LOWER LIMB MUSCLE SYNERGIES DURING GAIT IN HUMANS

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Abstract

Muscle synergies were extracted using non-negative matrix factorization from muscle activation patterns in six lower limb muscles during normal gait. Greater than 70% of the variance in the muscle activations was described by four extracted synergies and greater than 90% was described by five synergies. Considering the timing of synergy activation, the extracted synergies appear to be related to functional divisions of the gait cycle.

Introduction

Body movements, which are under the control of the central nervous system (CNS), are highly complex, involving coordination of a large number of degrees of freedom. To reduce the complexity of the control problem, it has been suggested that the CNS coordinates activation of several muscles via simpler underlying motor patterns or synergies, where the activation level of each synergy is a function of the desired biomechanical outcome [1] – [3].

Bizzi et al. [1] hypothesized that the spinal cord is organized in modular fashion, where a module is a functional unit that selects a pattern of muscle activations to achieve a desired motor output. In studies done using frogs, they determined that evoked motor responses of the hind limbs displayed discrete force orientations and that the force vectors are the expressions of synergistically active muscles. The observed muscle activation patterns can be predicted using:

$$\mathbf{m}_{obs} \approx \mathbf{m}_{pre} = \sum_{i=1}^{N} c_{ij}\mathbf{w}_i \qquad (1)$$

where $\mathbf{m}_{obs}$ is the observed muscle activation pattern, $\mathbf{m}_{pre}$ is the predicted muscle activation pattern, $\mathbf{w}_i$ are N vectors representing the muscle synergies and the c_{ij} are weighting coefficients such that the synergies are scaled and combined to estimate the observed activation patterns. $\mathbf{w}_i$ and c_{ij} are constrained to be non-negative and are found using an iterative optimization procedure [1].

Using the above algorithm, d'Avella and Bizzi [2] extracted five synergies for muscle activation patterns in 13 hind limb muscles during jumping, swimming and walking in freely moving frogs. The synergies were found, for the most part, to be significantly similar for the same activity across the three frogs studied. There also appeared to be some synergies shared across behaviors and some which were specific to particular behaviors.

Ting and Macpherson [3] examined the relationship between muscle synergies and biomechanical signals during postural responses in cats. EMG from left hind limb muscles and ground reaction forces (GRF's) were recorded in three cats, while the cats were exposed to postural perturbations in 16 directions. Using a non-negative optimization procedure similar to d'Avella and Bizzi [2], muscle activations were decomposed into four synergies, each characterized by a dominant subset of muscles. The GRF data were decomposed into four force basis vectors. It was found that the activation pattern of each synergy was correlated with the modulation of a specific basis force vector and that a unique set of synergies was activated for each perturbation direction.

Using a different processing method, Krishnamoorthy et al. [4] identified muscle synergies associated with balance control in humans. EMG was recorded from 11 leg and trunk muscles during standing. The center of pressure (COP) was altered by releasing a load from the hands with arms extended, by performing fast bilateral arm movements or by voluntarily shifting the COP forwards or backwards. Using principal component analysis, three M-modes were identified: push-back, push-forward and mixed. These M-modes were determined to be synergies which are accessed for stabilization during forward and backward shifts of the COP.

Given that there is evidence that muscle synergies are activated during hind limb movements in frogs, and during postural adjustments in cats and humans, it was hypothesized that gait in humans is also controlled via a set of underlying muscle synergies. In this work, muscle synergies were extracted, using non-negative matrix factorization, from activation patterns in lower limb muscles during a single gait cycle. The synergies were examined to assess commonalities on the right and left sides and across subjects and to determine how well muscle activations were predicted by the extracted synergies and coefficients.

Methods

Data were collected for a separate study from seven healthy adult subjects [5]. EMG data were recorded using bipolar Ag-AgCl electrodes, with interelectrode spacing of 3 cm, from the tibialis anterior (TA), medial gastrocnemius (GA), rectus femoris (RF), biceps femoris (BF), adductor longus (AL), gluteus medius (GM) and erector spinae (ES). The signals were amplified 500-1000× and sampled at 2400 Hz.

EMG data were full-wave rectified and low-pass filtered using a 4th-order Butterworth filter with a 10 Hz cut-off frequency. Ten trials were ensemble averaged and normalized to the peak value to obtain muscle activation profiles for each muscle [5]. Two averaged muscle activation profiles per subject were obtained.

Muscle activation profiles for the six lower limb muscles (TA, GA, RF, BF, AL and GM) on the right and left sides were processed using the algorithm of d'Avella and Bizzi [2]. For the sampled muscle activations:

$$\mathbf{M}_{obs} \approx \mathbf{M}_{pre} = \mathbf{WC} \quad (2)$$

where $\mathbf{M}_{obs}$ is a 6×100 matrix of observed muscle activation values (each row represents the activation profile for a single muscle); $\mathbf{M}_{pre}$ is a 6×100 matrix of predicted muscle activation values; **W** is a 6×N matrix of synergies, where N is the number of synergies; and **C** is an N×100 matrix of coefficients. **W** and **C** are initialized to random values between 0 and 1, with the constraint that the columns of **W** sum to 1. The coefficients, c_{ij} and synergies, w_{ij} are updated using the following rules:

$$c_{ij\_new} = c_{ij} \frac{\left(\mathbf{W}^T\mathbf{M}\right)_{ij}}{\left(\mathbf{W}^T\mathbf{WC}\right)_{ij}} \qquad (3)$$

$$w_{ij\_new} = w_{ij} \frac{\left(\mathbf{MC}^T\right)_{ij}}{\left(\mathbf{WCC}^T\right)_{ij}} \qquad (4)$$

After each update the predicted activations, $\mathbf{M}_{pre}$ are updated and the total squared error between $\mathbf{M}_{pre}$ and $\mathbf{M}_{obs}$ is calculated. The process iterates until the decrease in the total squared error is less than 0.0001. Correlations between the final predicted activations, $\mathbf{M}_{pre}$ and observed activations, $\mathbf{M}_{obs}$ are computed for each of the six muscle activations and the average correlation is calculated. The process is repeated 10 times and the set of synergies giving the highest average correlation between $\mathbf{M}_{pre}$ and $\mathbf{M}_{obs}$ is selected.

Results

Three, four and five synergies were extracted for each subject. Average R^2 values between predicted and observed activations for each muscle were calculated and are plotted in Fig. 1. In general, R^2 increases as the number of synergies increases, indicating that more variance is explained. Ranges for the coefficient of variation (cv) in the R^2 values were: 3 synergies – 0.035 to 0.477 (right), 0.057 to 0.444 (left); 4 synergies – 0.03 to 0.332 (right), 0.006 to 0.17 (left); 5 synergies – 0.027 to 0.183 (right), 0.002 to 0.109 (left). In all cases the lowest cv was obtained for GA; the highest cv was obtained for RF for 3 synergies/left side and for BF in all other cases.

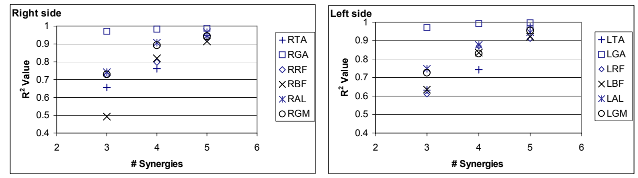

Fig. 1: Average R^2 values between predicted and observed muscle activations for 3, 4 and 5 synergies for each muscle for the right and left sides.

Given the low R^2 values for some muscles when three synergies were extracted, analysis was done using four and five synergies. Fig. 2 shows four and five synergies extracted for a single subject. To assess the similarities in the synergies across subjects, correlation matrices for the synergies from the right and left side muscles for all subjects were created. The degree of correlation across subjects varied from synergy to synergy.

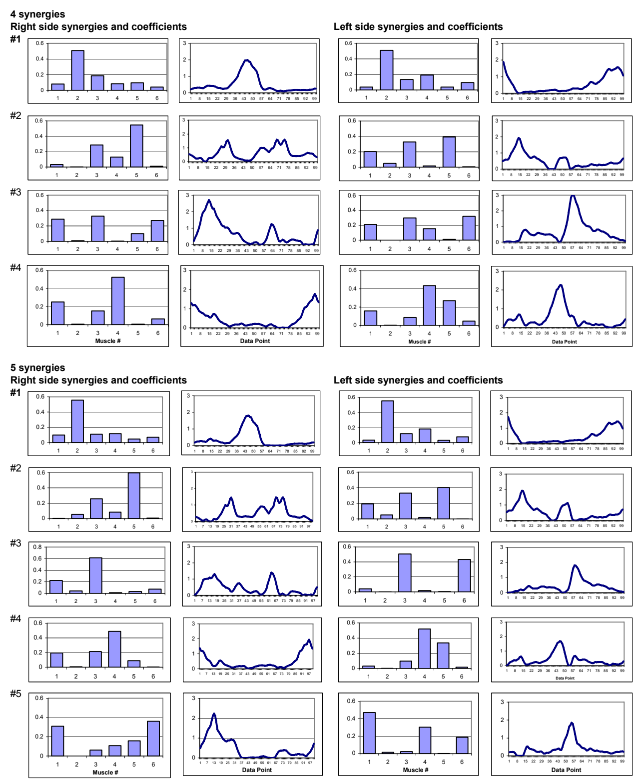

Fig. 2: Extracted synergies and coefficients for right and left side muscles of one subject. Muscles are TA, GA, RF, BF, AL and GM (from left to right). Correlations between the right and left side synergies are (from top to bottom): 0.928, 0.836, 0.801 and 0.737 (4 synergies) and 0.978, 0.835, 0.679, 0.747 and 0.601 (5 synergies). Coefficient patterns are shifted for the left side muscles, reflecting the relative time shift in activation between right and left side muscles.

For four extracted synergies, synergy #1, exhibited high activation of GA and lesser activation of the other muscles (see Fig. 2 - top) and was correlated across all subjects and on both right and left sides.

Synergy #2 was generally characterized by activation of AL and RF and lesser activation of TA, BF and GM, and was correlated across most subjects, although it was poorly correlated in two cases on the right side and three cases on the left side. Synergy #3 and #4 were more variable across subjects, often exhibiting a mixture of the two synergy patterns. The results for five extracted synergies were similar, with synergy #1 and #2 being well correlated across subjects. These synergies also generally matched synergy #1 and #2 for the four extracted synergies – this is apparent in Fig. 2. The remaining three synergies were less well correlated across subjects, and again exhibited a mixture of the synergy patterns. In all cases and across all subjects, GA is activated in synergy #1 and slightly or not at all in all other synergies.

Observed and predicted muscle activation patterns for four and five synergies are shown in Fig. 3, for the same subject as in Fig. 2. It is apparent that activation patterns for certain muscles, in particular RF and GM, are better predicted using five synergies.

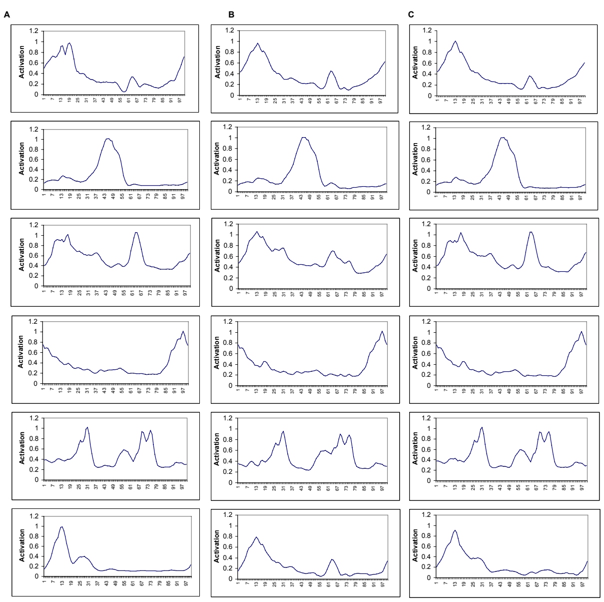

Fig. 3: A. Observed right side muscle activations and muscle activations predicted using B. four synergies and C. five synergies. Top to bottom: TA, GA, RF, BF, AL and GM. R^2 values between observed and predicted activations for four synergies: 0.911, 0.996, 0.755, 0.988, 0.944, 0.810; and for five synergies: 0.922, 1.000, 0.991, 0.991, 0.997, 0.937 (top to bottom).

Discussion and Conclusion

Muscle synergies and coefficients were extracted using non-negative matrix factorization for six lower limb muscles during normal human gait. Four and five synergies explained 74-99.3% and 91.1-99.8% respectively, of the variability in the muscle activations of the individual muscles.

Two synergies were well correlated across subjects. These synergies exhibit strong activation of GA which acts to plantarflex the ankle (synergy #1) and activation of AL and RF, which act to flex or stabilize the hip and extend the knee (synergy #2). The coefficients associated with these synergies indicate the relative timing of the synergies. For the right side, synergy #2 is activated partway into the gait cycle, resulting in hip stabilization and knee extension. As synergy #2 turns off, synergy #1 is turned on causing plantarflexion. As synergy #1 is deactivated, synergy #2 turns on again, to flex the hip and extend the knee at the beginning of the swing phase. Synergies which include activation of TA (synergy #3 and 4 for four synergies and #3, 4 and 5 for five synergies in Fig. 2) are turned on early in the gait cycle, to achieve ankle dorsiflexion. The synergy with a strong contribution from BF (synergy #4) turns on early in the gait cycle to extend the hip and later to flex the knee. These relative timings of synergy activations are consistent across subjects.

The results of this study indicate that muscle activations in six lower limb muscles during gait can be described by a set of muscle synergies and corresponding coefficients. The activations are reasonably well described by four synergies, which would reduce the dimensionality of the control problem in the CNS. The timing of the synergies indicates a correspondence between synergies and functional segments of the gait cycle, which is consistent with the notion that desired biomechanical outcome determines muscle synergy activation [3].

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