OS10- Assessment of Motor Status

Voluntary and Reflex Muscle Synergies in Upper Limbs

Tytus Wojtara, Fady Alnajjar, Shingo Shimoda, and Hidenori Kimura

RIKEN, Japan
wojtara@brain.riken.jp

Abstract. It is known that the human muscles can be controlled both intentionally and by automatic responses. However how exactly the neural signals received by the muscles are produced is still unknown. One of the concepts created to answer this question are the muscle synergies. This concept however, doesn't take into account whether the neural signals are of voluntary or involuntary origin. Most researchers apply this concept to analyze exclusively automatic responses or exclusively voluntary movements or both without distinguishing between them. We propose an extended synergy model that explicitly accounts for both voluntary and involuntary neural signals and try to verify it experimentally. We examine reaching movements with and without constraints that provoke automatic responses. The general goal of this research is the creation of a measure of recovery level in upper limb rehabilitation after brain stroke, as well as, a rehabilitation assisting device. We introduce the synergy stability index and with experiments we show that the synergy stability is lower for movements with disturbance that provoke an involuntary movement.

1 Introduction

The term muscle synergy describes a group of muscles that work together. Different ways of grouping muscles into synergies, as well as a good background about muscle synergies can be found in the literature [1].

In our work the synergies were calculated from the EMG experimental data and the factorization method used, was the non-negative matrix factorization (NMF) based on [2].

Muscles can be moved voluntarily or by automatic responses. Some researchers focus on voluntary movements such as walking, cycling or reaching movements of upper limbs [3], while others investigate automatic postural responses.

The neuronal signals that the muscles receive, originate in different places, the cerebrum, the cerebellum and the spine. In this paper we introduce a hierarchical synergy structure that distinguishes between voluntary and involuntary synergies.

While the synergies are regarded as constant by many researchers, we have been focused on its variability. We introduce synergy stability index (SSI) and our

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preliminary experiments show that voluntary movements with disturbance have a lower SSI in comparison with movements without disturbance. In our previous study [4] we observed that persons with good balance showed same synergies at every experimental trial (high SSI) while persons with bad balance showed different synergies (low SSI).

2 Material and Methods

To assess the quality of a movement we introduce *synergy stability index* (SSI), a quantitative index based on synergy calculations.

The rows of the synergy matrix W are the synergy vectors. The vectors were first normalized separately so that the sum of the elements of each vector was equal to one.

Next, we calculate the correlation coefficients for one synergy from several trials, for each pair of experimental trials. Next, the mean of all correlation coefficients was calculated.

Finally, the total correlation coefficient, that we called *synergy stability index* (SSI), is the mean of correlation coefficients for each synergy.

Generally, the SSI can be written as

$$SSI = \frac{1}{k}\sum_{i=1}^{k}\left[\frac{2}{p\,(p-1)}\sum_{j=1}^{p}\sum_{u=1,u\neq j}^{p} r\,(\hat{w}_{i,j},\hat{w}_{i,u})\right] \tag{1}$$

where p is the number of trials, k is the number of synergies and $\hat{w}_{i,u}$ and $\hat{w}_{i,j}$ are the i-th normalized synergy vectors of the u-th and j-th trial respectively. The number of synergies was decided by calculating to what extent the resulting matrices W and C can reproduce the original data. Pearson's correlation coefficient r was used to calculate SSI. It is defined as

$$r\,(x,y) = \frac{\sum_{j=1}^{m}(x_j-\bar{x})\,(y_j-\bar{y})}{mS_xS_y} \tag{2}$$

where x and y are two vectors to compare. $\bar{x}$ and $\bar{y}$ are their mean values, S_x and S_y are their standard deviations while m is the number of samples.

We regard resulting SSI as a quantitative measure of the arm movement and we used it to compare experimental data of reaching movements with and without disturbance.

2.1 Hierarchical Synergy

Synergies are usually calculated from processed EMG data and factorized into the synergy matrix W, the neural command matrix C and the error matrix E as in Fig. 3.

$$X = WC + E \tag{3}$$

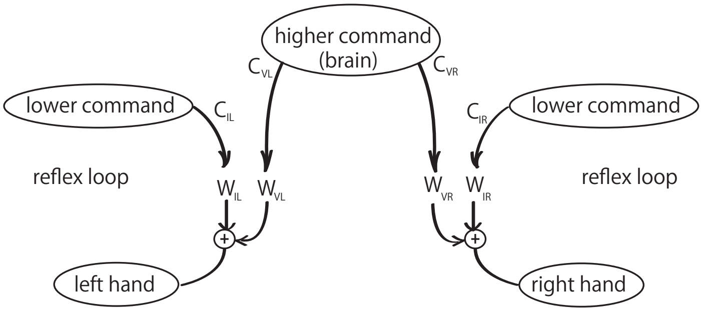

Fig. 1 Hierarchy of Synergy

We propose a hierarchical synergy structure that distinguished between voluntary and involuntary synergies, as illustrated in Fig. 1 and expressed in Eq. 4.

$$X = W_I C_I + W_V C_V + E \tag{4}$$

Here W_I and C_I denote the involuntary synergy matrix and neural command matrix, respectively, while W_V and C_V the voluntary synergy matrix and neural command matrix, respectively. During a purely voluntary movement the term with the indexes I can be neglected and during a purely involuntary movement the term with the indexes V can be neglected.

2.2 Experiments

Experiments were carried out to assess the differences between reaching arm movements with and without disturbance. The differences were expressed with the SSI. The subject was seated on a chair and using only the right hand, holding the knob of the manipulandum and pushing it from a position directly in front of him in a strait anterio-posterior line away from him as shown in Fig. 2. Ten trials for each experiment type were performend by one subject.

In the no-disturbance experiments the manipulandum didn't produce any significant resistance. During the disturbance experiments a sudden lateral disturbance was introduced. A disturbance of 9N into the negative y-direction was exerted on the subject, as long as, the knob was inside the disturbance zone shown in Fig. 3. The place and strength, direction or even the existence of the disturbance were not informed to the subject. The subject was instructed to move the knob from its original position 400mm towards the target on a possibly strait line within about one second. Muscle activity of the following muscles was recorded: brachialis, biceps, deltoid, triceps, superior trapezuis, infraspinatus, teres major and pectorialis. The 1kHz sampled EMG data were high-pass filtered with 30Hz, rectified using RMS and smoothed using moving average with sinus shaped window of length 10 samples. We used the manipulandum with the product name Delta3 from the company Force Dimension with a workspace of diameter 400mm and hight 260mm.

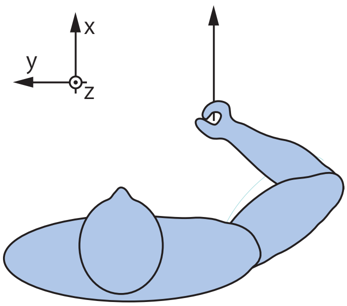

Fig. 2 Top view of a subject carrying out reaching movement

2.3 Results

The experiments without disturbance as shown in Fig. 3 (left) had a SSI of 0.5020 and the experiments with disturbance (right) had an SSI of 0.3365.

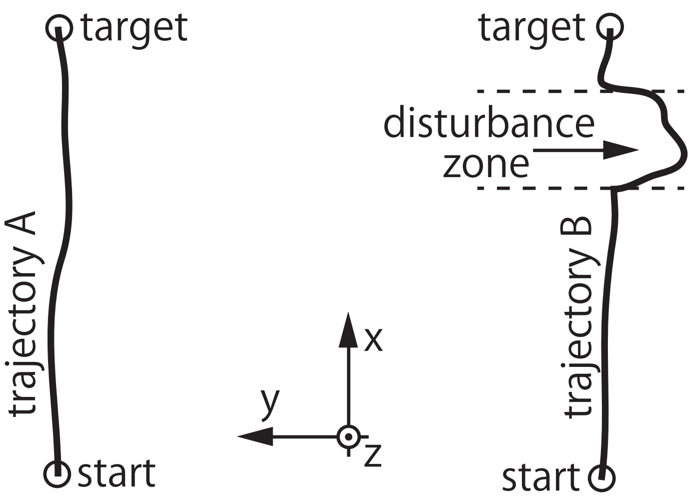

Fig. 3 Trajectory without disturbance(left). Trajectory subjected to lateral disturbance (right).

2.4 Discussion

Experiments were carried out to assess the differences between reaching arm movements with and without disturbance. We assume that reaching movements without disturbance can be regarded as entirely voluntary. On the other hand, reaching movements with disturbance include an unconstrained part that can be regarded as voluntary and a constrained part that includes an automatic response.

The movement without disturbance is a natural reaching movement for which the CNS is prepared. The reaching movement with disturbance however was unexpected to the subject, so the CNS didn't have a strategy ready to deal with the situation. The result was a trajectory that was different at every trial (low SSI).

We expect that repeating the experiment many times with disturbance will result in a lower SSI since the CNS will gradually develop a strategy to deal with it.

We hypothesize that with the hierarchical synergy model the synergy calculation could be divided into voluntary part with high SSI and an involuntary part with an SSI reflecting the quality of the automatic response. The model would explain the difference in SSI level in the experiments presented.

3 Conclusion

We showed that reaching movements without disturbance have higher SSI than reaching movements with disturbance. In this paper data of only one subject but several trials ware presented. Experiments with multiple subjects are needed to statistically prove the hierarchical model. Evaluation method of experimental data and a calculation model of the nervous system that produces the muscles command have to be created. Also the stability of the neural command C is currently under investigation.

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