SHARED AND TASK-SPECIFIC MUSCLE SYNERGIES DURING NORMAL WALKING AND SLIPPING

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INTRODUCTION

The CNS controls motor tasks using a low-dimensional modular organization of muscle activation (muscle synergies) [1] and some synergies might be shared across different behaviors [2]. Studying slip, as a leading cause of falling accidents that occur on the same level ground is of importance. A comprehensive knowledge about the slip-related muscle synergies in healthy subjects may lead to better understandings of the motor strategy to recover from slip and could be used as a gauge in diagnosis and rehabilitation in future studies.

The objective of this study is to study the muscle synergies during slip initiation while walking and how these synergies are compared with those during normal walking. Specifically, muscle synergies and the corresponding time courses of coefficients will be extracted during both normal walking and slip. Synergies during both normal walking and slipping will then be compared to study if some of the synergies are shared. Similarly, the corresponding coefficients will be compared to learn if they are similar or not during both normal walking and slipping.

METHODS

Eleven healthy young adults (6 male and 5 female, age=22-33yrs) were asked to walk on a floor with four force plates embedded, and informed that the floor would be dry. They were fitted with surface electromyography (EMG) electrodes and donned with a harness to prevent falling due to slipping throughout the trials. Starting location was chosen in a way that subjects hit their right foot on the first and third plates.

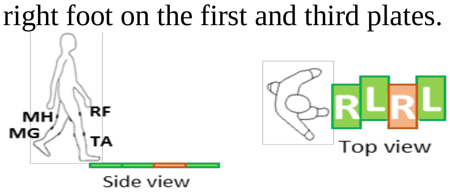

Figure 1: The side and top view of the experiment. Red plate shows the slippery surface for slip trials.

The experiment had five normal walking trials followed by an unexpected slip trial. During the slip trial, the third force plate was contaminated by applying a thin layer of a diluted glycerol (90% glycerol and 10% water). All subjects gave informed consent prior to their participation and this research was approved by the University Institutional Review Board. The EMG signals were collected during the task at 1000 Hz from eight different muscles: medial hamstring (*MH*), tibialis anterior (*TA*), rectus femoris (*RF*), and medial gastrocnemius (*MG*) on both legs. The EMGs for the first 300ms after the heel strike on the third plate were processed off-line using MATLAB (v2014a, Mathworks, Natick, MA). The EMG data of each channel were normalized by dividing the data with the maximum recorded activity of that channel during all trials for each subject, then rectified and low-pass filtered (4th order Butterworth, 30 Hz as cut-off frequency).

To extract muscle synergies, the EMG data were averaged for each 10ms (300ms resulted in 30 time steps). Using a nonnegative optimization algorithm [3, 4], muscle synergies (W) and the activation coefficients (C) were estimated. Considering the variability curve versus number of synergies [3], four synergies were picked for both normal walking and slipping for each subject. Since the order of subject-specific synergies does not match across the subjects, rearranging of synergies for all subjects were performed as described in the following paragraph.

To rearrange the order of synergies across all subjects for each condition, the following method was used. A reference subject was chosen for each condition, (one for normal walking and one for slipping) that showed the highest similarity with all the other subjects. Specifically, correlation coefficients (r) for every combination of synergies of an arbitrary subject and all other subjects' synergies were calculated. Then, a subject who has the greatest number of shared synergies (i.e., $r > 0.632$ [5]) with the other subjects was defined as a reference subject. Then the order of synergies (W) and the corresponding coefficients (C) were arranged in each subject to have the best matching synergies according to the order of the reference subject. This process was repeated for the other condition as well.

Once synergies and the corresponding coefficients were reordered across all subjects for both conditions, shared synergies and coefficients between both conditions were determined in the following ways. Correlation coefficients for all possible combinations of the four reordered normal walking synergies and four reordered slip synergies (sixteen "r" values for each subject) was calculated. One sample t-test was used to check if $r \geq 0.632$ (for shared synergies) and $r \geq 0.4$ (for marginally shared synergies) (SPSS v21, IBM, Chicago, IL). The significance level was set to $\alpha = 0.05$.

The same procedure was done for activation coefficients (C) only for the first 200ms because the corrective moments on the leading foot initiates about 200ms after the heel contact onto the slippery surface [6]. Assessment of the correlation between activation was restricted to the shared synergies and only the first 200ms after heel strike.

RESULTS AND DISCUSSION

Synergies and coefficients for both normal walking and slipping were successfully extracted (Fig. 2, 3). One sample *t*-test found one share synergy (W1 in Fig.2a, r=0.82±0.13, p=0.002) and one marginally shared synergy (W2 in Fig.2a, r=0.62±0.23, p=0.024) between two conditions. The first shared synergy (W1, Fig.2a) seems to be responsible for ankle dorsiflexion, knee flexion, and hip extension on the leading foot in gait as it activates *TA_R* and *MH_R*. The second shared synergy is knee extensor and hip flexor of the leading foot, since *RF_R* is the main activated muscle. The rest of the two synergies (Fig. 2b) did not seem to be shared and could be considered as task-specific synergies.

The third and fourth normal walking synergies are responsible for the propulsive power of the support leg (as *MG_L* is activated) and dorsiflexion on the support leg (*TA_L* is activated), respectively (Fig.2b, W3 and W4 walk). The function of the third slip synergy seems to stabilize the leading foot (as it activates all muscles almost equally), while the fourth slip synergy creates a dorsiflexion on the support leg (Fig.2b, W3/W4 slip).

For the first shared synergy, the activation coefficient showed a significant correlation between normal waking and slipping for the first 200ms (C1, Fig.3a, r=0.84±0.17, p=.004). For the second shared synergy, the activation coefficient showed a marginally strong correlation (C2, Fig.3a. r=0.59±0.21, p=.026). This agreed with the expectation of having the same activation pattern in the shared synergies before reaction of the CNS (Fig.3a, before 20 time steps). However, after 200ms, the peaks of activation for slip can be considered as the primary and secondary response of the CNS to slip. The primary response (see the first peak after 200ms in C1 slip, Fig 3a) is to dorsiflex the ankle for delayed foot flat, and to flex knee to bring body COM forward into base of support [6]. The secondary response of the CNS to slip (see the second peak after 200ms in C2 slip, Fig 3a) is to extend knee and flex hip [5], which is achieved by the second shared synergy.

CONCLUSIONS AND FUTURE WORK

In this study, shared and task-specific synergies and their corresponding activation coefficients were examined for normal walking and slipping. Two shared synergies and two task-specific synergies were found for normal walking and slipping tasks. Future work will include investigating the shared/task-specific synergies based on slip severity. Comparing synergies and coefficients of both severe and mild slip groups may help identify and intervene factors responsible for severe slips.

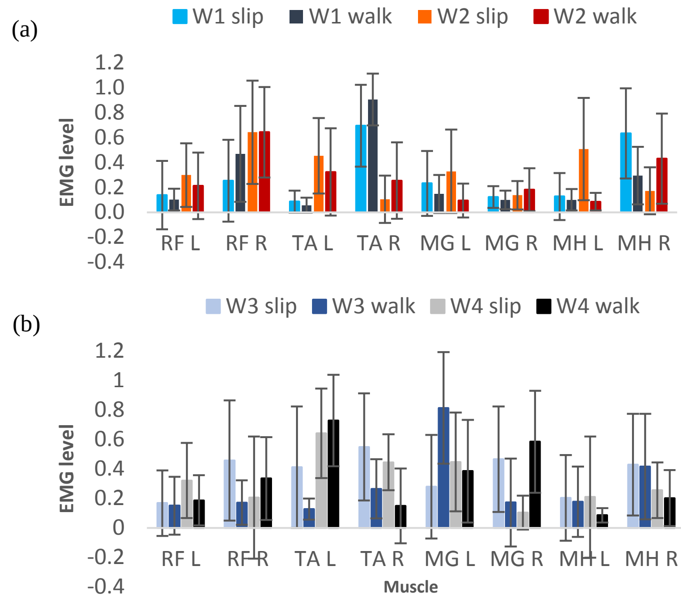

Figure 2: Four synergies for both normal walking and slipping conditions. a) Two shared synergies between both conditions. b) Task-specific (non-shared) synergies between both conditions. Error bar is one standard deviation.

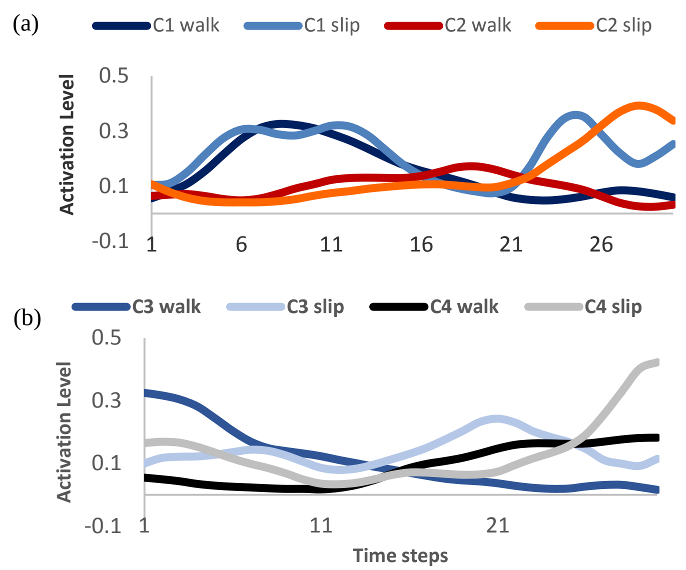

Figure 3: Activation coefficients of the corresponding 4 synergies in Fig. 2. a) Activation coefficients for the 2 shared synergies. b) Activation coefficients for the 2 task-specific synergies. One time step corresponds to 10ms.

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