LOWER LIMB MUSCLE SYNERGIES DURING NORMAL GAIT AND OBSTACLE AVOIDANCE IN HUMANS

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ABSTRACT

Synchronous muscle synergies were extracted from muscle activation patterns in six lower limb muscles as subjects avoided an obstacle (a real or virtual hole in the pathway) during walking. These synergies were compared to synergies previously extracted during normal walking [5]. Some reorganization in the synergy patterns during obstacle avoidance was found. The alterations can be explained in terms of maintaining stability while avoiding an obstacle.

INTRODUCTION

Body movements controlled by the central nervous system (CNS) are highly complex, involving coordination of a number of degrees of freedom. It has been suggested that the CNS coordinates activation of several muscles via simpler motor patterns or synergies and that these synergies are related to spinal cord modules, where a module is a functional unit that selects a pattern of muscle activations to achieve a desired motor output [1] - [3].

Bizzi et al. [1] applied an iterative non-negative matrix factorization (NNMF) technique to extract muscle synergies from hind limb muscle activation patterns observed in frogs. Patterns were predicted using:

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

where m_{obs} is the observed muscle activation pattern, 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, where the coefficients, c_{ij} and the synergy elements w_{ij} are updated using the following rules:

$$c_{ij\_new} = c_{ij}\frac{\left(\mathbf{W}^T\mathbf{M}\right)_{ij}}{\left(\mathbf{W}^T\mathbf{WC}\right)_{ij}} \qquad (2)$$

$$w_{ij\_new} = w_{ij}\frac{\left(\mathbf{MC}^T\right)_{ij}}{\left(\mathbf{WCC}^T\right)_{ij}} \qquad (3)$$

M is a P×K matrix of predicted muscle activations, **W** is a P×N matrix of muscle synergies and **C** is an N×K matrix of weighting coefficients [3]. Four synergies were extracted from muscle activation level (MAL) patterns recorded from 9 muscles during withdrawal reflexes in the hind limb in frogs. Muscle activations predicted using equation (1) explained more than 90% of the variance over the set of all recorded responses [1].

Using the NNMF algorithm, d'Avella and Bizzi [3] extracted five synergies for MAL patterns in 13 hind limb muscles during normal activities in freely moving frogs. It was found that the synergies were significantly similar for the same activity across the three frogs studied and that there appeared to be synergies which were shared across behaviours and synergies which were specific to particular behaviours. These synergies (called synchronous synergies) revealed the spatial interactions in the relevant MAL patterns but did not provide any insight into the temporal relationships among the muscle activations. D'Avella and Bizzi [3] extended the synergy extraction algorithm to generate time-varying synergies that reveal spatiotemporal interactions in the muscle activation patterns. As with the synchronous synergies, shared and specific time-varying synergies were obtained from the frog muscle activations and a single set of synergies characterized the spatiotemporal structure of the MAL patterns.

Time-varying synergies have been extracted from MAL patterns recorded during fast reaching movements in humans [4]. EMG was recorded from up to 19 shoulder and arm muscles, as subjects performed point-to-point movements in the sagittal or frontal plane. The resulting MAL patterns could be predicted using four or five time-varying synergies where the predicted activations explained 73-82% of the variation in the data [4]. These same synergies were used to reconstruct MAL patterns for reaching tasks performed with different arm postures and different loading conditions. A large fraction of the variation in the data was explained by the re-constructed patterns, providing evidence that the synergies represent a set of spatiotemporal components which with appropriate weightings generate requisite EMG patterns.

Synchronous muscle synergies have been extracted from muscle activations in six lower limb muscles during normal gait in humans [5]. It was found that more than 70% of the variance in the muscle activation patterns was described by four extracted synergies and that the timing of the synergy activations was related to functional divisions of the gait cycle.

The purpose of this study is to examine muscle synergies extracted from MAL patterns in the lower limb muscles for a single gait cycle as subjects avoided an obstacle in the pathway and to assess whether the synergies and/or the weighting coefficients are modified by gait alterations due to obstacle avoidance.

METHOD

EMG Recording and Muscle Activation Patterns

As part of a separate study, EMG data were recorded during normal gait and during gait when subjects were required to avoid an obstacle – a real or virtual hole – in the pathway [6]. The hole was positioned in the region of the right foot placement in one of six locations as shown in Fig. 1. Subjects were free to select a strategy to avoid the hole – stepping either lateral, medial, long or short with respect to normal foot placement. Subjects wore LCD goggles which were closed until two steps prior to the obstacle step, giving them two steps to plan an alternate foot placement.

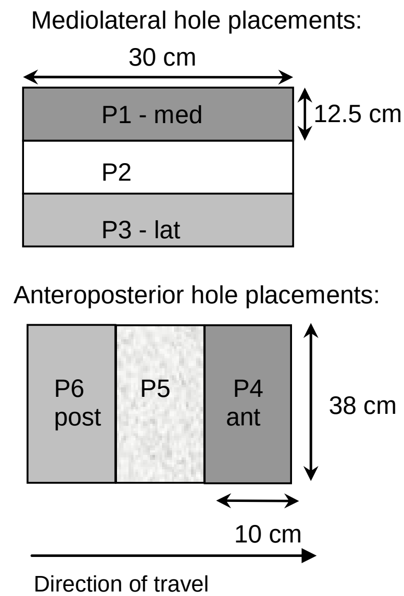

Figure 1: Hole position with respect to right foot placement.

EMG data were recorded from six lower limb muscles on both the right and left sides – tibialis anterior (TA), medial gastrocnemius (GA), rectus femoris (RF), biceps femoris (BF), gluteus medius (GM) and adductor longus (AL). EMG signals were rectified and low pass filtered with corner frequency at 10Hz. For each hole placement, the EMG profiles were grouped according to the choice of foot placement, ensemble averaged from right-heel contact to right-heel contact and normalized to the peak value of the normal walking trials [6].

Muscle Synergy Extraction

Using the algorithm of d'Avella and Bizzi [3], synchronous muscle synergies were extracted from MAL patterns recorded for avoidance of a hole at positions P1 and P2 employing a lateral foot placement. Previously, it was found that MAL patterns were well modeled by four synergies during normal walking [5], thus four synergies were extracted from the obstacle avoidance data. The extracted synergies were compared across conditions – hole vs. no hole, real vs. virtual hole and position P1 vs. position P2.

RESULTS

In the previous study [5], it was found that four extracted synergies explained 74-99.3% of variance in the MAL patterns for normal walking. In this work, four extracted synergies explained 63-99.6% of variance in the MAL patterns as subjects stepped laterally to avoid a real or virtual hole at position P1 or P2.

Representative synergies extracted from one subject for three conditions: normal walking, a real hole at P1 (P1R) and a real hole at P2 (P2R), are shown in Fig. 2. From top to bottom, synergy #1 exhibits high activation of GA and lesser activation of the other muscles; synergy #2 is characterized by high activation of GM which may be accompanied by some activation of TA and RF; synergy #3 exhibits high activation of RF, which may be accompanied by some activation of TA and AL and synergy #4 exhibits high activation of BF, generally accompanied by activation of TA. The coefficient patterns show some alterations during obstacle avoidance, particularly synergy #2 and synergy #3 for hole position P2, which are a reflection of alterations in the synergy patterns.

In order to assess the consistency of the synergies across subjects and conditions, correlation matrices were computed in Excel. Synergy #1 was highly correlated across all subjects and conditions. Synergies 2, 3 and 4 were less well correlated, often exhibiting mixed patterns. Synergies extracted from all subjects during normal walking and two obstacle avoidance conditions are shown in Fig. 3. The pattern for synergy #1 is consistent across subjects and conditions. In synergy #2, there is a relative increase of activation of RF with respect to activation of GM during hole avoidance. The pattern in synergy #3 is consistent from normal to hole avoidance at P1, but for hole avoidance at P2, there is a higher relative activation of AL. In synergy #4, there is a relative increase in activation of TA and increasing activation of GM with hole avoidance. Similar alterations were evident for muscle synergies extracted from right leg MAL's and for the virtual hole conditions.

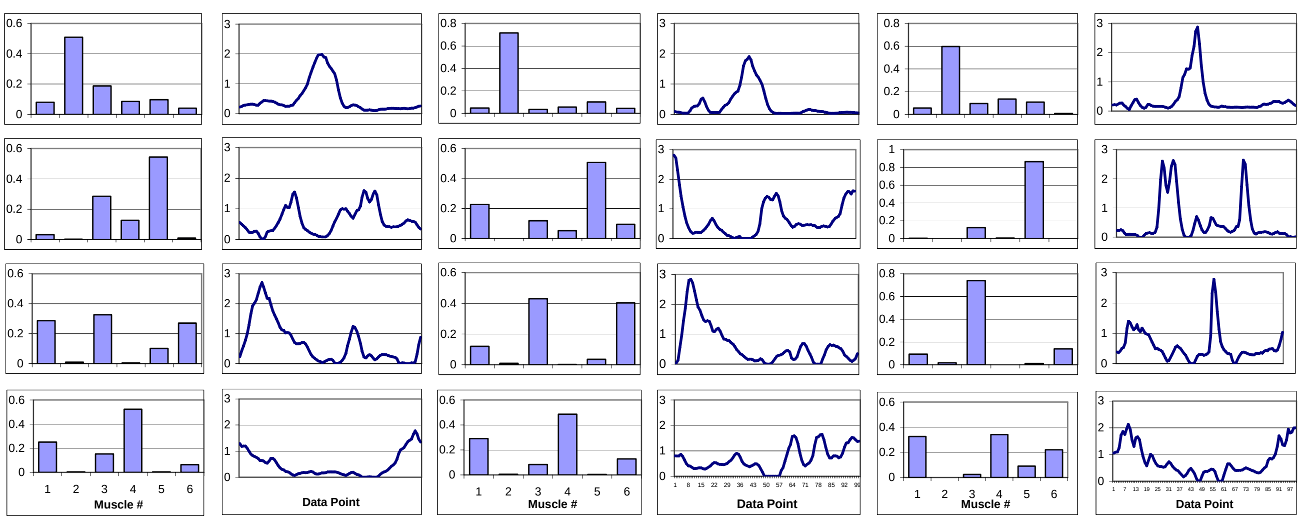

Figure 2: Synergies and coefficients extracted from MAL patterns recorded in the right leg of a single subject for no obstacle (normal walking) – left; a real hole at position P1 – centre; and a real hole at position P2 – right. Muscle # 1-GA; 2-TA; 3-RF; 4-BF; 5-GM and 6-AL.

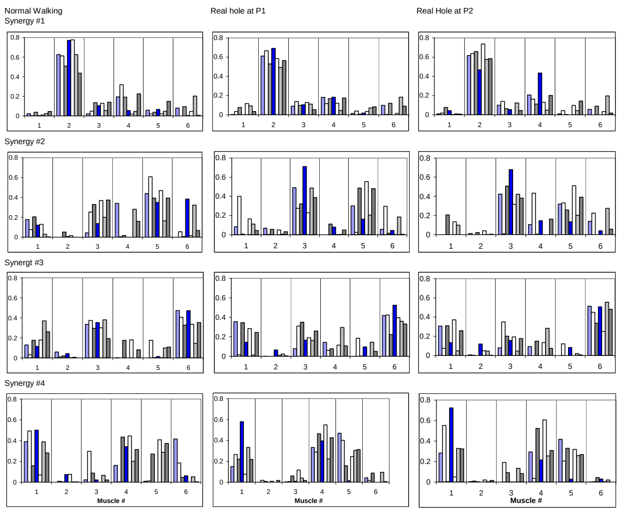

Figure 3: Muscle synergies extracted from left leg muscles for all subjects during normal walking, and during avoidance of a real hole at P1 and at P2. Muscle #'s are as in Fig. 2.

The areas under the muscle coefficient curves were compared to assess whether overall weightings increased for the normal walking versus obstacle avoidance conditions. For the right leg data, the area was significantly less ($p<0.02$) for synergy #2, for avoidance of a real hole at P2 (P2R) versus normal walking; there were no significant differences for any other conditions. For left leg data, the coefficient curve area for synergy #2 was significantly higher ($p<0.05$) for avoidance of a virtual hole at P2 (P2V); there were no significant differences for any other conditions.

DISCUSSION

In normal walking, and in stepping laterally to avoid an obstacle, four synchronous muscle synergies explain a substantial fraction of the variation in the MAL patterns recorded from six lower limb muscles. In normal walking, the synergy patterns are similar across individuals and from right to left legs. The synergies extracted from MAL patterns during obstacle avoidance are similar to those for normal walking, indicating that there are underlying patterns by which muscle activations are coordinated. However, there are shifts in the relative levels of the individual muscle activations during obstacle avoidance. As noted previously, the synergies are related to the gait cycle and the coefficients indicate the relative timing [5]. Synergy alterations when an hole is present can be explained in terms of maintaining stability. Increased activation of RF in synergy #2, serves to increase stabilization of the knee; increased activation of AL (synergy #3) aids in hip stabilization and increased activation of TA and GM (synergy #4) results in dorsiflexion and hip abduction, thus lifting the toes and moving the leg outward to avoid the obstacle.

The overal weighting of the synergies was not significantly different across conditions, except in two cases, indicating that the level of muscle activation, in general, does not change due to obstacle avoidance.

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