Associating Endpoint Accuracy and Similarity of Muscle Synergies

Liming Cai[1,2][a], Shuhao Yan[2,3], Chuanyun Ouyang[2,3], Tianxiang Zhang[2,3], Jun Zhu[1][b], Li Chen[1,4,*] and Hui Liu[5,*][c]

[1]*Academy for Engineering&Technology, Fudan University, Shanghai, 200433, China*

[2]*Suzhou Institute of Biomedical Engineering and Technology Chinese Academy of Sciences, Jiangsu,215163, China*

[3]*School of Biomedical Engineering (Suzhou), Division of Life Sciences and Medicine University of Science and Technology of China, Suzhou, China*

[4]*Department of Orthopedics, Huashan Hospital, Fudan University, Shanghai, China*

[5]*Cognitive Systems Lab, University of Bremen, Bremen, Germany*

* *

Keywords: Muscle Synergy Extraction, Muscle Synergy Similarity, Accuracy, Manipulate, Electromyography, EMG, sEMG.

Abstract: Recently, extracting the muscle synergy from surface electromyographic (sEMG) signals has become a standard method for evaluating motor control strategies during exercise. The synergy of the upper extremity in various stretch and reach tasks has been described in many studies, but few of them have analyzed the relationship between task performance and muscle synergy. This study provides an experimental device and analysis method for muscle coordination in the joystick task for the specific action of the pilots' joystick manipulation. Eight healthy subjects performed the joystick manipulation. For upper limbs, the task content included isotonic tasks with three load levels and recorded ten muscles' EMG and acceleration information. The muscle synergy effect was extracted and the correlation between muscle synergy similarity and manipulation performance and interaction load was studied. The experiment data showed that the manipulation performance varied under different loading conditions, but did not show significant changes in synergistic muscle structure. We found significant correlations between the similarity of some synergistic muscle structures and manipulation performance. However, between single-action performance and the average of their likeness, there was no strong correlation. Through the analysis of muscle synergy, we can determine that there is a fixed muscle synergy pattern during rocker manipulation, of which the structure is independent of the rocker load level, and muscle synergy similarity was negatively correlated with manipulation performance. The findings of this study significantly contribute to enhancing the ergonomic design of the flight stick, offering specific insights for its optimization. Additionally, they pave the way for developing specialized muscle training techniques, which are tailored to augment the accuracy and precision of executing complex flight maneuvers.

1 INTRODUCTION

Fine manipulation is one of the basic abilities of pilots, and it is a necessary and preferred ability in the selection and training process (Franklin et al., 2003). Fine manipulation refers to the power of the physiological reflex conducted by the optic nerve to reflect on the action quickly. The visual system uses the reflection and conduction of many visual functions to input the information obtained from observing the surrounding environment into the center of the brain. Then it transmits and drives the neuromusculoskeletal motor system and reflects it in the center of the brain on delicate movements of the hands or feet (Sepehrikia et al., 2023). The joystick manipulation is one of the main contents of the flight action; manipulation's accuracy and stability are essential.

The joystick manipulation is a multi-joint-coordinated movement. In motion control of the human body, the corresponding control modes are numerous for multi-joint motion. Actions are inherently variable, and professional athletes can use repetition to make them as consistent as possible. Muscle synergy has been used to study complex motor control patterns in recent years. Numerous studies

[a] https://orcid.org/0000-0003-2952-0109
[b] https://orcid.org/0000-0003-1311-4333
[c] https://orcid.org/0000-0002-6850-9570
*Correspondence E-mails

Cai, L., Yan, S., Ouyang, C., Zhang, T., Zhu, J., Chen, L. and Liu, H.
Associating Endpoint Accuracy and Similarity of Muscle Synergies.
DOI: 10.5220/0012586800003657

In *Proceedings of the 17th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2024) - Volume 1*, pages 683-694
ISBN: 978-989-758-688-0; ISSN: 2184-4305

have indicated that the CNS generates motor commands through synergistic combinations of muscles (d'Avella and Bizzi, 2003; Bizzi et al., 2008; Bizzi and Cheung, 2013), which is called muscle synergy. Applications of muscle synergy triggers studying the effects of nerve damage (Tang et al., 2017; Roh et al., 2013), human posture control (Torres-Oviedo and Ting, 2007; Robert and Latash, 2008; Asaka et al., 2011), robot-assisted technology (Miyazaki, 2011; Salman et al., 2010; C et al., 2021; Wang et al., 2021), and locomotion (A et al., 2019).

In isometric tasks, against speed changes, the module structures of muscle synergies were robust; the neural commands to muscle synergies changed in response to speed changes (Kojima et al., 2017). The motor control strategy might be modified depending on the requirement of the accuracy of the isometric reaching task considered (Tsubasa et al., 2020; Ettema et al., 2005). In the isotonic contraction task, previous studies have shown that the CNS could acquire knowledge between stiff-ness level and size of targets in some way (Osu et al., 2004; Sangwan et al., 2015), and change the mechanical impedance of the human body through the simultaneous activation of antagonist muscle groups (Burdet et al., 2001; Feldman and Levin, 1995), which reveals the critical role of co-contraction in upper limbs accuracy movement.

In addition to co-contraction indices, inter- and intra-subject similarity have previously been a hotspot in motor coordination (Alnajjar, 2017; Barnamehei et al., 2018a; Esmaeili and Maleki, 2020). Studies have shown that expertise did not cause significant differences in muscle synergy in controlled experiments between elites and non-elites (Barnamehei et al., 2018b). Although many studies support the similarity of synergistic components between different subjects under task conditions (K et al., 2021; Choi et al., 2019; Curado et al., 2015; Taborri et al., 2017; Velden et al., 2022), only a few studies have compared the relationship between intra-subject similarity and motion accuracy under different conditions (Choi et al., 2019). In comprehensive studies, the researchers have not assessed the within-subject variability in detail, and data are often averaged across trials to obtain average patterns without detailed analysis of individual manipulations (A et al., 2019; Zhao et al., 2019; Mira et al., 2021).

The extraction of muscle synergy holds great potential for enhancing fine motor skills. In this context, this study explores an objective and effective method to investigate the relationship between muscle synergy similarity, manipulation performance, and interaction load. Specifically, the study designs isotonic manipulation tasks with three different load levels. From these tasks, muscle synergy structure and similarity are extracted from sEMG data. Subsequently, the manipulation performance, muscle synergy structure, and their likeness are thoroughly analyzed and compared. Finally, the study delves into the relationship between manipulation performance and muscle synergy, offering insights into their interplay.

2 MATERIALS AND METHODS

2.1 Subjects and Experimental Apparatus

In this study, a sample population of 8 healthy subjects (all males, ages from 22 to 24, with heights of 170 ± 5 cm, and weighted 68 ± 5kg) volunteered to participate. The experiment procedure was informed to the subjects.

The joystick manipulation experimental apparatus was self-developed by the project team. As shown in Figure 1, it can realize the X and Y direction joystick manipulation and record the space position of the stick in real-time through the data from the encoder all of the subjects manipulated the experimental apparatus according to the upper computer interface, as shown in Figure 2A, and after completing the practical record of a single task, the description is shown in Figure 2B.

2.2 Three Tasks

Joystick manipulation was usually done by coordinating the shoulder, elbow, wrist, and fingers. This study designed the reciprocating motion under three loading conditions(Figure 2B). The study performed internal rotation and external rotation during the experiment. At the same time, the elbow joint was flexed and extended on the sagittal plane and retracted on the coronal plane. For the convenience of discussion, the entire experimental action was described by supination and pronation.

The subjects carried out simple manipulation learning under guidance before the start of the tests. All issues were asked to sit upright on a chair throughout the investigation. The issues held the joystick and moved back and forth along the X-axis (Figure 2A). The joystick moved to the right along +X, and the blue ball rolled to the B circle synchronously Figure 2B). The initial position of the blue ball was in the middle. Meanwhile, The black circle (diameter 2cm) was symmetrical on both sides of the blue ball. The joystick load was set to 3 levels (task 1, drag torque 0.72

Nm; task 2, drag torque 2.16 Nm; task 3, drag torque 6 Nm).

The subjects were required to 1) keep a distance between the elbows and the thighs, 2) exert force on the upper limbs, 3) blue balls reciprocate between the black circles, and 4) speed up while giving priority to accuracy.

Operating Procedures. Each set of 16 reps, then rest for 5 minutes before doing the next set. In this way, there were 24 sets of trials, and each set of trials contained 16 cyclic actions.

Data Induction. There were 24 clusters of experiments for eight subjects, each completed three tasks. The data includes the manipulation accuracy of the left and right positions and the similarity of the muscle synergy.

2.3 EMG Data Acquisition

Manipulation performance was recorded by the self-made joystick manipulation experimental prototype (position sampling frequency: 200Hz). Meanwhile, while subjects performed the movement tasks, A surface EMG system (Diese Trigno, USA DELSYS. Inc)was used to measure EMG and acceleration from 10 muscles of the upper arm (Figure 1A) including brachioradialis (BRAD), the short head of biceps (BICS), long head of biceps (BICL), anterior deltoid (DA), long head of triceps (TRIL), lateral head of triceps (TRILA), pectoralis major (PM), infraspinatus (INF), teres minor (T.M.), and posterior deltoid (D.P.). Electrodes are shown in Figure 1B/C, and the placement of electrodes follows the guidelines of surface EMG (Hermens et al., 2000). The sampling frequency of surface EMG is 1249Hz, and the sampling frequency of acceleration is 149Hz. The acquired signals were recorded and imported into Matlab 2017 (The Mathworks, Natick, MA) to be processed by means of custom routines.

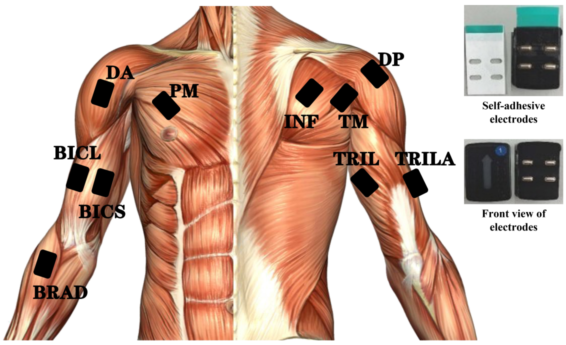

Figure 1: Placement and sensing muscles of sEMG sensors. Top right: self-adhesive electrodes. BRAD: brachioradialis; BICS: the short head of biceps; BICL: the long head of biceps; PM: pectoralis major; DA: anterior deltoid; TRIP: the long head of triceps; TRILA: the lateral head of triceps; INF: infraspinatus; T.M.: teres minor; D.P.: posterior deltoid (Cai et al., 2023b).

2.4 Manipulation Performance Data

The data of manipulation was derived from the motor encoder(Figure 2C), which was pre-processed in the following way:

a. Perform absolute value and normalization processing on the original data in order to detect the setting of the threshold;

b. Perform median filtering on the data obtained in (a) to filter out noise (abnormal burr) interference;

c. Analyze the data, set the detection threshold, obtain the position index of the data more significant than this threshold, and take the maximum and minimum value of the position index to obtain 4: the start and end position indexes of the valid data segment.

d. Calculate and obtain valid data in the original data according to the detection results in (c), and calculate the mean and variance.

e. Quantification of Manipulation Performance:

Positon deviation (P.D.): the difference between the mean of all data and the value of the ideal position.

Positon accuracy (P.A.): the difference between the value of the actual and the ideal position

Positon repeatability (P.R.): variance of all actual values.

Positon stability (P.E.): inferior for all manipulation data.

2.5 Muscle Synergies Extraction and Analysis

2.5.1 EMG Preprocessing

The custom routines were used for the sEMG Preprocessing in Matlab. The EMG pretreatment was in the following way:

a. Removes drifts: A mean shift was used to eliminate baseline shifts caused by trial or subject electrode shifts.

b. Band-pass (B.P.): filtering (40-250Hz), Removing high-frequency noise and motion artifacts.

c. Notch: 50Hz, 150Hz notch, removed fixed frequency noise.

d. Rectification: it is a standard method used for an envelope of non-negative sEMG signals

e. Low-pass (L.P.) filtering (20Hz), applied to the rectified sEMG signals, Cutoff frequency of 0.5Hz ensured smooth envelope and affected NMF results (Kieliba et al., 2018; Ouyang et al., 2023).

f. Normalization: normalized by the maximum value

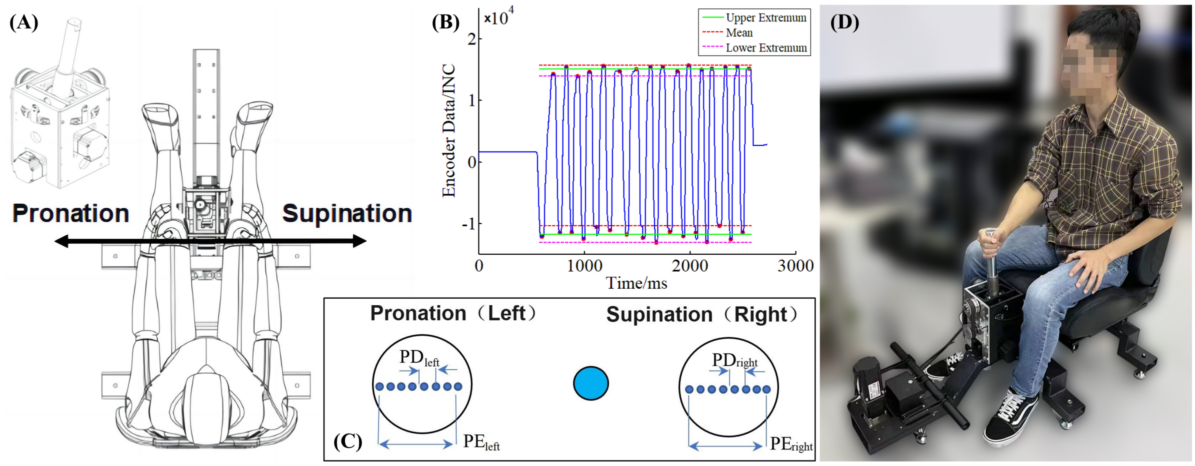

Figure 2: Self-developed experimental device and software interface. **(A)** Top view of the device for experiments; **(B)** A screenshot of the software interface; **(C)** An exemplar result record. PD: position deviation; PE: extreme range of the position (Cai et al., 2023b).

of the data itself during the trials.

g. Segmentation: The ACC signal was obtained synchronously with the EMG signal, but the sampling frequency of the ACC signal was lower than that of the EMG signal, so the ACC signal should be interpolated first to ensure that the length of the ACC signal was consistent with the sEMG signal, after median filtering the ACC signal was used to divide the EMG signal. This paper extracted data from the first 14 cycles, each containing one supination and one pronation.

2.5.2 Extraction of Muscle Synergies

A Non-negative Matrix Factorization (NMF) algorithm was employed to extract muscle synergies (Lee and Seung, 1999). The pre-processed signal ($V_{m\times t}$, where m represents the muscle channels and t denotes time, was decomposed into two matrices: $W_{m\times n}$ and $H_{n\times t}$. Here, n is the number of extracted muscle synergies, W is the basis matrix representing muscle activation patterns, and H is the matrix of activation coefficients for the muscle activations across m channels.

$$\begin{aligned} V_{m\times t} &\approx W_{m\times n} \times H_{n\times t} \\ &= W_1 \times H_1 + W_2 \times H_2 + \cdots + W_n \times H_n \end{aligned} \quad (1)$$

W_i is a vector from the Muscle synergy matrix, specifying the muscle activity pattern defined by muscle synergy. Each element of $W_i$was between 0 and 1 (Cai et al., 2023a). Muscle synergy formed by these is functionally activated by the activation coefficient matrixH_i. The activation coefficient represented the purported neural command from CNS, and determined the relative contribution for establishing the muscle synergy matrix (Torres-Oviedo and Ting, 2007; Cai et al., 2023c).

The number of muscle synergies n was between 1 and 10. The reconstructed matrix $V'_{m\times t}$ has been expressed as (2). Then, the minimum number of synergies was selected that could adequately reconstruct the pre-processed signals $V_{m\times t}$ in all trials, as the variability accounted for (VAF shown in formula 3) > 90% in each muscle data vector (Tang et al., 2017).

$$\begin{aligned} V'_{m\times t} &= W_{m\times n} \times H_{n\times t} \\ VAF &= 1 - \left(V_{m\times t} - V'_{m\times t}\right)^2 / V^2_{m\times t} \end{aligned} \quad (2)$$

2.5.3 Quantitative Similarity of Muscle Synergies

To determine the synergies' similarity among the tasks between the clusters, we used the intraclass correlation coefficient (ICC) analysis (Choi et al., 2019; Curado et al., 2015; Taborri et al., 2017; Velden et al., 2022; McGraw and Wong, 1996), each subject performed 14 round trips in a single task. First, individual synergies from a single subject were collected in one cluster. Then, we examined the similarity of the synergies within the cluster by using the R_{icc-wi} as formula (4), wi= [w_1,w_2,w_i,..w_n], wi is the synergy matrices. In the formula (4), m represents the number of trips which was 14, and i ranges from 1 to n.

$$R_{icc-wi} = ICC\left(W_{i1}, W_{i2}, \ldots, W_{im}\right) \quad (3)$$

In the single cluster, the likeness between two muscle synergies matrices was assessed by r (Pearson's correlation coefficients). Assume the number of trials was S for each subject, $Subject$ 1 correlation coefficients were expressed as R_{i-wi}= $[r_1, r_2, \ldots r_{i-1}, r_{i+1}, \ldots r_S]$, with the ri has represented the likeness of wi from the data of i-th trial and other trials. Then the dispersion of all the averaged Ri

was analyzed using the quartile method (Tang et al., 2017). After filtrating data, muscle synergies for each subject R_{task} were averaged.

$$
\begin{aligned}
R_{i-wi} &= \frac{1}{S-1}\sum_{i=1}^{S}(r_1 \ldots + r_{i-1} + r_{i+1} + r_s) \\
R_{task-wi} &= \frac{1}{S}\sum_{i=1}^{S}(R_{1-wi} + R_{2-wi} \ldots + R_{S-wi})
\end{aligned} \tag{4}
$$

2.5.4 Statistics Methods

This study's descriptive statistics included the mean and standard deviation of experiment data. One-way ANOVA was used to evaluate between-cluster and within-cluster R_{icc-wi}/R_i differences between different loadings and subjects. Coefficients were considered significant for $p < 0.1$ and $p < 0.05$ in this study.

3 RESULTS

3.1 Muscle Synergy Analysis

Muscle synergies extracted from three tasks of 8 healthy subjects are shown in Figure 3. Four muscle synergies were recruited in three tasks. W1 mainly reflected the activation of BRAD, INF, and DA; W2 contained the activation of DA, PELA, TRILA, and TRIL; W3 was mainly BICL and BICS; W4 was composed of D.P., T.M., INF, TRIAL, TRAIL, BRAD. When the load increased, the effect of INF decreased, and the effect of A.D. increased in the synergy (W1). As a small muscle group, BRAD was lowered in all four synergistic modes as the load increased.

Within the cluster, a pronounced structure was observed among the eight subjects. The average of R_{icc-wi} across all tasks and subjects was 0.87 ± 0.05 (R_{icc-w2} = 0.97 ± 0.02, R_{icc-w3} = 0.89 ± 0.09, R_{icc-w4} = 0.96 ± 0.03), as shown in Figure 4. A one-way analysis was conducted to evaluate the subjects and tasks for R_{icc-w1}. There was a significant difference in R_{icc-w2} among different subjects ($F = 3.674$, $p = 0.015$), and no statistical difference was found in the level of R_{icc-w1}, which is affected by different tasks. The table 1 presents all the ICC results of muscle synergies in all trials.

In the cluster, One-way analysis was used to assess R_{icc-w1} of the subjects and tasks of. There was a significant difference in R_{icc-w1} among different subjects: R_{icc-w1} $(F = 10.754, p = 0)$; R_{icc-w2} $(F = 16.675, p = 0)$; R_{icc-w3} $(F = 43.418, p = 0)$; R_{icc-w4} $(F = 25, p = 0)$, and statistical differences in the level of R_{icc-w1} $(F = 5.903, p = 0.003)$ affected by task.

3.2 Manipulation Accuracy Analysis

During pronation, six subjects exhibited smaller manipulation errors in task 2 compared to the other two tasks. Furthermore, seven subjects had smaller manipulation errors in task 2 than in task 1, and the same seven subjects had smaller errors in task 2 than in task 3, as shown in Figure 5A. Regarding supination, as depicted in Figure 5B, five subjects experienced smaller manipulation errors in task 2 than in the other two tasks, and five subjects had greater errors in task 1 compared to the other tasks.

The average similarity *ri* of a single trial in the whole process was calculated. Meanwhile, the *ri* with low similarity was proposed according to the four-class classification method. According to this method, the experimental results left by each subject are shown in Figure 5 and Figure 6, during pronation, there are seven subjects whose manipulation error of task 2 was smaller than the other two tasks. During supination, the manipulation error of task 2 with six subjects was smaller than that of the other two tasks. The number of the subjects with this characteristic was higher than before the treatment.

One-way analysis was used in the cluster to assess manipulation accuracy P.A.–L, P.A.–R. There was a significant difference in P.A.–L among different subjects $(F = 3.374, p = 0.002)$, and different loads $(F = 5.143, p = 0.006)$.

3.3 Analysis of Correlation

Between the cluster, View Table 2, as shown in Figure 7 The correlation between P.D.–L and load is -0.29 (p = 0.168), the r between P.D.–R and load is -0.41*(p = 0.05), the r between P.R.–L and load is -0.3 (p = 0.15), the r between P.D.–R and load is -0.24 (p = 0.261), and r between P.E.–L and load is -0.32 (p = 0.12). The load correlation between the P.E.–R load correlation is -0.27 (p = 0.2).

In the cluster, the relationship between the performance of a single manipulation and *ri* (the similarity of the muscle synergy from the single manipulation) was shown in Table 3. Among the 96 groups of correlation indicators, 18 were significant, W_4 was significant six times, W_3 and W_2 appeared four times each, and W_1 appeared three times ($p < 0.1$).

4 DISCUSSION

In this study, the muscle activity of 10 channels was measured by EMG when a rocker manipulated the upper limb, and the muscle synergy was extracted.

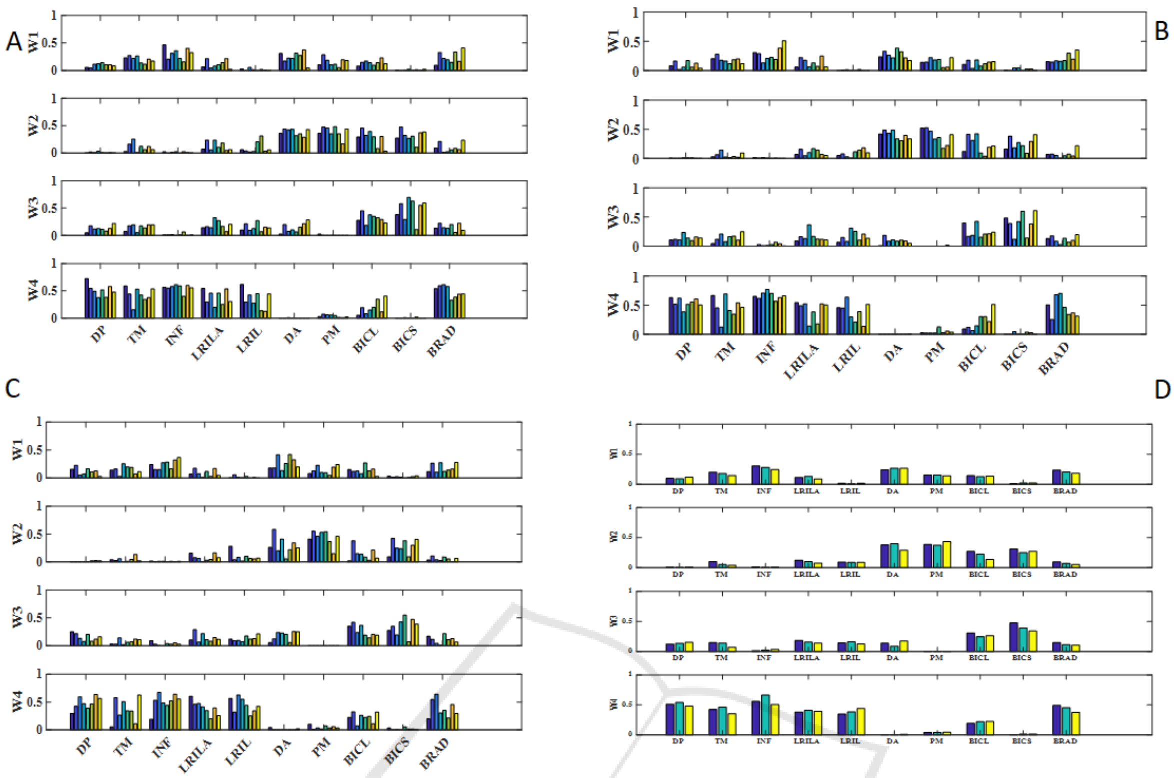

Figure 3: Muscle synergies extracted from 8 subjects **(A)**, **(B)**, **(C)**Y-axis is the muscle synergies under the different task **(D)** the mean muscle synergies from all subjects, The horizontal axis is all corresponding to the selected ten muscles.

The results showed that approximately four individual synergistic effects were extracted from separate EMG datasets with a 90% VAF criterion. Under different load conditions, the similarity between the manipulation performance and muscle synergy of each action was collected for analysis, and the research between the manipulation performance and the muscle synergy effect was clarified from the perspective of manipulation performance.

4.1 The Load and the Structure of Muscle Synergy

In this study, we found that changes in loading did not cause differences in muscle synergy, and muscle synergy was substantially similar in each subject. This is consistent with previous studies that changes in loading have a limited effect on synergistic structure (Nicolas A et al., 2020). Giving the arm a certain amount of assistance or resistance did not alter the composition of the muscle synergy used by the subjects during the stretch but instead changed the magnitude of the activation spectrum of the muscle synergy. (Coscia et al., 2014)Previous studies have found that 3 to 5 muscles work together in the three-dimensional force generation of the upper extremity (Roh et al., 2012). The four muscle synergies we found in our study can be analyzed, and the extracted muscle synergy is influenced by biomechanics and task constraints (Todorov et al., 2005). During pronation, the muscle further weights of D.P., PM, BICL, and BICS in the W2 synergistic effect are louder, which means that these muscles work coordinately in pronation. In the supination action, the muscle weights of D.P., T.M., INF, TRILA, and TRIL, synergistic effects of W4, are more significant. We found that small muscle groups like BRAD have lower weights in all 4 synergistic modes when the load was increased.

Muscle synergy similarity (R_{icc-w2}) per cluster was not significantly correlated with load (r = 0 $\sim$ 0.17). A study of three-digit force generation reported that the EMG–EMG coherence was not significantly affected by force, suggesting that the distribution of neural drive to multiple hand muscles is force-independent (Santos et al., 2010). Manipulation performance has a certain correlation with the load (r = -0.41, $p < 0.05$). Several studies have investigated how the motor system modulates limb stiffness to achieve accurate movements in the presence of unstable force loads (Burdet et al., 2001; Franklin and Theodore E., 2007).

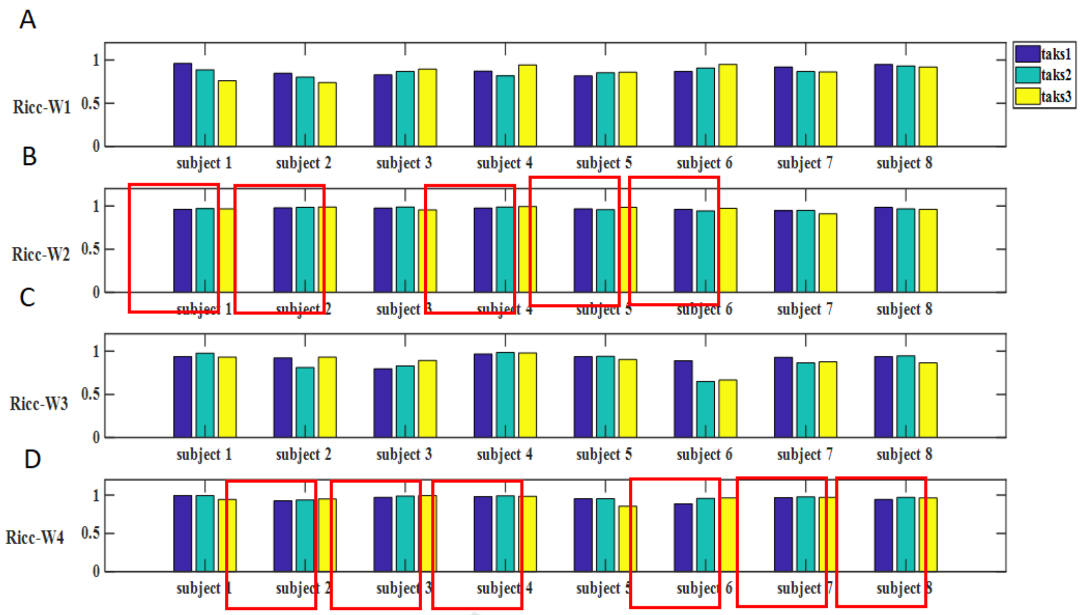

Figure 4: Intragroup correlation coefficients of muscle synergy in three tasks, **(A)**$W1$, **(B)**$W2$, **(C)**$W3$, **(D)**$W4$. The horizontal axis represents eight subjects; The vertical axis represents the intra-group correlation coefficient of muscle synergy in the three tasks of the subjects.

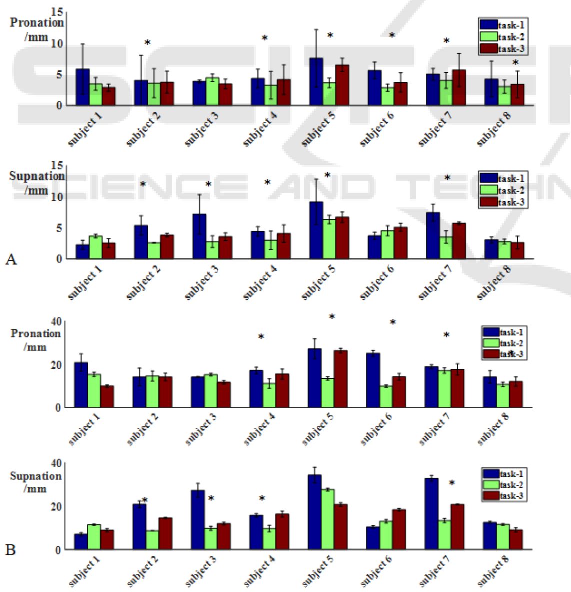

Figure 5: Results of manipulation for three tasks, the horizontal axis represents eight subjects **(A)** P.D. during pronation, **(B)** P.E. during Supination.

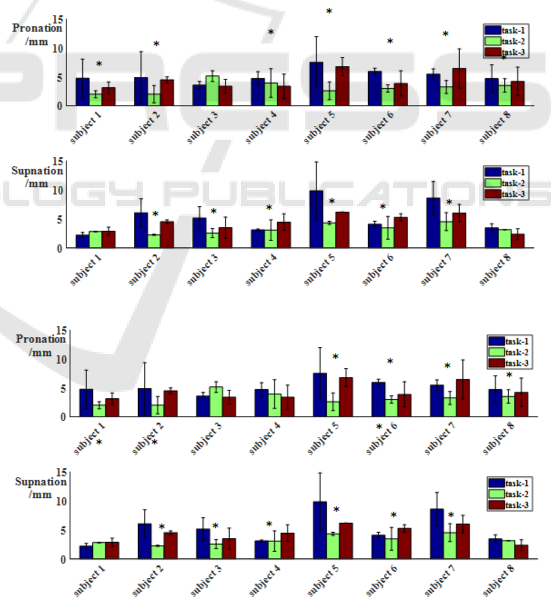

Figure 6: Filtered results of manipulation for three tasks, the horizontal axis represents eight subjects **(A)** P.D. during pronation, **(B)** P.E. during Supination.

4.2 Manipulation Performance and the Structure Similarity of Muscle Synergy

Many studies have shown that there are usually many compensatory solutions for any motor task, and these different solutions can achieve the same movement (McKay and Ting, 2008; L. H. Ting, 2004). In our study, all three tasks were isometric, and the position distribution at the end of the exercise changed with the load, which was similar to the previous study (Kojima et al., 2017). We found that among the three tasks,

Table 1: ICC of muscle synergies and results of manipulation for all trials.

	W1	W2	W3	W4	PD-L	PD-R	Task	PR-L	PR-R	PE-L	PE-R
Subject1	0.96	0.96	0.94	0.99	4.02	0.74	1	5.85	2.25	20.74	6.98
Subject1	0.89	0.97	0.98	0.99	1.02	0.32	2	3.47	3.65	15.31	11.4
Subject1	0.76	0.97	0.93	0.94	0.57	0.71	3	2.88	2.53	9.9	8.91
Subject2	0.85	0.98	0.92	0.93	4.06	1.57	1	4.02	5.35	14.12	20.76
Subject2	0.8	0.98	0.81	0.94	2.34	0.02	2	3.57	2.58	14.53	8.6
Subject2	0.74	0.99	0.93	0.95	1.76	0.29	3	3.74	3.81	14.12	14.54
Subject3	0.83	0.97	0.8	0.97	0.24	3.17	1	3.85	7.16	14.1	27.19
Subject3	0.87	0.99	0.83	0.99	0.63	0.94	2	4.44	2.77	15.19	9.74
Subject3	0.89	0.96	0.89	0.99	0.78	0.61	3	3.46	3.56	11.63	11.92
Subject4	0.87	0.97	0.97	0.98	1.49	0.77	1	4.33	4.41	17.09	15.7
Subject4	0.82	0.99	0.98	0.99	2.22	1.49	2	3.25	2.99	11.08	9.62
Subject4	0.94	0.99	0.98	0.98	2.39	1.4	3	4.15	4.07	15.43	16.31
Subject5	0.82	0.97	0.94	0.95	4.61	3.63	1	7.58	9.15	27.05	34.2
Subject5	0.85	0.96	0.94	0.96	0.78	0.67	2	3.65	6.31	13.42	27.54
Subject5	0.86	0.99	0.9	0.86	1.07	0.86	3	6.51	6.7	26.28	20.69
Subject6	0.87	0.96	0.89	0.89	1.36	0.59	1	5.63	3.71	25.03	10.41
Subject6	0.91	0.94	0.65	0.96	0.59	0.81	2	2.86	4.52	9.84	12.96
Subject6	0.95	0.97	0.67	0.96	1.56	0.64	3	3.71	5.07	14.16	18.29
Subject7	0.92	0.95	0.93	0.97	0.93	1.37	1	5.02	7.42	18.8	32.69
Subject7	0.87	0.95	0.86	0.98	1.28	0.99	2	4.02	3.51	17.04	13.3
Subject7	0.86	0.91	0.88	0.97	2.65	0.22	3	5.7	5.72	17.55	20.7
Subject8	0.95	0.98	0.94	0.94	2.86	0.48	1	4.25	3.06	14.13	12.46
Subject8	0.93	0.97	0.94	0.97	1.06	0.39	2	3.03	2.78	10.63	11.48
Subject8	0.92	0.96	0.86	0.96	2.14	1.01	3	3.39	2.62	11.97	9.05

Table 2: Pearson correlation of ICC and results of manipulation.

	W1	W2	W3	W4	PD-L	PD-R	Task	PR-L	PR-R	PE-L	PE-R
W1	1	-0.22	-0.14	0.23	0.08	-0.14	-0.13	0.04	-0.12	0.02	-0.09
W2		1	0.28	-0.18	0.06	0.13	0	-0.11	-0.18	-0.02	-0.17
W3			1	0.08	0.29	0.03	-0.17	0.21	-0.05	0.2	0.04
W4				1	-0.04	0.05	-0.02	-0.37	-0.24	-.48*	-0.13
PD-L					1	0.26	-0.29	.501*	0.1	0.36	0.1
PD-R						1	-.41*	0.37	0.65**	0.3	0.63**
Task							1	-0.3	-0.24	-0.32	-0.27
PR-L								1	0.55**	0.94**	0.46*
PR-R									1	0.50*	0.97**
PE-L										1	0.39
PE-R											1

Table 3: Pearson correlation between similarity and results of manipulation in the cluster.

		PA-L				PA-R			
	Task	W1	W2	W3	W4	W1	W2	W3	W4
Subject1	1	0.223	255	0.022	0.36	-0.47*	-0.512*	**-0.04**	**0.213**
Subject1	2	0.341	0.345	0.33	-0.093	0.208	0.294	0.053	-0.502*
Subject1	3	0.343	0.254	-0.229	-0.197	-0.076	0.045	-0.356	0.05
Subject2	1	0.318	-0.133	0.093	-0.026	0.017	0.057	-0.215	-0.811***
Subject2	2	-0.245	0.137	-0.587**	-0.362	-0.279	-0.158	0.136	0.089
Subject2	3	0.036	-0.267	0.195	-0.038	0.452*	0.279	0.322	-0.337
Subject3	1	0.057	0.383	-0.25	-0.525**	-0.033	0.042	0.289	-0.491*
Subject3	2	-0.13	0.083	-0.219	-0.423	-0.288	0.395	0.232	0.235
Subject3	3	0.16	0.038	-0.253	0.403	-0.06	0.141	0.089	0.433
Subject4	1	-0.025	0.094	0.229	0.245	0.097	-0.186	0.229	0.295
Subject4	2	-0.33	-0.285	0.344	0.314	-0.015	0.091	0.17	-0.192
Subject4	3	0.371	0.284	0.018	-0.002	0.189	0.031	0.029	-0.379
Subject5	1	0.242	-0.083	0.024	-0.198	-0.128	-0.325	0.421	0.108
Subject5	**2**	**-0.332**	0.425	-0.314	0.059	-0.609**	-0.22	0.043	-0.028
Subject5	3	-0.15	0.072	-0.279	-0.039	0.298	0.242	-0.186	-0.125
Subject6	1	-0.046	0.197	0.166	-0.033	0.073	-0.495*	-0.429*	-0.108
Subject6	2	-0.221	-0.014	-0.539**	-0.356	0.102	-0.228	0.292	-0.573**
Subject6	3	0.072	0.434	-0.424	0.386	0.149	0.242	-0.006	-0.165
Subject7	1	0.159	0.322	0.371	-0.225	0.265	0.097	-0.282	0.36
Subject7	2	0.093	-0.017	0.061	0.336	-0.373	-0.332	0.156	0.016
Subject7	3	0.42	-0.482**	0.228	-0.2	0.121	0.209	-0.302	-0.461*
Subject8	1	-0.127	-0.161	-0.113	-0.507**	0.16	-0.258	0.185	0.335
Subject8	2	0.104	-0.484**	-0.369	-0.056	-0.185	0.139	0.2	-0.004
Subject8	3	0.278	0.368	0.175	0.169	0.058	-0.182	0.424	0.366

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

the manipulation error of task 2 was smaller than that of the other two tasks, and this rule was more evident when the experimental data was screened by the quartile method. This means that manipulation performance is not linearly related to loading. According to the results of Figure 5 and Figure 6, the load causes a decrease in the manipulation accuracy, but there is an optimal value within a specific range.

We hypothesize that motion accuracy is related not only to loading, co-contraction index, and impedance (Sangwan et al., 2015), but also to muscle synergy similarity (Choi et al., 2019). This hypothesis is supported by our macroscopic experimental results. As Table 2 shows, the intra-group correlation coefficient of W_4 was significantly negatively correlated with P.E.-L (r = -0.48, $p < 0.05$). In the pronation action, D.P., T.M., INF, TRILA, and TRIL within the W_4 synergy are antagonistic muscles. This finding suggests that the CNS activates antagonistic muscles to adjust motor impedance, minimizing load-induced interference and improving movement accuracy (Serres and Milner, 1991; Wong et al., 2009).

Further research on a single manipulation was conducted to observe the correlation between its accuracy and the average similarity of this manipulation with other manipulations in 7. No apparent statistical law was found, and the number of significant correlations between W2 and W4 was greater than that of the other two. From the analysis of the results with significant correlations, W4 was negatively correlated with bilateral manipulation errors like the previous results, and W2 was also negatively correlated with bilateral manipulation results, which proved the role of the antagonist's muscles in performing precision-targeted movements. The manipulating error was smaller as the synergistic similarity of the antagonistic muscle groups increased.

5 CONCUSION

Our experiments and in-depth data analysis revealed that the synergistic structure of muscles remained strikingly constant across various load levels when healthy subjects skillfully performed rocker manipulations, the similarity of muscle synergy was then negatively correlated with load level. Our interpretation of this result also highlights the body's capacity

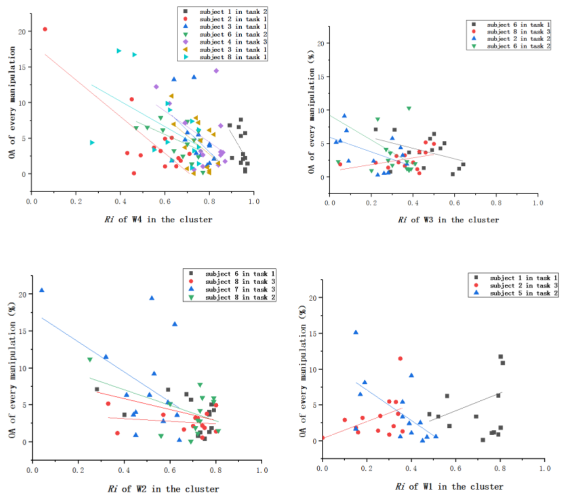

Figure 7: O.A. versus the R_i of muscle synergy in the cluster **A**(W_4), **B**(W_3), **C**(W_2), **D**(W_1).

to adapt to varying loading levels through the modification of biomechanical strategies, reflecting an innate and efficient adaptability mechanism. We also observed the performance of joystick manipulation was negatively correlated with the similarity of certain muscle synergy. These results also supported the alternative hypothesis that the human body increased the activation of antagonistic muscle groups to achieve better manipulation outcomes. Our results showed that the muscle coordination model was effective as an understanding of the effect of load on muscle coordination and manipulation performance in joystick manipulation. Such an understanding would help in the ergonomic design of flight joysticks and the training methods for improving pilots' upper limb manipulation.

ACKNOWLEDGEMENTS

The authors sincerely express their gratitude for the generous financial support of "National Key R&D Program of China"(No.2020YFC2007402, No.2020YFC2007401, No.2020YFC2007404, No.2020YFC2007403, No.2020YFC2007405, No.2020YFC2007400), Basic Research Program of Suzhou (SJC2022011), and Special project of basic research on frontier leading technology in Jiangsu Province (BK20192004C).

REFERENCES

A, S., L, D., F, M., H, G., LM, T., and A, d. (2019). A comprehensive spatial mapping of muscle synergies in highly variable upper-limb movements of healthy subjects. *Frontiers In Physiology*, Vol.10:1231.

Alnajjar, F. (2017). Muscle synergies indices to quantify the skilled behavior in human. *CONVERGING CLINICAL AND ENGINEERING RESEARCH ON NEUROREHABILITATION II, VOLS 1 AND 2*, Vol.15:959–963.

Asaka, T., Yahata, K., Mani, H., and Wang, Y. (2011). Modulations of muscle modes in automatic postural responses induced by external surface translations. *Journal of Motor Behavior*, Vol.43(No.2):165.

Barnamehei, H., Razaghi, M., Panahi, S., Modabberibejandi, M., Lashgari, M., Safaei, M. A., and Rezaei, A. (2018a). *Identification and quantification of modular control during Roundhouse kick executed by elite Taekwondo players*. Department of Biomedical Engineering, Islamic Azad University, Tehran, Iran Department of Biomedical Engineering, Islamic Azad University, Tehran, Iran Department of Biomedical Engineering, Islamic Azad University, Tehran, Iran Tehran Taekwondo Division, Iran Taekwondo Federation, Tehran, Iran Tehran Taekwondo Division, Iran Taekwondo Federation, Tehran, Iran Tehran Taekwondo Division, Iran Taekwondo Federation, Tehran, Iran Tehran Taekwondo Division, Iran Taekwondo Federation, Tehran, Iran.

Barnamehei, H., Tabatabai Ghomsheh, F., Safar Cherati, A., and Pouladian, M. (2018b). Upper limb neuromuscular activities and synergies comparison between elite and nonelite athletics in badminton overhead forehand smash. *Applied Bionics & Biomechanics*, Vol.2018:1–10.

Bizzi, E. and Cheung, V. (2013). The neural origin of muscle synergies. *FRONTIERS IN COMPUTATIONAL NEUROSCIENCE*, Vol.7(No.1):51.

Bizzi, E., Cheung, V. C. K., d'Avella, A., Saltiel, P., and Tresch, M. (2008). Combining modules for movement. *Brain Research Reviews*, Vol.57(No.1):125–133.

Burdet, E., Osu, R., Franklin, D. W., Milner, T. E., and Kawato., M. (2001). The central nervous system stabilizes unstable dynamics by learning optimal impedance. *Nature*, Vol.414(No.6862):446.

C, W., S, Z., J, H., Z, H., and C, S. (2021). Upper-limb muscle synergy features in human-robot interaction with circle-drawing movements. *Applied bionics and biomechanics*, Vol.2021:8850785.

Cai, L., YAN, S., DONG, Y., Zhu, J., Chen, L., Liu, B., and Ma, X. (2023a). Evaluation method and experimental study of pilot fine handling ability under different loads. *Journal of Xi 'an Jiaotong University*, 57(06):39–46.

Cai, L., Yan, S., Ouyang, C., Zhang, T., Zhu, J., Chen, L., Ma, X., and Liu, H. (2023b). Muscle synergies in joystick manipulation. *Frontiers in Physiology*, 14:1282295.

Cai, L. M., Yan, S. H., Ouyang, C. Y., Zhang, T. X., Zhu, J., Chen, L., Ma, X., and Liu, H. (2023c). Muscle synergies in joystick manipulation. *Frontiers in Physiology*, 14.

Choi, Y., Kim, Y., Kim, M., and Yoon, B. (2019). Muscle synergies for turning during human walking. *Journal of Motor Behavior*, Vol.51(No.1):1–9.

Coscia, M., Cheung, V. C., Tropea, P., Koenig, A., Monaco, V., Bennis, C., Micera, S., Bonato, P., and Cheung, V. C. K. (2014). The effect of arm weight support on upper limb muscle synergies during reaching movements. *Journal of neuroengineering and rehabilitation*, Vol.11(No.1):22.

Curado, M. R., Cossio, E. G., Broetz, D., Agostini, M., Cho, W., Brasil, F. L., Yilmaz, O., Liberati, G., Lepski, G., Birbaumer, N., and Ramos-Murguialday, A. (2015). Residual upper arm motor function primes innervation of paretic forearm muscles in chronic stroke after brain-machine interface (bmi) training. *PloS one*, Vol.10(No.10):e0140161.

d'Avella, Andrea.and Saltiel, P. and Bizzi, E. (2003). Combinations of muscle synergies in the construction of a natural motor behavior. *Nature neuroscience*, Vol.6(No.3):300–308.

Esmaeili, J. and Maleki, A. (2020). Muscle coordination analysis by time-varying muscle synergy extraction during cycling across various mechanical conditions. *Biocybernetics and Biomedical Engineering*, Vol.40(No.1):90–99.

Ettema, G. J. C., Taylor, Emma.and North, J. D., and Kippers, V. (2005). Muscle synergies at the elbow in static and oscillating isometric torque tasks with dual degrees of freedom. *Motor Control*, Vol.9(No.1):59–74.

Feldman, A. G. and Levin, M. F. (1995). The origin and use of positional frames of reference in motor control. *Behavioral and Brain Sciences*, Vol.18(No.4):723–806.

Franklin, D. W., Osu, R., Burdet, E., and Kawato, Mitsuo.and Milner, T. E. (2003). Adaptation to stable and unstable dynamics achieved by combined impedance control and inverse dynamics model. *Journal of Neurophysiology*, Vol.90(No.5):3270–3282.

Franklin, D. W. and Theodore E., e. a. (2007). Endpoint stiffness of the arm is directionally tuned to instability in the environment. *The Journal of Neuroscience*, Vol.27(No.29):7705–7716.

Hermens, H. J., Freriks, B., Dißelhorst-Klug, C., and Rau, G. (2000). Development of recommendations for semg sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology*, Vol.10(No.5):361–374.

K, Z., Z, Z., H, W., and A, S. (2021). Intra-subject and inter-subject movement variability quantified with muscle synergies in upper-limb reaching movements. *Biomimetics*, Vol.6(No.4):63.

Kieliba, P., Tropea, P., Pirondini, E., Coscia, M., Micera, S., and Artoni, F. (2018). How are muscle synergies affected by electromyography pre-processing? *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Vol.26(No.4):882–893.

Kojima, S., Takeda, M., Nambu, I., and Wada, Y. (2017). Relations between required accuracy and muscle synergy in isometric contraction tasks. *2017 IEEE INTERNATIONAL CONFERENCE ON SYSTEMS, MAN, AND CYBERNETICS (SMC)*, pages 1191–1195.

L. H. Ting, J. M. M. (2004). A limited set of muscle synergies for force control during a postural task. *Journal of Neurophysiology*, Vol.93(No.1):609–613.

Lee, D. D. and Seung, H. S. (1999). Learning the parts of objects by non-negative matrix factorization. *Nature*, Vol.401(No.6755):788.

McGraw, K. O. and Wong, S. P. (1996). Forming inferences about some intraclass correlation coefficients. *Psychological Methods*, Vol.1(No.1):30–46.

McKay, J. L. and Ting, L. H. (2008). Functional muscle synergies constrain force production during postural tasks. *Journal of biomechanics*, Vol.41(No.2):299–306.

Mira, R. M., Tosatti, L. M., Sacco, M., and Scano, A. (2021). Detailed characterization of physiological emg activations and directional tuning of upper-limb and trunk muscles in point-to-point reaching movements. *Current Research in Physiology*, Vol.4:60–72.

Miyazaki, H. T. K. H. (2011). *Extraction and Implementation of Muscle Synergies in Hand-Force Control*. Department of Mechanical Science and Bioengineering,Graduate School of Engineering Science,Osaka University,Japan.

Nicolas A, T., Romain, M., and Mickael, B. (2020). Shoulder muscle activation strategies differ when lifting or lowering a load. *European journal of applied physiology*, Vol.120(No.11):2417–2429.

Osu, Rieko.and Kamimura, N., , Nakano, E., and Harris, Chris M.and Wada, Y. (2004). Optimal impedance control for task achievement in the presence of signal-dependent noise. *Journal of Neurophysiology*, Vol.92(No.2):1199–1215.

Ouyang, C. Y., Cai, L. M., Liu, B., and Zhang, T. X. (2023). An improved wavelet threshold denoising approach for surface electromyography signal. *Eurasip Journal on Advances in Signal Processing*, 2023(1).

Robert, T. and Latash, M. (2008). Time evolution of the organization of multi-muscle postural responses to sudden changes in the external force applied at the trunk level(article). *Neuroscience Letters*, Vol.438(No.2):238–241.

Roh, J., Rymer, W., and Beer, R. (2012). Robustness of muscle synergies underlying three-dimensional force generation at the hand in healthy humans(article). *Journal of Neurophysiology*, Vol.107(No.8):2123–2142.

Roh, J., Rymer, W., Perreault, E., Yoo, S., and Beer, R. (2013). Alterations in upper limb muscle synergy structure in chronic stroke survivors(article). *Journal of Neurophysiology*, Vol.109(No.3):768–781.

Salman, B., Vahdat, S., Lambercy, O., Dovat, L., Burdet, E., and Milner, T. (2010). *Changes in Muscle Activation Patterns Following Robot-assisted Training of Hand Function after Stroke*. Sion Frser Universiy, Burnby, BC CndMcGi Universiy, Monre, QC CndETH Zurich, Zurich, SwizerndGoech, SwizerndIeri Coege of Science, Technoogy nd Medicine, London UKMcGi Universiy.

Sangwan, S., Green, R. A., and Taylor, N. F. (2015). Stabilizing characteristics of rotator cuff muscles: a systematic review. *Disability and Rehabilitation*, Vol.37(No.12):1033–1043.

Santos, Alessander Danna-Dos.and Poston, B., Jesunathadas, Mark.and Bobich, L., and Hamm, T. M. M. C. (2010). Influence of fatigue on hand muscle coordination and emg-emg coherence during three-digit grasping. *Journal of Neurophysiology*, Vol.104(No.6):3576–3587.

Sepehrikia, M., Abedanzadeh, R., and Saemi, E. (2023). Brain gym exercises improve eye-hand coordination in elderly males. *Somatosensory & motor research*, pages 1–6.

Serres, S. J. D. and Milner, T. E. (1991). Wrist muscle activation patterns and stiffness associated with stable and unstable mechanical loads. *Experimental brain research*, Vol.86(No.2):451–458.

Taborri, J., Palermo, E., Masiello, D., and Rossi, S. (2017). *Factorization of EMG via muscle synergies in walking task: Evaluation of intra-subject and inter-subject variability*. Juri Taborri:Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Roma, Italy Eduardo Palermo:Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Roma, Italy Denisa Masiello:Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Roma, Italy Stefano Rossi:Department of Economics and Management-Industrial Engineering (DEIM), University of Tuscia, Viterbo, Italy.

Tang, L., Chen, X., Cao, S., Wu, D., Zhao, G., and Zhang, X. (2017). Assessment of upper limb motor dysfunction for children with cerebral palsy based on muscle synergy analysis. *Frontiers in Human Neuroscience*, Vol.11(No.0):130.

Todorov, E., Li, W., and Pan, X. (2005). From task parameters to motor synergies: A hierarchical framework for approximately-optimal control of redundant manipulators. *Journal of robotic systems*, Vol.22(No.11):691–710.

Torres-Oviedo, G. W. H. and Ting, L. H. (2007). Muscle synergies characterizing human postural responses. *Journal of Neurophysiology*, Vol.98(No.4):2144–2156.

Tsubasa, Sano and Misaki, T., Isao, N., and Yasuhiro, W. (2020). Relations between speed-accuracy trade-off and muscle synergy in isometric contraction tasks. *Annual International Conference of the IEEE Engineering in Medicine and Biology Society.*, Vol.2020:4803–4806.

Velden, L. L. v. d., Benner, J. L., Onneweer, B., Haarman, C. J. W., Selles, R., Ribbers, G., and Roebroeck, M. E. (2022). Reliability and validity of a new diagnostic device for quantifying hemiparetic arm impairments: An exploratory study. *Journal of Rehabilitation Medicine*, Vol.54:jrm00283.

Wang, T., Okada, S., Guo, A., Makikawa, M., and Shiozawa, N. (2021). *Effect of Assist Robot on Muscle Synergy during Sit-to-Stand Movement*.

Wong, J., Wilson, Elizabeth T.and Malfait, N., and Gribble, P. L. (2009). Limb stiffness is modulated with spatial accuracy requirements during movement in the absence of destabilizing forces. *Journal of Neurophysiology*, Vol.101(No.3):1542–1549.

Zhao, K., Zhang, Z., Wen, H., Wang, Z., and Wu, J. (2019). Modular organization of muscle synergies to achieve movement behaviors. *Journal of Healthcare Engineering*, Vol.2019:8130297.