculoskeletal system, possesses 11 independent degrees of freedom (DoF), which is combined by muscles to complete certain movements [2]. Therefore, the research of synergy has become an entry point to explore the CNS's perplexing programs that were executed to reply on the multi-dimensional and redundant DoF problem. Recently, the synergy has been studied from its different levels of existence, including muscles co-activation [3], joint angles co-variation [4] [5] [6] [7], postural [8] and mechanical synergies [9]. Herein, we chose the kinematic synergy in angular velocity space of human upper limb joints on account of its immediate interaction with environment.

The upper limb spatiotemporal kinematic synergy, running through human activities of daily living (ADL), is a coupling of kinematic degrees of freedom, which is achieved by neural co-activation of muscles actuating different upper limb joints [4]. It is not as directly as the muscle co-activation pattern in reflecting the physiological properties of the limb. Even so, it interprets the interaction between upper limb and environment in comparison with muscle coordination more immediately, without breaking away from the physiological meaning. For further study, it is essential to extract the synergy using a sparse optimization algorithm. The principal component analysis (PCA) algorithm is frequently used to derive motion synergy. The literature [4], [5] and [6] used this method to represent spatiotemporal synergy of inter-joints in low dimension. [5] used PCA to derive the synergy of bilateral upper limbs. The team found that the first three synergies were relevant within ten subjects. And the first two highly correlated synergies seemed to reflect symmetrical hand movements, whereas the rest was not. In another word, only the higher-order synergies represented asymmetries between bilateral arms. The results of [6] suggested that different levels of synergies were equally vital and they played different roles in reaching movement. The lower order synergies indicated the overall trend of right upper limb's motion patterns, nevertheless the outcomes of higher order synergies described fine motions. In addition, much research paid attention to utilizing several synergistic features to discover similarities and differences across certain tasks or participants, such as explained variance, reconstructed errors and Pearson's correlation coefficient of synergies. They are a sort of useful and reliable tool for analysis, while only using these features might miss some details, which remained to be understood in deep. For instance, little was known about the differences in recruitment and control strategies of DoFs. Hence, we expanded the scope of concern to the variance of synergy isle.

In this study, we obtained spatiotemporal kinematic synergies from a series of reaching movements, part of ADL. Ten healthy subjects were recruited here, and synergies across five joint angular velocity profiles of right arm were extracted by PCA. Further, we compared time-varying kinematic synergies among the ipsilateral, central, and contralateral tasks in the motion duration, aiming at discovering the potential physiological characteristics in synergies. We believe that our results would strengthen the bridge crossing kinematic

*This work was supported by the National Natural Science Foundation of China (31971287, 31771069), and the National Key R&D Program of China (2020YFC2004200)

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synergy and motor rehabilitation.

## II. METHODS

### A. Participants and Data collection

Ten right-handed healthy subjects (eight males and two females) were recruited for this study. All subjects had no neuromuscular disorders or joint injuries. The experiment was carried out in the Perceptual Robotics Laboratory in Italy, according to the Declaration of Helsinki and approved by the Ethics Review Board of Scuola Superiore Sant' Anna.

A motion capture system (Perception Neuron, Noitom Technology Ltd., Beijing, China) integrated with Inertial Measurement Unit (IMU) was used to acquire the kinematics of subjects' upper limb during tasks. And data were recorded by its software (Axis Neuron). Each subject wore seven IMU sensors (Ds1, Ds2 and D1-D5), as shown in Figure 1A: spine1, spine2, left shoulder, right shoulder, right elbow and right wrist. About the task, eleven targets on the task board were arranged in this experiment. Ten of them were distal marked with "a" to "j" and the rest one "start" is proximal for subjects. The distal targets were placed on the contralateral, central and ipsilateral side relative to subject's right upper limb. We arranged three buttons on the distal positions and one button on the proximal position each trial. The experimental scene and the task board are shown in Figure 1 BC (more details described in [5]). Specifically, we combined different positions into "a-e-i", "b-f-j", "c-e-g" and "d-f-h" tasks. The reaching movement started with the releasing of the proximal button, and ended with the pressing of distal button.

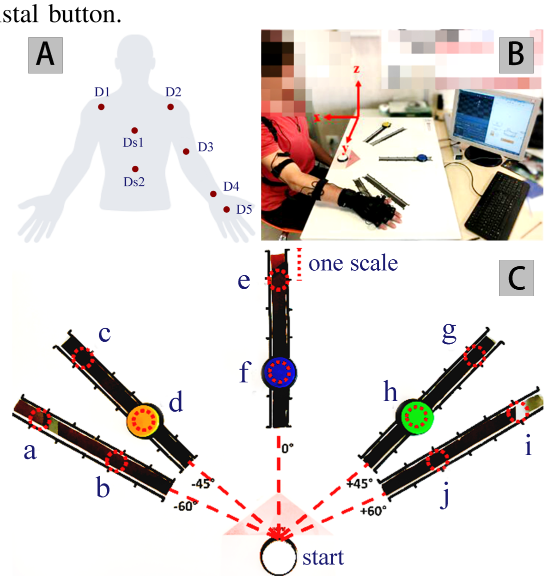


Fig. 1. (A) Sensor placement on body. (B) The experimental scene diagram. (C) Tasks executed during study.

### B. Kinematic Model

Based on the cosine theorem and projection principle, the angle of each joint can be calculated from the kinematics data of upper limb during movements. These angles were calculated using five vectors:

$$d_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \tag{1}$$

$$\overline{s}_{12} = d_2 - d_1 \quad \overline{s}_{32} = d_2 - d_3 \tag{2}$$

$$\overline{s}_{34} = d_4 - d_3 \quad \overline{s}_{45} = d_5 - d_4 \tag{3}$$

$$\overline{s}_{s_{21}} = d_{s_1} - d_{s_2} \tag{4}$$

Where $d_i$ is the displacement of one joint relative to the origin of the world coordinate, and $\overline{s}_{ij}$ is the vector passing through two adjacent joints. In this paper, five joint's degrees of freedom (DoF) were used for kinematic modeling: shoulder flexion/extension (SFE), shoulder horizontal abduction/ adduction (SHAA), shoulder internal/external rotation (SIR), elbow flexion/extension (EFE), and wrist ulnar/radial deviation (WUR). And the angles (°) of the DoFs mentioned above are denoted as $\theta_{sfe}$, $\theta_{shaa}$, $\theta_{sir}$, $\theta_{efe}$ and $\theta_{wur}$. Then, the $\overline{s}_{ij_x}$, means the value of the vector $\overline{s}_{ij}$ on the x-axis is 0.In other words, it is the projection of vector $\overline{s}_{ij}$ onto the coronal plane.

$$\theta_{sfe} = \arccos \frac{\overline{s}_{32} \cdot \overline{s}_{s_{21}}}{||\overline{s}_{32}||||\overline{s}_{s_{21}}||} \cdot \frac{180}{\pi}, \overline{s}_{s_{21y}} = 0, \overline{s}_{12y} = 0 \tag{5}$$

$$\theta_{shaa} = \arccos \frac{\overline{s}_{32} \cdot \overline{s}_{12}}{||\overline{s}_{32}||||\overline{s}_{12}||} \cdot \frac{180}{\pi}, \overline{s}_{12z} = 0, \overline{s}_{32z} = 0 \tag{6}$$

$$\theta_{efe} = \arccos \frac{\overline{s}_{32} \cdot \overline{s}_{34}}{||\overline{s}_{32}||||\overline{s}_{34}||} \cdot \frac{180}{\pi} \tag{7}$$

$$\theta_{wur} = \arccos \frac{\overline{s}_{34} \cdot \overline{s}_{45}}{||\overline{s}_{34}||||\overline{s}_{45}||} \cdot \frac{180}{\pi}, \overline{s}_{34z} = 0, \overline{s}_{45z} = 0 \tag{8}$$

$$\theta_{sir} = r_{2x} \tag{9}$$

Note, $r_{2x}$ is the rotation angle of the arm about x-axis (the axis of the arm), acquiring from sensors.

Finally, the joints' angular velocities were obtained by differentiating the duration (t) corresponding to the angle change of each joint. For further processing, we segmented the intermedia results and resampled them to 150Hz (See [5]).

### C. Kinematic Synergy Extraction

A PCA function ("psych::principle") in Rstudio (R language integrated development, IDE, USA) was applied to extract kinematic synergy of reaching and return motions. In our experimental task, every participant was asked to do four groups of trials. It contained three distal buttons and a proximal button each group, which was repeated twice. Therefore, the same motion was performed six times by one. Then, the six sections data were constructed as matrix W frame by frame:

$$\begin{bmatrix} w_1^1(1) & \cdots & w_J^1(1) & \cdots & w_1^1(T_{max}) & \cdots & w_J^1(T_{max}) \\ w_1^2(1) & \cdots & w_J^2(1) & \cdots & w_1^2(T_{max}) & \cdots & w_J^2(T_{max}) \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ w_1^M(1) & \cdots & w_J^M(1) & \cdots & w_1^M(T_{max}) & \cdots & w_J^M(T_{max}) \end{bmatrix} \tag{10}$$

Where $w_j^m(t)$ is the angular velocity of the j-DoF at frame t in a certain period, M = 6, J = 5, $T_{max}$ = 150. Variance maximization is the core of the PCA algorithm:

$$\max_W tr\left(F^T W W^T F\right) \quad s.t. \quad F^T F = I \tag{11}$$

Eq.(8) is solved out by Lagrange multiplier method:

$$W W^T F = \Sigma \cdot F \tag{12}$$

$WW^T$ is the covariance matrix of W. "I" is the identity matrix. So, $F^T$ and F formed by the first k eigenvectors are orthogonal to each other. The $\Sigma$ in Eq.(8) is defined as a diagonal matrix composed of eigenvalues from the ordered sequence: $\lambda_1, \lambda_2, \ldots, \lambda_M$ ($\lambda_k > 0$, k, $\lambda_k > \lambda_{k+1}$).

$$\begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_M \end{bmatrix} \tag{13}$$

And the kinematic synergies were reconstructed into C using raw data and F:

$$C_{J \cdot T_{max} \times k} = W_{J \cdot T_{max} \times M} \cdot F_{M \times k} \tag{14}$$

However, the determination of k indicated the end of synergy extraction. It was fixed by the cumulative contribution rate (or cumulative explained variance) of PCs. The greater the contribution rate of PCs, the closer C was to the original data. According to the literature [5] [6], 94% explained by PCs (or synergies) of is sufficient in general. Thus, the threshold was set to 94% in this study. The k was the minimum when the contribution rate is greater than or equal to the threshold.

$$\sum_{i=1}^{k} \lambda_i / \sum_{i=1}^{M} \lambda_i \tag{15}$$

## III. RESULTS

### A. Synergies number

By calculating the average cumulative explained variance of PCs across 10 subjects in reaching motion, we got the determination of synergies number. Figure 2 shows that the explained variance of PCs. The first synergy accounted for 59.61 ± 12.97%, whereas the first three synergies account for 88.96 ± 6.24%, and the sum of four synergies account for 95.16 ± 3.3%. So, four synergies were sufficient for us.

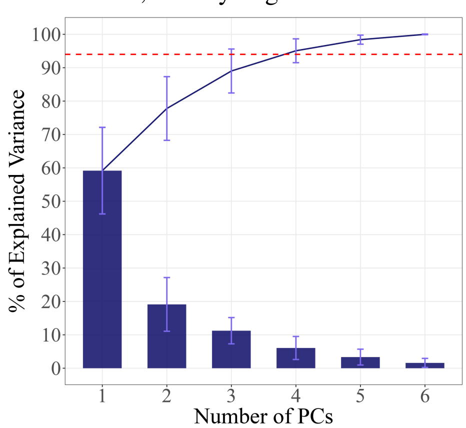


Fig. 2. The explained variance for each synergy (bars) and cumulative explained variance from 1 to 6 synergies (line). The red dotted line displays 94% threshold.

### B. Correlation of synergies inter subjects

The comparison between each pair of subjects' synergies was presented in the form of heat maps, as depicted in Figure 3. The color grids replaced the Pearson's correlation coefficients, r. Clearly, only synergy 1 displayed positively correlated within 10 subjects, and the mean value of the overall correlation coefficient was 0.4310 ± 0.1125, between 0.4 and 0.6, which was moderate correlation. But there were some positive/negative correlations in synergy 2, 3 and 4 that the overall averaged r of them was 0.0039 ± 0.0600, -0.0030 ± 0.0403 and 0.0100 ± 0.0583, respectively. And the relative correlation intensities were very weak or irrelevant. Therefore, we believed that only the first synergy belonged to a common characteristic among all subjects.

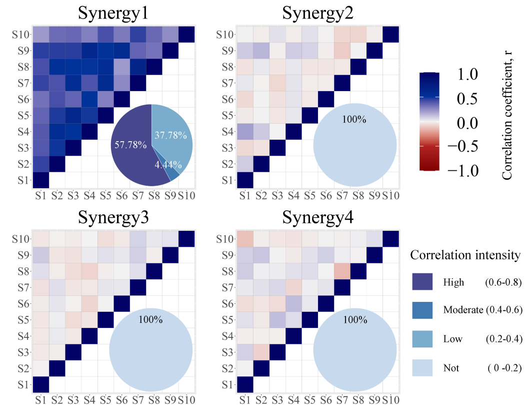


Fig. 3. Pearson's correlation coefficient, r, and the relative intensity between each pair of subjects for synergies 1, 2, 3 and 4.

### C. Difference of synergies between positions

Figure 4 illustrates that three positions of each given combination were compared to each other using the explained variance based on synergy 1. It could be seen that no statistically significant differences were found between targets by one-way ANOVA tables ($\alpha = 0.05$). Namely the synergy 1 retained similar amount of raw data to contralateral, central, and ipsilateral targets.

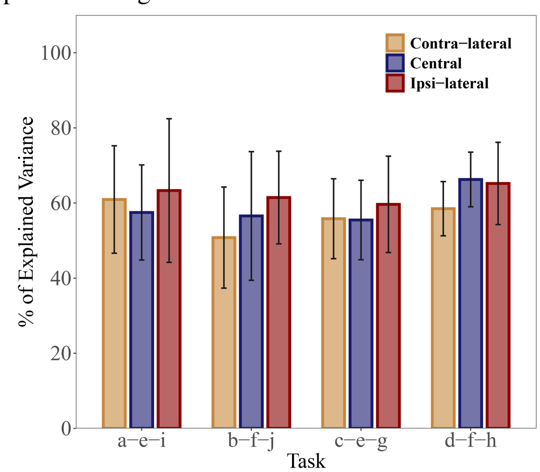


Fig. 4. Grouped comparison of the impact of contralateral, central and ipsilateral targets on synergy 1's explained variance using one-way ANOVA tables with Tukey post hoc tests ($\alpha = 0.05$).

Furthermore, one-way ANOVA tables ($\alpha = 0.05$) was also performed at the time profile of the first synergy of all participants, and Tukey post hoc tests were used to acquire specific differences at each frame among the three given positions. In Figure 5, it is clear that statistically significant synergistic differences existed inter positions. And once statistical differences occurred, they persisted for a period of time. As for specific differences, they were mainly between contralateral and ipsilateral positions, followed by central and ipsilateral positions. In terms of time course, the significant differences appeared principally between one-third and two-thirds of the motion cycle. What is more, the otherness was mainly reflected in the angular velocity profiles of SFE and EFE, while the variations of SHAA, SIR and WUR of synergy 1 preferred to be accordant.

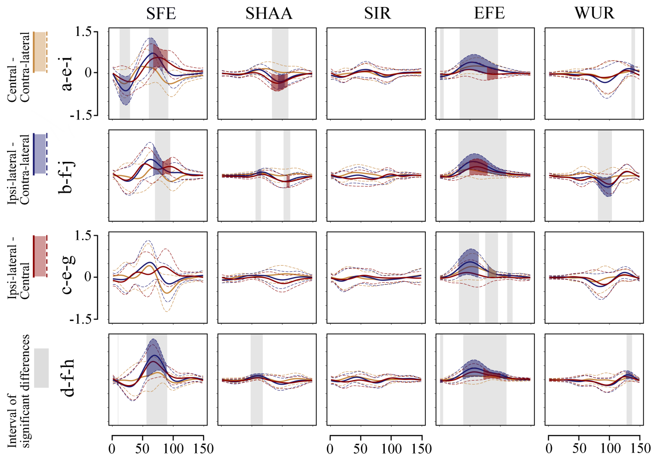


Fig. 5. The angular velocity profile of the first synergy across 10 subjects between three distinct positions. Vertical axis is score of synergy. Horizontal axis includes 150 frames of motion cycle. Significant differences appeared in a period of time using one-way ANOVA tables with Tukey post hoc tests ($\alpha = 0.05$). The transparent color blocks indicate the existence of differences. Different colors represent the comparisons of contralateral, central and ipsilateral positions in pairs.

## IV. DISCUSSION

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

The first four synergies we extracted had a 95.16 ± 3.3% contribution rate, which the linear combinations of them were sufficient to describe raw data [5]. Only the first synergy showed a clear correlation inter subjects. This preliminary finding of this study was corresponding to the results of reference [6], where the lower order synergies indicated the overall trend of right upper limb's motion patterns, nevertheless the outcomes of higher order synergies did not. That meant the first synergy reflected the overall trend of subjects' right upper limbs during reaching movement. To compare with the other synergies, the reason it was distinctive might be its less affected by individual variation. Hence, synergy 1 was deemed as the common characteristic among all subjects during reaching tasks.

In this paper, we focused on exploring the differences on synergies of the goal-directed movements, and what was described in Figure 4 ensured that synergy 1 retained approximately the same information of original motion data at different locations. As far as possible to exclude the effects of individual and information differences, we got the results illustrated in Figure 5. In Figure 5, the first synergy would be diverse in a period of time depending on targets, and shoulder flexion/extension and elbow flexion/extension were two DoFs associating with the target reaching motion. Physiologically, the reaching movement was completed by the dynamic couplings of multiple DoFs of right upper limb. SFE and EFE made distinct contribution to the control procedure performed by CNS after targets were confirmed. Namely, reaching movements might require comparatively constant scheduling of SHAA, SIR and WUR by CNS, while scheduling of SFE and EFE depends on the objectives. It might have the same implications on other motions of human ADL by excavating the angular velocity profiles of time-varying synergy.

## V. SUMMARY

This study explored the physiological properties of right upper limb from joint angular velocity of spatiotemporal kinematic synergy. Statistically different interval appeared in the time course of SFE and EFE between goal-directed movements. It indicated that reaching movements might require fixed scheduling of SHAA, SIR and WUR by CNS, while scheduling of SFE and EFE depends on the objectives. Kinematic synergy has been integrated into the control of robotic systems with the aim of achieving nearly biological control scheme for assisting to treat hemiplegic patients [10]. Therefore, the findings of this paper may provide a novel dynamic control evidence based on CNS for realizing near-natural control of assistive devices in motor rehabilitation area.

Future works will extend the number of subjects and tasks to explore what specific differences of synergy were between goal-directed movements to get a more reliable control approach for facilitating the development of synergy in rehabilitation area.

## ACKNOWLEDGMENT

We would like to thank the Perceptual Robotics Laboratory, Scuola Superiore Sant'Anna, Italy, for their continued support of ongoing research and assistance in performing the experiment.

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