

Functional Coupling between Hand Muscles during Dynamic Handgrip Exercise in Post-Stroke Patients

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Abstract

Stroke results in impairments of motor function, which are frequently assessed by using clinical scales. However, these scales can only reflect patients' global motor performance and may not be sensitive to subtle changes in motor function. This study investigates functional coupling between hand muscles during dynamic handgrip exercise in post-stroke patients. Ten post-stroke patients with chronic hemiparesis and 10 healthy young aduts were recruited into this study. The subjects performed dynamic handgrip exercise at 30% maximal voluntary contraction while surface electromyographic (sEMG) signals from the flexor digitorum superficialis (FDS), flexor carpi ulnaris (FCU), and extensor carpi ulnaris (ECU) were recorded. Wavelet coherence between the sEMG signals within the frequency bands 0-5 Hz, 8-12 Hz (α band), 15-35 Hz (β band), and 35-60 Hz (γ band) was quantified by the area under the time-avereged coherence function of the original data and above the threshold obtained from surrogates.

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The resuts showed that changes in EMG-EMG coherence caused by handgrip exercise in post-stroke patients differed from that in healthy controls and that these changes were muscle pair specific and particularly frequency band specific. During the handgrip period, EMG-EMG coherence for the muscle pair FDS/FCU showed a significantly higher value in the α band and a significantly lower value in the γ band in post-stroke patients compared to healthy controls; for the muscle pair FCU/ECU, coherence showed a significantly higher value in the β band and a significantly lower value in the γ band inpost-stroke patients. These findings contribute to a better understanding of altered control mechanisms of hand muscles in post-stroke patients, which could be useful in the development of diagnostic and treatment strategies.

Keywords: Stroke; handgrip exercise; sEMG; wavelet coherence .

1. Introduction

Stroke is a leading cause of death and disabilities in many countries [1]. Nearly one-third of stroke survivors suffer persistent disabilities, primarily characterized by motor impairments [2]. Stroke survivors can experience various motor disorders such as abnomal muscle activation patterns [3], impairment of agonist recruitment and antagonist inhibition [4], disruption of interjoint in spastic hemiparesis [5], and muscle weakness [6]. These disorders result in poor performance during activities of daily life. Motor impairments are frequently assessed by using clinical scales such the Ashworth scale, Fugl-Meyer assessment, and Action Research Arm Test. These scales can only reflect individuals' global motor performance and may not be sensitive to subtle changes in motor function. It is well known that a fundamental feature of the musculoskeletal system is its redundancy and thus the mechanisms of controlling involved muscles to achieve specific motor tasks are an active research area. It has been suggested that during voluntary muscle contractions, there exist intermuscular couplings between synergistic muscles due to common corticospinal drives and that these couplings play an important role in the regulation of muscle activities and maintenance of neuromuscular performance [7]. Moreover, it have been found that intermuscular couplings are altered following a stroke [8-11]. This means that altered intermuscular couplings may be an important aspect of motor impairment in post-stroke patients.Reaearch studies have reached a broad consensus that intermuscular coupling can be assessed by coherence between surface electromyographic (sEMG) signals, which could reflect the common central to the muscles [12, 13]. EMG-EMG coherence in several frequency bands is linked to different neural processes [12, 13]. Coherence in the frequency band 0-5 Hz is associated with the common drive. Coherence in the alpha band (8-12 Hz) involves subcortical and spinal mechanisms, reflecting physiological tremor associated with postural control and involuntary contractions. Coherence in the beta frequency band (15-35 Hz) has been linked to voluntary isometric contractions and likely reflects descending corticospinal drive. Increased coherence in the beta band is associated with increased force production. Coherence in the gamma frequency band (35-60 Hz) has been associated with drives to muscles during strong tonic contractions and cognitive processes. EMG-EMG coherence has been used to investigate alterations of neuromuscular control in stroke survivors [8, 9, 14, 15]. Kisiel-Sajewicz and his colleagues. [9] investigated muscular co-activation between the anterior deltoid and triceps brachii during reaching movement in stroke patients and observed a lower EMG-EMG coherence in the frequency band 0-11 Hz compared to controls. Wang and his colleagues. [15] investigated the influence of muscle fatigue on the coupling bwtween the biceps brachii and triceps brachii in patients with post-stroke

spasticity during isometric elbow flexion. They observed significant increases in EMG-EMG coherence in the alpha and beta frequency bands in stroke patients during severe fatigue compared to minimal fatigue, whereas in healthy controls, no significant changes in coherence were observed. Another study by Yu and his colleagues. [8] compared the coupling between the biceps brachii and triceps brachii between post-stroke patients and healthy controls during elbow tracking tasks. The results showed that wavelet coherence between the sEMG signals in the alpha frequency band was lower in post-stroke patients than in healthy controls. Although these studies provided evidences that muscular couplings in post-stroke patients differ from that in healthy controls, it still remains unclear how the intermuscuar couplings are altered in post-stroke patients. The present study aims to investigate the influence of stroke on intermuscular couplings. Since the hand is one of the most complex musculoskeletal systems, it represents an ideal model for understanding the mechanisms of controlling muscle force coordination between synergistic muscles [13]. In this study, we focused on coherence between sEMG signals from three muscles, i.e., the flexor digitorum superficialis (FDS), flexor carpi ulnaris (FCU), and extensor carpi ulnaris (ECU), during dynamic handgrip exercise. These muscles represent finger flexors, wrist flexors, and wrist extensors, respectively. We hypothesized that alterations in EMG-EMG coherence in post-stroke patients depend on specific muscle pair and thus can be used to assess motor impairment.

2. Methods

2.1. Participants

Ten post-stroke patients with chronic hemiparesis and 10 healthy young aduts were recruited into this study. Their demographic data are listed in Table 1. All the healthy participants reported no musculoskeletal or neuromuscular impairments. For post-stroke patients, the inclusion criteria were 1) hemiplegia after an ischemic or hemorrhagic stroke; 2) the occurrence of stroke at least 6 months before participating the study; 3) score of Fugl-Meyer assessment of the upper limb lower than 30/66; 4) able to perform handgrip exercise; and 5) able to understand the instructions related to the experimental protocols. This study was approved by the Ethics Committee of Xi'an Peihua University. Informed consent was provided by each participants prior to any test.

2.2. Experimental protocols

The experiments were conducted in the Detection Technology Labrotory at Xi'an Peihuan University. Roomteperature was maintained at 24±2 °C. Prior to the tests, the participant was required to complete a demographic form and a medical history form. Then, a blood pressure monitor cuff was placed on the participant's *left arm* for measuring systolic blood pressure, diastolic blood pressure and heart rate while the participant was seated in a comfortable position. Next, the participant performed maximal voluntary contraction (MVC) of hand handgrip for 1-2 seconds. The post-stroke participants used their affected hands, while the healthy controls used their dominant hands. This procedure was repeated three times seperated by 1 minute. The highest force generated from the 3 trials was set as each participant's 100% MVC. After 10 min rest, the participant completed a handgrip exercise protocol, consisting of a 5 min baseline period and a 3 min exercise period during which the participant performed dynamic rhythmic handgrip exercise at 30% MVC. The sEMG

signals from FDS, FCU, and ECU were recorded at a sampling rate of 1 kHz using an electromyographic monitor (MP150, Biopac Systems Inc., Goleta, CA, USA) with bipolar electrodes [16]. Figure 1 shows typical sEMG signals from a post-stroke participant during baseline period and exercise period.

Table 1: Demographic data of the participants		
	Post-stroke	Control
Gender (male/female)	7/3	5/5
Age (years)	64.3±5.7	22.1±3.2
Height (m)	1.67±5.9	1.74 ± 6.8
Weight (kg)	63.4±5.8	65.8±7.2
Duration of stroke (months)	9.4±7.6	/
Score of Fugl-Meyer assessment of the affected limb	18±2.2	/

Data are represented as mean±standard deviation

for measuring systolic blood pressure, diastolic blood pressure and heart rate while the participant was seated in a comfortable position. Next, the participant performed maximal voluntary contraction (MVC) of hand handgrip for 1-2 seconds. The post-stroke participants used their affected hands, while the healthy controls used their dominant hands. This procedure was repeated three times seperated by 1 minute. The highest force generated from the 3 trials was set as each participant's 100% MVC. After 10 min rest, the participant completed a handgrip exercise protocol, consisting of a 5 min baseline period and a 3 min exercise period during which the participant performed dynamic rhythmic handgrip exercise at 30% MVC. The sEMG signals from FDS, FCU, and ECU were recorded at a sampling rate of 1 kHz using an electromyographic monitor (MP150, Biopac Systems Inc., Goleta, CA, USA) with bipolar electrodes [16]. Figure 1 shows typical sEMG signals from a post-stroke participant during baseline period and exercise period.

2.3. Data analysis

Traditionally, coherence between two signals is computed through Fourier transform. This metod is based on the assumption that the signals are stationary. For nonstationary signals such as sEMG signals, wavelet-based coherence should be employed. In the following, we will briefly discuss Fourier coherence and wavelet coherence.

2.3.1. Fourier coherence

Given two signals x(t) and y(t), let $S_{xx}(f)$ and $S_{yy}(f)$ be the auto spectra of x(t) and y(t), respectively,



Figure 1: Typical sEMG signals from (A) FDS, (B) FCU, and (C) ECU during the baseline period and exercise period

and $S_{xy}(f)$ be the cross-spectra, the coherence function is defined as

$$C_{xy}(f) = \frac{S_{xy}(f)}{\left[S_{xx}(f) \cdot S_{yy}(f)\right]^{1/2}}$$
(1)

Theoretically, the exact values of $C_{xy}(f)$ can only be obtained from infinite length signals. For two finite length signals x(t) and y(t), an intuitive estimation of $S_{xy}(f)$ is $\hat{S}_{xy}(f) = X(f) \cdot Y^*(f)$, where X(f) and Y(f) are the discrete Fourier cofficients of x(t) and y(t), respectively, and $Y^*(f)$ is the complex conjugate of Y(f).

The computation of Fourier coherence is based on the assumption that the signals are stationary. However, sEMG signals are non-stationary, i.e., their frequency properties change with time. To address this problem, wavelet coherence has been proposed as an alternative to Fourier coherence.

2.3.2. Wavelet coherence

Wavelet coherence (*WC*) is a measure of the relationship between two signals as a function of frequency and time. Unlike Fourier analysis, wavelet analysis is designed to analyze non-stationary signals. In wavelet analysis, a family of basis functions is created by dilating and translating a window function $\psi(u)$, called mother wavelet, in time

$$\psi_{s,t}(u) = \frac{1}{\sqrt{s}}\psi(\frac{u-t}{s}) \tag{2}$$

where s is scale and t is time. In this study, we adopted the Morlet wavelet

$$\psi(u) = \frac{1}{\sqrt[4]{\pi}} e^{i\omega_b u} e^{-u^2/2} \tag{3}$$

as the mother wavelet, where ω_0 and u are dimensionless frequency and dimensionless time, respectively. ω_0 characterizes the balance between time and frequency localization of $\psi(u)$. When choosing $\omega_0 = 6$, the Fourier period of $\psi(u)$ $\lambda = 1.03s$.

The continuous wavelet transform of a signal x(t) is defined as

$$W_x(s,t) = \int_{-\infty}^{+\infty} x(u)\psi_{s,t}^*(u)du$$
(4)

where * denotes the complex conjugate. Because $\psi_{s,t}(u)$ is localized in both time and frequency, wavelet transform of a signal is equivalent to applying a series of band-pass filters to the signal. Let $W_x(s,t)$ and $W_y(s,t)$ be the wavelet transforms of two signals x(t) and y(t), respectively, the cross-spectrum is given by

$$S_{xy}(s,t) = W_x(s,t)W_y^*(s,t)$$
(5)

where * indicates complex conjugate. The wavelet coherence of two signals is defined

as
$$WC(s,t) = \frac{|\langle S_{xy}(s,t)\rangle|}{[\langle |W_x(s,t)|\rangle \cdot \langle |W_y(s,t)|\rangle]^{1/2}}$$
(6)

where $\langle \cdot \rangle$ denotes smoothing along the scale axis and smoothing in time.

2.3.3. Computation of WC threshold

Because even for completely independent signals, WC can be non-zero, it is necessary to estimate a threshold to determine whether exists genuine coherence between the signals. In this study, we estimated WC threshold using surrogate data generated by autoregression (AR) model. For each pair of sEMG signals, 100 pairs of surrogates were generated. At each time and frequency, the 95th percentile of the WC values of surrogates was set as the threshold.

2.3.4. Application of WC to experimental data

To investigate the influence of stroke on intermuscular coupling of the hand, we computed coherence for each pair of the sEMG signals from FDS, FCU, and ECU. Then, 100 pairs of surrogate time series were generated using AR model. The threshold level was taken as the 95th percentile of the WC values of surrogates. The coherence was quantified in four frequency bands: 0-5 Hz, 8-12 Hz (α), 15-35 Hz (β), and 35-60 Hz (γ). As shown in Figure 2, within each frequency band, the coherence was quantified by the area under the time-averaged coherence of the original data $C_{WC}^{(o)}(f)$ and above the time-averaged threshold obtained from surrogates $C_{\phi}^{(s)}(f)$. If $WC^{(o)}$ is lower than $WC^{(s)}$ for all frequencies in the frequency band, A_{f_L,f_H} was defined to be zero.

2.3.5. Statistical analysis

The differences in $A_{[f_L, f_H]}$ between the baseline and handgrip exercise period was examined using the Wilcoxon signed rank test, while the differences in $A_{[f_L, f_H]}$ between post-stroke patients and healthy controls was examined using the Wilcoxon signed rank sum test. These analyses were performed using the SPSS software (Version 26, Chicago, IL, USA).



Figure 2: Ilustration of the index of WC

3. Results

Figure 3 shows the results of coherence between sEMG signals form FDS and FCU. Either for post-stroke patients or healthy controls, coherence in four frequency bands significantly increased during the handgrip exercise period compared to the baseline period. During the exercise period, coherence in α frequency band (A_{α}) was significantly higher in post-stroke patients than in healthy controls. On the contrary, coherence in γ frequency band (A_{γ}) was significantly lower in post-stroke patients than in healthy controls

Figure 4 shows the results of coherence between sEMG signals form FDS and ECU. Coherence in the frequency band 0-5 Hz (A_{0-5Hz}) significantly increased during the exercise period compared to baseline period in both groups (Figure 4A), while coherence in γ band significantly increased from the baseline period to exercise period only only in healthy controls (Figure 4D). For coherence in α and β bands, no significant changes were observed in both groups (Figure 4B and 4C).

Figure 5 shows the results of coherence between sEMG signals form FCU and ECU. In healthy controls, coherence in all the frequency bands significantly increased from the baseline period to exercise period, while in post-stroke patients, coherence in γ band did not show a significant change (Figure 5D). During the exercise period, coherence was significantly higher in β band (Figure 5C) but significantly lower (Figure 4D) in γ band in post-stroke patients compared to healthy controls.



Figure 3: Comparison of coherence between sEMG signals from FDS and FCU in 0-5 Hz (A), α band (B), β band (C), γ band (D) between the baseline period and handgrip period and between two groups. The symbol * indicates p<0.05, ** p<10⁻², and *** indicates p<10⁻³ (Wilcoxon signed rank test); + indicates p<0.05 (Wilcoxon signed rank sum test)



Figure 4: Comparison of coherence between sEMG signals from FDS and ECU in 0-5 Hz (A), α band (B), β band (C), γ band (D) between the baseline period and handgrip period and between two groups. The symbol ** indicates p<10⁻², and *** indicates p<10⁻³ (Wilcoxon signed rank test)

4. Discussion

The main finding of this study is that changes in EMG-EMG coherence caused by handgrip exercise in poststroke patients differed from that in healthy controls and that these changes were muscle pair specific and particularly frequency band specific. This finding suggested that EMG-EMG coherence could provide useful information for assessing motor impairment in post-stroke patients.



Figure 5: Comparison of coherence between sEMG signals from FCU and ECU in 0-5 Hz (A), α band (B), β band (C), γ band (D) between the baseline period and handgrip period and between two groups. The symbol * indicates p<0.05, ** p<10⁻², and *** indicates p<10⁻³ (Wilcoxon signed rank test); + indicates p<0.05 (Wilcoxon signed rank sum test)

Our results showed that for all the muscle pairs, handgrip exercise leaded to a significant increase in EMG-EMG coherence in 0-5 Hz in both groups but the increase was less significant in post-stroke patients (Figure 3A, 4A, and 5A). EMG-EMG coherence in this frequency band is thought to represent the common drive [12]. This observation was somewhat consist with that of the study by Kisiel-Sajewicz and his colleagues. [9], who observed a significantly lower coherence in the frequency interval 0-3.9 Hz between sEMG signals from the anterior deltoid and triceps brachii during reaching movement in stroke patients compared to healthy controls. Our results suggested that reduced EMG-EMG coherence in 0-5 Hz might be due to stroke-induced damage to the corticospinal pathways.

EMG-EMG coherence in the α frequency band is thought to be associated with the control of joint stability and be of subcortical origin and mediated by spinal sources [13]. Our results showed that changes in EMG-EMG coherence in α frequency band induced by handgrip exercise were muscle pair specific. For the muscle pairs FDS/FCU and FCU/ECU, the coherence significantly increased in both groups, especially in post-stroke patients (Figure 3B and 5B), whereas for the muscle pair FDS/ECU, no significant change was observed (Figure 4B). Since FDS and FCU act together to flex the wrist joint, while FCU and ECU have antagonistic actions, whereas FDS and ECU are not directly antagonistic or synergistic, our results suggested that during handgrip exercise, the muscle pairs FDS/FCU and FCU/ECU of post-stroke patients need to make much effort to stabilize the wrist joint compared to healthy controls. On the other hand, during handgrip exercise, EMG-EMG coherence in the α band for the muscle pair FDS/FCU was significant higher in post-stroke patients than in healthy controls (Figure 3B). This observation also suggested a higher degree of co-contraction of FDS and FCU in post-stroke patients. Additionally, because muscle fatigue can result in increased coherence in the α and β frequency bands [15], the higher value of coherence in the α band in post-stroke patients (Figure 3B) might indicate more severe muscle fatigue during handgrip exercise.

EMG-EMG coherence in the β frequency band has been linked to the regulation of muscle force coordination and muscle fatigue [15]. Our results showed that for the muscle pairs FDS/FCU and FCU/ECU, coherence in the β frequency band significantly increased during handgrip exercise in both groups, especially in post-stroke patients (Figure 3C and 5C). In particular, for the muscle pair FCU/ECU, coherence in the β frequency band was significantly higher in post-stroke patients than in healthy controls (Figure 5C). These results were roughly consist with those reported by Wang and his colleagues. [15]. They showed that when post-stroke patients performing a fatiguing isometric elbow flexion, coherence between sEMG signals from the biceps brachii and triceps brachii muscles in the β frequency band significantly increased due to muscle fatigue, whereas in healthy controls, such a phenomenon was not observed. Therefore, our results suggested that post-stroke patients made more effort in the regulation of muscle force coordination and/or exhibited more severe muscle fatigue during handgrip exercise.

Our results also showed that for the muscle pairs FDS/FCU and FCU/ECU, EMG-EMG coherence in the γ frequency band significantly increased during handgrip exercise in both groups (Figure 3D and 5D). This observation is consist with the suggestion that coherence in this frequency band is associated with drives to muscles during strong tonic contractions [15]. Furthermore, we observed a less significant increase in post-stroke patients. This observation might support the suggestion that coherence in the γ frequency band may reflect the implication of cognitive processes such as focused attention.

This study has two limitations. First, the two groups were not matched in age and gender. However, the main purpose of this study was to investigate the influence of stroke on intermuscular coupling. Our results showed that changes in EMG-EMG coherence caused by handgrip exercise in post-stroke patients differed from that in healthy controls. Second, we only considered EMG-EMG coherence between three muscles, i.e., FDS, FCU, and ECU, while handgrip exercise involves other muscles such as extensor carpi radialis. However, we successfully revealed that changes in EMG-EMG coherence were muscle pair specific and particularly frequency band specific. Future studies may investigate activities of the other muscles during handgrip exercise.

5. Conclusion

This study investigates the influence of stroke on functional coupling between three muscles of hand using wavelet coherence. The resuts showed that changes in EMG-EMG coherence caused by handgrip exercise in post-stroke patients differed from that in healthy controls and that these changes were muscle pair specific and particularly frequency band specific. These findings contribute to a better understanding of altered control mechanisms of hand muscles in post-stroke patients, which could be useful in the development of diagnostic and treatment strategies.

References

- S.S. Virani, A. Alonso, E. J. Benjamin, M. S. Bittencourt, C. W. Callaway, A. P. Carson, A. M. Chamberlain, A. R. Chang, S. Cheng, F. N. Delling, L. Djousse, M. S. V. Elkind, J. F. Ferguson, M. Fornage, S. S. Khan, B. M. Kissela, K. L. Knutson, T. W. Kwan, D. T. Lackland, T. T. Lewis, J. H. Lichtman, C. T. Longenecker, M. S. Loop, P. L. Lutsey, S. S. Martin, K. Matsushita, A. E. Moran, M. E. Mussolino, A. M. Perak, W. D. Rosamond, G. A. Roth, U. K. A. Sampson, G. M. Satou, E. B. Schroeder, S. H. Shah, C. M. Shay, N. L. Spartano, A. Stokes, D. L. Tirschwell, L. B. VanWagner, C. W. Tsao. "Heart Disease and Stroke Statistics-2020 Udate: A Report From the American Heart Association". *Circulation*, vol. 141, pp. e139-e596, 2020.
- [2] R.S. Calabrò, G. Sorrentino, A. Cassio, D. Mazzoli, E. Andrenelli, E. Bizzarini, I. Campanini, S. M. Carmignano, S. Cerulli, C. Chisari, V. Colombo, S. Dalise, C. Fundarò, V. Gazzotti, D. Mazzoleni, M. Mazzucchelli, C. Melegari, A. Merlo, G. Stampacchia, P. Boldrini, S. Mazzoleni, F. Posteraro, P. Benanti, E. Castelli, F. Draicchio, V. Falabella, S. Galeri, F. Gimigliano, M. Grigioni, S. Mazzon, F. Molteni, G. Morone, M. Petrarca, A. Picelli, M. Senatore, G. Turchetti, D. Bonaiuti. "Robotic-assisted gait rehabilitation following stroke: a systematic review of current guidelines and practical clinical recommendations". *Eur J Phys Rehabil Med*, vol. 57, pp. 460-471, 2021.
- [3] J.P. Dewald, P. S. Pope, J. D. Given, T. S. Buchanan, W. Z. Rymer. "Abnormal muscle coactivation patterns during isometric torque generation at the elbow and shoulder in hemiparetic subjects". *Brain*, vol. 118(Pt 2), pp. 495-510, 1995.
- [4] M. C. Hammond, S. S. Fitts, G. H. Kraft, P. B. Nutter, M. J. Trotter, L. M. Robinson. "Co-contraction in the hemiparetic forearm: quantitative EMG evaluation". *Arch Phys Med Rehabil*, vol. 69, pp. 348-51, 1988.

- [5] M.F. Levin. "Interjoint coordination during pointing movements is disrupted in spastic hemiparesis". *Brain*, vol. 119 (Pt 1), pp. 281-93, 1996.
- [6] C. Mercier, D.Bourbonnais. "Relative shoulder flexor and handgrip strength is related to upper limb function after stroke". *Clin Rehabil*, vol. 18, pp. 215-221, 2004.
- [7] S.F. Farmer, J. Gibbs, D. M. Halliday, L. M. Harrison, L. M. James, M. J. Mayston, J. A. Stephens. "Changes in EMG coherence between long and short thumb abductor muscles during human development". J Physiol, vol. 579(Pt 2), pp. 389-402, 2007.
- [8] H. Yu, W. Xu, Y. Zhuang, K. Tong, R. Song. "Wavelet coherence analysis of muscle coupling during reaching movement in stroke". *Comput Biol Med*, vol. 131, pp. 104263, 2021.
- [9] K. Kisiel-Sajewicz, Y. Fang, K. Hrovat, G. H. Yue, V. Siemionow, C. K. Sun, A. Jaskólska, A. Jaskólski, V. Sahgal, J. J. Daly. "Weakening of synergist muscle coupling during reaching movement in stroke patients". Neurorehabil Neural Repair, vol. 25, pp. 359-68, 2011.
- [10] J. Roh, W. Z. Rymer, E. J. Perreault, S. B. Yoo, R. F. Beer. "Alterations in upper limb muscle synergy structure in chronic stroke survivors". *J Neurophysiol*, vol. 109, pp. 768-781, 2013.
- [11] H. Liu, Y. Gao, W. Huang, R. Li, M. Houston, J. S. Benoit, J. Roh, Y. Zhang. "Inter-muscular coherence and functional coordination in the human upper extremity after stroke". *Math Biosci Eng*, vol. 19, pp. 4506-4525, 2022.
- [12] M.E. Héroux, S.C. Gandevia. "Human muscle fatigue, eccentric damage and coherence in the EMG". Acta Physiol (Oxf), vol. 208, pp. 294-295, 2013.
- [13] C. Charissou, D. Amarantini, R. Baurès, E. Berton, L. Vigouroux. "Effects of hand configuration on muscle force coordination, co-contraction and concomitant intermuscular coupling during maximal isometric flexion of the fingers". *Eur J Appl Physiol*, vol. 117, pp. 2309-2320, 2017.
- [14] N. Lodha, Y. T. Chen, T. E. McGuirk, E. J. Fox, S. A. Kautz, E. A. Christou, D. J. Clark. "EMG synchrony to assess impaired corticomotor control of locomotion after stroke". J Electromyogr Kinesiol, vol. 37, pp. 35-40, 2017.
- [15] L.J. Wang, X. M. Yu, Q. N. Shao, C. Wang, H. Yang, S. J. Huang, W. X. Niu. "Muscle Fatigue Enhance Beta Band EMG-EMG Coupling of Antagonistic Muscles in Patients With Post-stroke Spasticity". *Front Bioeng Biotechnol*, vol. 8, pp. 1007, 2020.