Motor Primitives and Rehabilitation

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Abstract— **To generate movements the CNS must handle the large number of degrees of freedom of the musculo-skeletal apparatus. Our results show the CNS solves this problem with an architecture based on the utilization of discrete building blocks to construct a variety of movements. The experimental evidence indicates that a small number of building blocks can explain a large fraction of the variation in the muscle pattern. The results represent a remarkable simplification in view of the high dimensionality of the space of all possible muscle pattern.**

I. INTRODUCTION

TO generate goal-directed motor behavior the central nervous system (CNS) must activate and coordinate the many degrees of freedom of the musculo-skeletal system, take into account the non-linear characteristic of the muscle and predict the dynamic interactions among the moving body segments. To perform these daunting tasks a simplified neural architecture based on a modular and hierarchical control has been proposed. We and others have put forward the hypothesis that the CNS handles this large space with an architecture based upon the utilization of discrete building blocks whose combinations results in the construction of a variety of different movements.

II. RESULTS

We have provided evidence that the "building blocks "are group of muscles that are activated in a fixed balance (synergies). To identify muscle synergies our laboratory utilized a computational analysis [5, 6]. In experiments with frogs and rats we started by recording the electromyographic activity from 12-13 muscles of the hind limb during a variety of natural behaviors such as walking, swimming, jumping and kicking. We then used a multidimensional factorization algorithm to extract invariant amplitude and timing relation-ship among the muscle activations. A decomposition of the instantaneous muscle activations as combinations of non-negative vectors revealed a spatial organization in muscle patterns. A decomposition of the same activations as combinations of temporal sequences of non-negative vectors, time-varying muscle synergies, further uncovered specific characteristics in the muscle activation waveform [2].

We found that a small number of synergies could explain a large fraction of the variation in the muscle patterns. d'Avella et al. [3] analyzed the muscle patterns of intact and unrestrained frogs during kicking and showed that combinations of three time-varying synergies underlie the variety of muscle patterns required to kick in different directions. Fig 1 shows the three synergies extracted from the entire kicking data set [3].

The three extracted synergies (Fig. 1) include by definition all 13 muscles and comprise 30 samples,

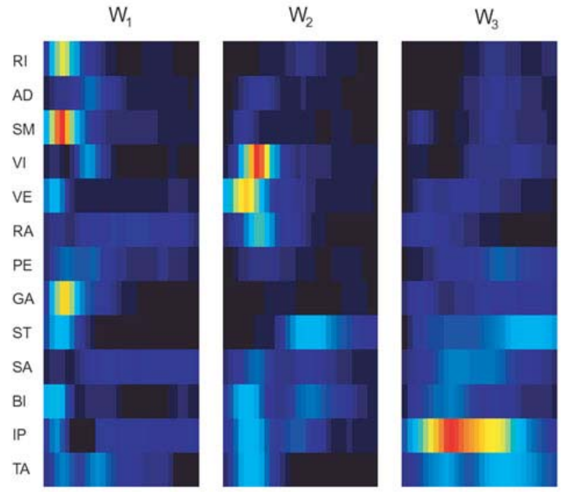

Fig. 1. Three time-varying synergies extracted from the entire kicking dataset. The first three columns (W_1 to W_3) represent the three extracted synergies as color-coded (same scale as in Fig. 1) activation time course of 13 muscles over 30 samples (300 ms total duration) normalized to the maximum sample. The three synergies capture different features of the kicking muscle patterns: W_1 and W_2 show a high level of activation, especially in extensor muscles (in particular the hip extensor RI and SM for the first synergy and the knee extensor VI and VE for the second). Mostly flexor muscles (IP, ST, TA, SA, BI) are recruited in W_3. The fourth column indicates the sign (flexion or extension) of the moment arms around hip, knee and ankle joints of the 13 muscles included in each synergy (HE: hip extension; HF: hip flexion; KE: knee extension; KF: knee flexion; AE: ankle extension; AF: ankle flexion).

corresponding to 300 ms of electromyogram (EMG) recording. The first two synergies (W_1 and W_2 in Fig. 1) represent short bursts of various, mainly extensor, muscles. The third synergy (W_3) describes instead longer bursts involving mainly flexor muscles. The muscle composition and the temporal structure of these synergies suggest a functional specificity: the first two synergies appear to be responsible for the faster extension phase of the kicks and the third synergy for the flexion phase. Of the two extension synergies, the first involves mainly hip extensor muscles and the second mainly knee extensors.

The essential features of the observed EMG patterns are well reconstructed by scaling in amplitude and shifting in

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time the three time-varying synergies.

The first pattern (left column i), recorded during a medially directed kick involving hip extension and some knee flexion, is constructed by combining the first and the third synergy (Fig. 2b, column 1). The second synergy is not recruited for this kick. In contrast, the third pattern (Fig. 2a, right column iii), producing a lateral kick consisting of a knee extension, is constructed by the combination of the second and third synergies with a minimal contribution from the first synergy (Fig. 2b, column 6). These two examples suggest that the first two synergies can be independently added to the third synergy to generate different patterns. The second example (Fig. 2a, middle column ii), a pattern observed in a caudally directed kick involving hip and knee extension, shows that the recruitment of the first two synergies is not exclusive, but they can be activated together (Fig. 2b, column 3).

A gradual transition from a pattern with only the first and third synergies to one with only the second and third synergies can be seen considering additional examples (Fig. 2b). In addition to a clear modulation of the synergy amplitudes, these examples also show a modulation of the synergy onset times, shifting from an onset of the first synergy before the second synergy (columns 1 to 3) to an onset of the second synergy before the first synergy (columns 5 and 6).

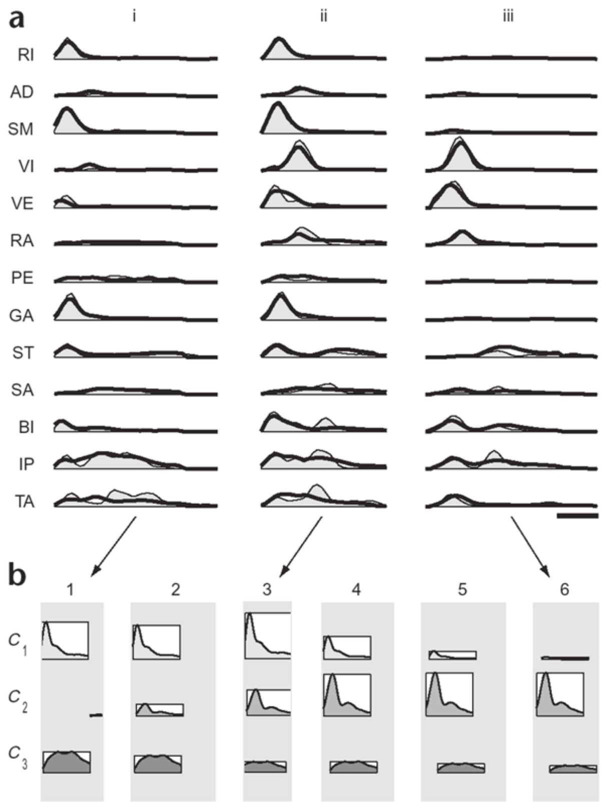

Fig. 2. Reconstruction of kick muscle patterns as combinations of time-varying synergies. (a) Three different patterns (rectified, filtered and integrated EMGs, i to iii, thin line and shaded area) are reconstructed by scaling in amplitude, shifting in time, and summing together the three synergies extracted from pooled data (thick line). Scale bar, 100 ms. (b) The amplitude coefficients (c_1 to c_3) for the three kicks in (**a**) (1, 3 and 6) and three other kicks are illustrated as the height of three rectangles, whereas the horizontal position of the rectangles represents the position in time of the synergies with respect to the extent of the muscle pattern (gray background). The profiles within each rectangle represent the time-course of the synergies averaged over the 13 muscles. The three examples in (a) show how the first two synergies are independently combined to generate different kicks: the first synergy and not the second is recruited for a medially directed kick (i and 1), involving mainly hip extension; the second synergy and not the first is recruited for a lateral kick (iii and 6), obtained with a knee extension; a caudal kick (ii and 3), involving both a knee and a hip extension, is constructed by a combination of the two synergies. A systematic modulation of amplitude and timing of the recruitment of the first two synergies can be seen in the six examples shown in (b).

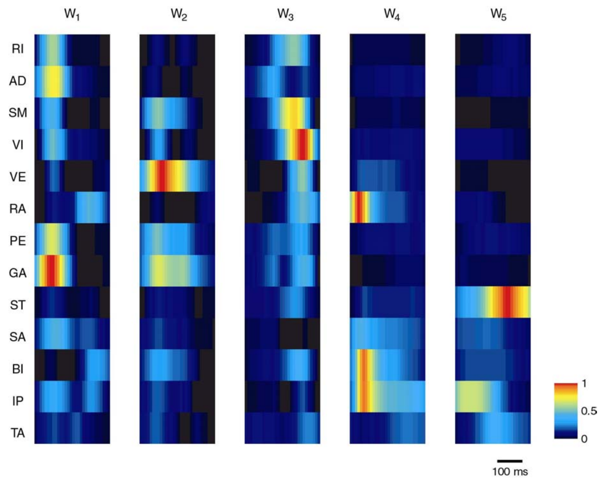

Fig. 3. Time-varying muscle synergies extracted from jumping, swimming, and walking muscle patterns in three frogs**.** Each synergy (columns W_1 to W_5) represents the activation time-course (in color code) of 13 muscles over 30 samples (300 ms total duration) normalized to the maximum sample of each muscle [1].

These results represent a remarkable simplification in view of the high dimensionality of the space of all possible time-varying muscle patterns. One potential explanation for this observed low-dimensionality might be the existence of constraints on the muscle patterns deriving from the specific movements required by the task. However, we think that it is unlikely that the observed dimensionality reduction simply arises from task-dependent constraints.

To further test the idea of modularity, we examined a variety of natural behaviors such as locomotion, swimming, jumping and defensive reflexes, again in freely moving frogs.

In fig.3 we show the five time-varying synergies extracted from all the rectified, low- pass filtered, and integrated (10 ms) EMGs recorded during a total of 2174 jumps, walking cycles, and swimming cycles in 3 frogs. The five extracted synergies include all 13 muscles. The first 3 synergies (W_1, W_2, and W_3) recruit mainly extensors while W_4 and W_5 recruit mainly flexors. The most active muscles of synergy W_1 are the hip extensors rectus internus (RI), adductor magnus (AD), and semimembranosus (SM), the knee extensor vastus internus (VI), and the ankle extensors peroneus (PE) and gastrocnemius (GA). The most active muscles of the synergy W_2 are SM, vastus externus (VE), and GA. In W_3 RI, SM, and VI are the most active. The flexors dominate synergy W_4 with rectus anterior (RA), biceps (BI) and ilio-psoas (IP). Synergy W_5 mainly semitendinosus (ST) and IP. Note that some of the muscles are present in more than one synergy---lack of recognition of this fact has affected the interpretation of amplitude scaling [4].

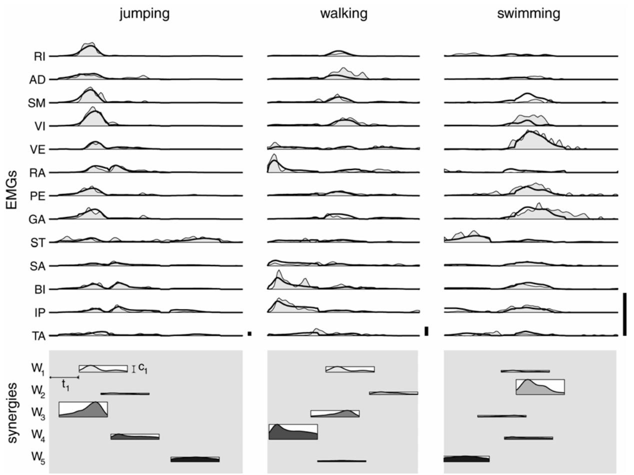

Fig. 4. Examples of reconstruction of EMG patterns as combinations of time-varying muscle synergies. The three columns are examples of a jump, a walking cycle, and a swimming cycle. Upper section (EMGs): the thick line shows the reconstruction of muscle patterns and the shaded area represents the rectified, filtered and integrated EMGs. The lower section (synergies) shows the coefficients of the five synergies as the horizontal position (onset delay, t_1) and the height (amplitude, C_1) of a rectangle whose width corresponds to the synergy duration. The shaded profile in each rectangle illustrates the averaged time-course of the muscle activation waveforms of the corresponding synergy. Note the different amplitude scaling used in the three columns

The R^2 for the five synergies extracted from the entire data set was 0.78. Thus a large fraction of the total variation of the data was described by a model that has just 10 parameters (5 amplitude and 5 timing coefficients) once the synergies are determined.

The examples illustrated by fig. 2 demonstrate two important points: 1) that the same synergies are found in different behaviors and; 2) that different behaviors may be constructed by combining the same synergies with different timing and amplitude.

Fig. 4 shows the reconstruction of muscle patterns (rectified, filtered, and integrated EMGs, *thin line and shaded area*) for a jump, a cycle of walking, and one of swimming as combinations of the five synergies of fig. 1 (*thick line*). The synergy's amplitude is shown as the height of the rectangles below the EMGs, and the delay coefficients by their horizontal position. The essential features of the three patterns are well captured by scaling in amplitude and shifting in time the five time-varying synergies. In jumping (first column) two of the three extension synergies are active (W_1 and W_3) together with the two flexion synergies (W_4 and W_5). In walking (second column) synergies one, three, and four appear again but their amplitude balance and recruitment order are radically different from jumping ---W_4dominates in amplitude, while W_1 and W_3 are relatively small, and the timing between W_3 and W_4 is reversed. Swimming (third column), in contrast, is dominated by W_2 and to a lesser extent by W_5.

The examples shown here indicate that combining muscle synergies is a strategy that the CNS utilizes for the construction of movements in the frog. Recent results from the study of the muscle patterns during reaching in humans [2] suggest that this is a general strategy used by all vertebrates for simplifying the control of limb movements.

III. CONCLUSION

The relevance of the work on muscle synergies as invariant patterns of activation across muscles is that it makes it possible to examine the EMG patterns in patients with stroke and to ask a number of novel questions. For instance, we could examine whether the motor disturbances following a stroke are the result of missing one or more synergies, or a failure of supraspinal structures to provide the correct coefficient of activation to one or more synergies, or a failure to select the proper synergies to accomplish a specific goal and /or a change in the balance of individual muscles within a given synergy. An answer to these questions will enhance our understanding of the role of the CNS in motor control, but could also be beneficial to patients because it may result in developing a more targeted therapeutic intervention.

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