TEMPORAL RECRUITMENT OF FORELIMB PROXIMAL AND DISTAL MUSCLES DURING REACHING AND GRASPING

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Abstract

Reaching and grasping is a voluntary movement based on the stereotyped recruitment from proximal to distal muscles of the forelimb in order to grasp an object. It is the unique movement behavioral model which allows the study of voluntary motor control and the underlaying connectome controlling skilled hand movements. Rodents models are very similar to the humans' ones. Electromyographic (EMG) signals of successful attempts from a healthy rat have been analyzed. Algorithms have been designed and developed in order to characterize the reaching and grasping movement in terms of temporal recruitment, synchronization along the cycle, muscle activity pattern repeatability, muscle energy and center of gravity. This study claims to offer useful tools that collaborate on the better understanding of the control of neural network extending from the cortex to the spinal cord.

1. Introduction

Manual dexterity is indispensable for carrying out the vast majority of our normal daily activities, ranging from object manipulation to nonverbal communication. The central system neurons are unable to regenerate and the damage produced persists along the patient's lifestyle. We need to understand the spinal and cortical networks controlling hand function to further develop reliable therapies to promote plasticity and recovery. Whereas hand function is being extensively studied in non-human primates [1], much less is known in rodents. We will first need to develop behavioral and electrophysiological models to characterize the network architecture and function.

The hypothesis is that the stereotyped sequence of movements observed during reaching and grasping are under control of neuronal network extending from the cortex to the spinal cord. Thus, electrophysiological recordings from proximal and distal muscles of the preferred limb used to reach and grasp will show the synchronized temporal recruitment of these muscles. It is expected most proximal muscles, i.e the Deltoid and the Biceps are active during the whole reaching and grasping cycle, whereas the most distal muscles controlling extrinsic hand muscles are activated during grasping.

The aim of this work is to design and implement algorithms to obtain, from a large data set of raw reaching and grasping EMG recordings of rats, fast, precise and quantitative information to study in detail the forelimb proximal and distal muscles activity, temporal recruitment and synchronization.

2. Material & Methods

2.1. Data Acquisition

A group of animals were trained to reach and grasp. The preferred paw to reach and grasp was identified and wire electrode were implanted intramuscular in selected muscles (Figure 1). Each animal was placed individually inside a plastic cage, with an opening to a platform, in which a chocolate pellet was placed. Simultaneously, the EMG wire electrodes were connected through a headplug and cable to an amplifier and data acquisition system (sampling frequency 10 kHz). Simultaneously, while the animals were reaching and grasping EMG and synchronized video recording were obtained (extensively described in Alam et al., 2017 [2].

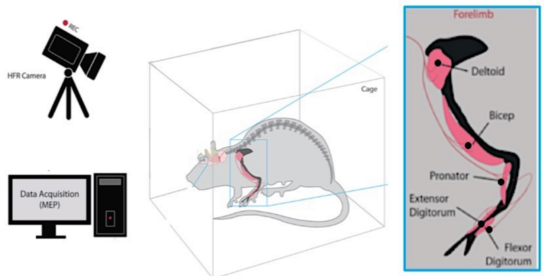

Figure 1. *(A) Rat EMG recording setting up. (B) Sequence of forelimb movements performed by a rat during reaching and grasping a food pellet.*

2.2. Onset and offset detection

From the entire EMG recording session, the segments in which the animals successfully reached and grasped were selected. This selection was done manually, using the video recording as a guide. For that reason, extra EMG information previous and after the movement was maintained (Figure 2). We have first designed an automatic onset and offset detection algorithm to define the start and end point of the muscles activation involved in this reaching and grasping movement.

Two defined threshold methods have been proposed. The first one consists to use a multiplicative factor of the standard deviation (SD) of EMG baseline [3]. The onset-offset time-points were defined as the values in which the muscle activity is over the mean value plus a factor of the SD of the baseline; commonly used x2 or x3. The second one uses each signal maximal peak of activity as reference; the threshold is defined as a percentage of this maximal value, ranging from 5 to 25 percent of each muscle maximum peak value.

In order to avoid local maximums, it has been introduced a refining step that evaluates the mean of the following samples to confirm if the muscle activity has started.

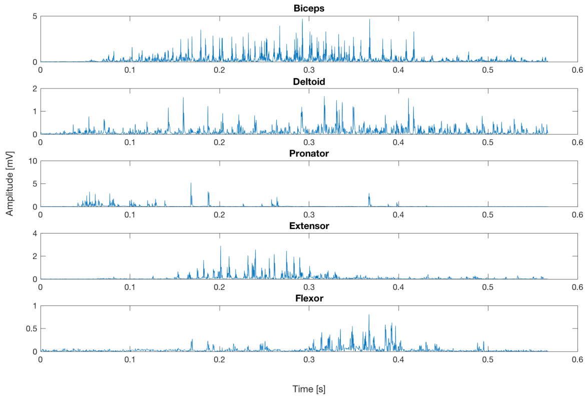

Figure 2. *Raw EMG signals of the five muscles involved on the reaching and grasping.*

The results of both methods have been compared with those obtained by manual annotations done by an expert, obtained under blind conditions. For each signal, the difference, in seconds, between the values of the onset and offset of both methods and the reference value were calculated. Afterwards, the mean and standard deviation of these individual differences were calculated for each muscle activity. The lowest the difference obtained in seconds with respect to the reference values, the greater the quality guarantee of the detection method.

2.3. Data normalization

In order to compare the muscle activity patterns, time normalization is needed to bring all signal to an equivalent duration with the same samples number. The signal with the greater duration between its onset and offset is taken as the reference.

The reference duration is the maximal number of samples comprehended between onset and offset of all the signals, multiplied by original sampling period. This duration will be fixed, and the new sampling frequency for each attempt is calculated dividing it by the number of sample between each onset-offset instant of each attempt. The ratio of resampling is calculated as the division between the new desired frequency and the original one, and if it is greater than 1, the attempt signal is interpolated to achieve the same duration than the reference one.

The amplitude normalization has been based on the peak muscle activity of each attempt and for each muscle during the reaching and grasping movement [4]. Taking this value as the reference one for each muscle and attempt, all the values have been rescaled from 0 to 1.

2.4. Muscle variability

Amplitude and time normalized signals were transformed as the percentage of the total muscle activity, ranging from 0 to 100. Normalized signals of the specific muscle activity were studied to report to compare activity and energy between attempts.

Due to the burst distribution of the signals, different envelopes were tested. These envelopes were obtained as an interpolation of the signal between a finite number of samples. The greater the number of samples used the greater the smoothing effect.

In order to obtain a visual activity pattern during the total activity of each muscle, we calculated an envelope over the local maximums. High number of samples were selected for smoothing the signal until that level. The mean pattern and SD was calculated, for the five muscles involved individually. This method reports the variability of the activation pattern. The greater the standard deviation in determined areas, the lowest the synchronicity between attempts and the stability of the pattern.

A most adjusted envelope of the normalized signal, with much less number of samples used between the interpolation steps, was used to calculate the energy of each signal, as the numerical integral under the curve. It has been also calculated the mean and the standard deviation of this accumulative normalized energy for each muscle. An important parameter is the center of gravity, defined as the point in which the muscle achieves the 50% value of its total energy.

2.5. Muscles temporal synchronization

The onset of the reaching and grasping cycle was defined by the onset of the biceps activity, because it is considered that the movement starts when the animal lifted the paw. The offset was defined as the offset of the digit flexor, when the animal gripped the pellet and took it to the mouth. The cycle absolute duration comprehends the time during the onset and offset, which has been transferred to the five muscles involve to have a unique time duration. Once the time domain was transformed into percentage, the latency between the onset of the movement and the onset of each muscle, in percentage of the cycle, was calculated. These values offer a sequential distribution perspective of the activation of each muscle and synchronization between them.

3. Results

3.1. Onset and offset methods comparison

For each signal the difference in seconds between the values of the onset and offset results was calculated with both methods and the referenced value.

The results obtained by multiplying the SD of a fix baseline x2, are shown in table 1. Other higher multiplicative factors were also tested and are not shown. The second column shows for the onset and for the offset, the percentage factor (in brackets) of the max peak, which with we obtained the lowest mean ± SD difference to the reference values.

We conclude that the best threshold method to calculate the onset and the offset is based on the percentage of the max peak analysis. In addition, we have shown that each individual muscle, both the onset and offset, will have a specific percentage factor. Therefore, the algorithm is very adapted to the needs of each signal type.

		MEAN+2*SD	%AXPEAK
BICEPS	ON	48.3 ± 77.7	18.2 ± 56.2 (5%)
	OFF	157.8 ± 115.7	4.7 ± 11.2 (25%)
DELTOID	ON	23.5 ± 24.6	3.2 ± 5.1 (5%)
	OFF	125.3 ± 190.5	4.8 ± 7.1 (10%)
PRONATOR	ON	36.7 ± 27.1	5.6 ± 17 (5%)
	OFF	296.4 ± 137.5	66.9 ± 70.9 (25%)
EXTENSOR	ON	119.8 ± 73.3	9.4 ± 13.5 (10%)
	OFF	168.1 ± 113.5	44.3 ± 34 (15%)
FLEXOR	ON	171.7 ± 95.2	16.1 ± 23.3 (15%)
	OFF	39.6 ± 48.6	11.7 ± 43.5 (15%)

Table 1. *Results of the methodology employed to calculate the onset and the offset; based on SD analysis (left column) and percentage of the max peak (right column). The values indicate the difference, in miliseconds, between each instant obtained with both methods and the reference value, which was manually annotated.*

3.2. Muscle variability

We identified two envelopes: 1) the first is aimed to present a smooth envelop which surfs the local max peaks, offering an easy visual representation of the muscle activity pattern over time; 2) a second envelop was used to calculate the energy beneath the curve. For this reason, an envelope which reliably adjusted to the signal morphology, avoiding excess information due to the interpolation.

The upper row in figure 3 shows the mean ± SD pattern of muscle activity, using the smoothest envelope. Note the muscle's behavior repeatability between attempts is higher in the areas with the low SD. The lower panel of figure 3 shows the normalized accumulative muscle energy using the most adjusted envelope. It is another indicator of the level of activity of that muscle along its total activation time.

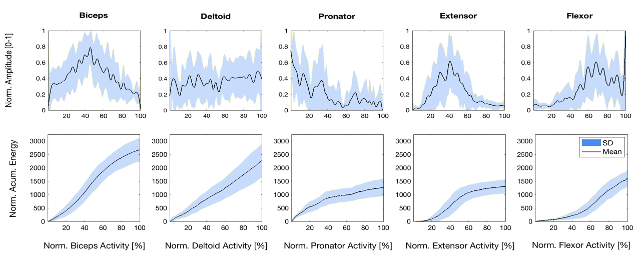

Figure 3. *Muscle activity patterns and their accumulative energy curves along their total local activation in percentage.*

The center of gravity of each muscle was calculated as the mid value of their total accumulated energy (table 2). It gives an idea on the dispersion and density of the individual muscle activity.

	Biceps	Deltoid	Pronator	Extensor	Flexor
Mean±SD (%)	46 ± 8	55 ± 11	26 ± 11	42 ± 9	69 ± 9

Table 2. *Localization of the center of gravity at the local muscle activity in percentage.*

Figure 4 shows the efficacy of the methodology designed and employed to calculate the onset and offset (locally and globally), and the extrapolation of the center of gravity (locally) to the raw data.

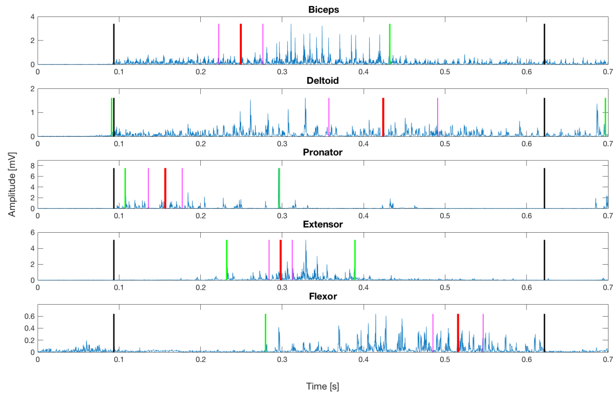

Figure 4. *Raw data from a single reaching and grasping movement. Green: local onset and offset temporal marks. Black: onset and offset temporal marks of the reaching and grasping cycle. These temporal marks have been calculated after applying to each muscle the percentage of the maximum peak, which calculated mean results in the smallest difference with the reference values (see Table 1). The center of gravity percentage (Table 2) has been extrapolated to the local muscle activity on the raw data. Magenta: position of the center of gravity. Red: SD of the center of gravity.*

3.3. Muscles temporal synchronization

We have calculated for each attempt the latency between the onset of the biceps, equivalent to the onset of the movement, and the onset of the individual muscle, and presented as the percentage of the total reaching and grasping cycle. The digit Extensor and flexor muscles shows a clear sequential activation following the most proximal Deltoid, biceps and pronator muscles.

	Deltoid	Pronator	Extensor	Flexor
Mean ± SD (%)	-4 ± 3	-3 ± 5	25 ± 10	38 ± 11

Table 3. *The Latency of the onset for each muscle, presented as the percentage within the total cycle. Note, that in some muscles, the mean may be negative, indicating that the onset of that muscle may precede the beginning of the biceps activity.*

4. Discussion

It has been designed and implemented novel MATLAB algorithms to analysis a large data set of raw EMG data obtained from the forelimbs muscles of a rat while was performing reaching and grasping. So far, the results have evidenced a clear spatial-temporal pattern of muscle recruitment, which corroborates the original hypothesis. It further, opens the development of a wider set of mathematical tools to analyze in depth the function of the central nervous system controlling skilled hand function.

The first objective has been to determine the onset and offset of the muscle activity for each individual muscle at each individual attempt. Two threshold methods have been tested: The first method defines the threshold as the mean of the baseline plus a multiplicative factor of the SD of a fix baseline for all the signals. The second method uses, for each attempt, the maximum amplitude peak multiplied by a % factor to define the threshold.

Due to the manual cutting the fix baseline selected usually takes part of the muscle activity. If it takes a part of the signal with a large range of values and it is multiplied by a factor, it is very usual that the algorithm does not find a value that overcome the threshold and no value is reported. In the case the baseline selected no contains muscles activity the values are very close to zero and it is needed very high SD multiplication factor to obtain values near the reference one. Both problems report error of the algorithm and it is not possible to calculate at the same time for all the attempts for many possibilities. For that reason, only one factor value is tested (as shown in table 1).

On the other hand, the second approach uses each maximum attempt amplitude peak, and defines the threshold as a proportion of it. In this case, it does not dependent on a fix baseline value nor on the manual cutting of the signals. Both methods have been compared against the reference markers, and the method based on a proportion of the amplitude is the one with closest results to the manual annotated values. This method has been used for the rest of the study.

Due to the burst distribution of the EMG signal, envelopes with more or less smoothing grave have been used to obtained patterns and study the muscle variability. Clear pattern is observable during the total activity of each muscle. Less variability is traduced in more similarity between signals and more determinist behavior although the stochastic nature of the signals. The different muscle activity patterns are also reflected on their accumulative normalized energy behavior and the center of gravity.

4.1. Limitations

Although 17 attempts have been analyzed, they all belong to the same animal and were recorded in separate days. Unfortunately, due to this low number, the conclusions must be taken with caution and interpreted as preliminary. Nevertheless, the consistency of the patterns obtained, and the visual examination of recording from other animals, suggest a wider analysis will reach the same conclusions.

The data recording procedure has shown several signs, which has difficulted the EMG analysis, especially for identifying the onset and off set data points. These should be taken in account when future electromyography laboratories are design. First, the visual examination of the EMG raw signals to identify the onset and off set data points was difficult. On one hand, the use of low video frame recording (30Hz) limits the synchronicity between the forelimb movement and EMG data. In addition, the lack of kinematical markers further unable the precise correlation between the forelimb articulation's movement, due to specific muscle activation, and the EMG data.

4.2. Future directions

It is imperative to increase the number of animals' analysis. Measuring the inter-individual variability will be necessary to accept the conclusion and the validity of the tools used.

It will be necessary to analyze those failed attempts and to correlate the differences in the EMG activity pattern and the behavioral mistake with the healthy. The differences, if any, will strongly evidence the fine relationship between muscles activity. The EMG of animals with selective injuries to the brain or the spinal cord will give precious information on the role of the brain to spinal pathways controlling arm and hand function, and the putative hierarchical role between the different muscles on manual dexterity. Within the signal analysis, further explorations are needed on the design of activity heat maps to illustrate the results obtained. The next step is the frequential study, that can give us relevant information about the MUAPs type recruitment and on the nature of the spinal networks that are active during the performance of this motor task.

5. Conclusion

In this study, mathematical algorithms have been developed in MATLAB environment to study in detail raw EMG data from a healthy animal while performing voluntarily a fine motor task. The analysis has focused firstly on the definition of the onset and offset of each muscle to normalize their activity during the reaching and grasping cycle. The activity pattern has allowed us to evaluate the muscles repeatability. The accumulative energy has been also calculated for each muscle along the cycle, as well as the center of gravity. By comparing each muscle center of gravity, we can conclude the temporal and synchronized recruitment of the distal muscles for efficiently reaching and grasping a pellet. The methodology tested opens a new venue to analyze forelimb EMG data in rodents and to study the brain and spinal cord function in heath and disease.

6. References

[1] B. Alstermark and T. Isa, 'Circuits for Skilled Reaching and Grasping', *Annu. Rev. Neurosci.*, vol. 35, no. 1, pp. 559–578, Jul. 2012.

[2] M. Alam *et al.*, 'Electrical neuromodulation of the cervical spinal cord facilitates forelimb skilled function recovery in spinal cord injured rats', 2017.

[3] A. S. Lee, J. Cholewicki, and N. P. Reeves, 'The effect of background muscle activity on computerized detection of sEMG onset and offset.', *J. Biomech.*, vol. 40, no. 15, pp. 3521–6, 2007.

[4] M. Halaki and K. Gi, 'Normalization of EMG Signals: To Normalize or Not to Normalize and What to Normalize to?', *Comput. Intell. Electromyogr. Anal. - A Perspect. Curr. Appl. Futur. Challenges*, 2012.