INCREASED MOTOR MODULE COMPLEXITY WITH AN ANKLE EXOSKELETON

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INTRODUCTION

Patterns of motor activity, commonly referred to as motor modules or muscle synergies, provide a tool to quantify muscle coordination during dynamic tasks. Modules are calculated from experimental electromyography (EMG) signals and describe weighted groups of muscles that are commonly activated together. In unimpaired individuals, only a small set (*e.g.,* 3-5 modules) are required to describe over 95% of the variance in muscle activity during a task such as walking [1, 2]. Modules are theorized to represent the neural mechanisms underlying coordinated movement.

The goal of this research was to investigate whether patterns of motor activity are altered when unimpaired individuals walk with an ankle exoskeleton. Prior studies have investigated changes in activity of individual muscles with ankle exoskeletons, but not changes in modules or coordination. For example, ankle exoskeletons can reduce activity of the primary ankle muscles during walking [3], but whether these changes alter module structure or complexity remains unknown. Evaluating modules with ankle exoskeletons can provide insight into changes in neuromuscular control with external devices and the stability of modules in response to altered task constraints.

METHODS

We evaluated motor modules while ten unimpaired individuals (age: 24.9 ± 4.7 yrs., leg length: 0.89 ± 0.03 m, mass: 76.6 ± 6.4 kg, 7/3 M/F) walked with a unilateral powered ankle exoskeleton [4]. The ankle exoskeleton consisted of a lightweight instrumented frame worn on the foot and shank, which was connected to an off-board motor that could apply a peak plantarflexor torque of 120 N·m. Each participant completed nine trials (randomized order) walking on a treadmill at 1.25 $m \cdot s^{-1}$: a normal walking trial without the exoskeleton, four trials with varying exoskeleton work (-100-700% of normal net ankle work), and four trials with varying exoskeleton torque (0-45% of normal ankle torque). Participants completed one training day before data collection.

EMG data were collected at 2000 Hz (Trigno, Delsys Inc.) from up to eight muscles on the exoskeleton leg: medial and lateral soleus, medial and lateral gastrocnemius, tibialis anterior (TA), vastus medialis, biceps femoris, and rectus femoris. The maximum number of muscles with EMG data available for all trials was used to calculate modules for each participant. EMG data was high-pass filtered at 35 Hz (3rd order Butterworth), rectified, low-pass filtered at 40 Hz (3rd order Butterworth), and downsampled to 50 ms time bins.

We used nonnegative matrix factorization (NNMF) to calculate modules for each trial (Matlab, settings: 50 replicates, $1x10^{-4}$ and $1x10^{-6}$ convergence and completion thresholds). For a given number of modules (*n*), NNMF identifies weighted groups of muscles (*W)* and their activation patterns (*C*) whose product ($W \cdot C$) explains the greatest variance in the EMG data. For each trial, we analyzed modules for 150 bootstrapped datasets with replacement [5]. To evaluate module complexity, we evaluated total variance in the EMG data accounted for by $n = 1–5$ modules. We used a paired t-test to evaluate whether module weights changed with an exoskeleton compared to normal walking. Linear mixed effects models with random effects for participants were used to determine whether module weights or activations changed with increasing exoskeleton work or torque.

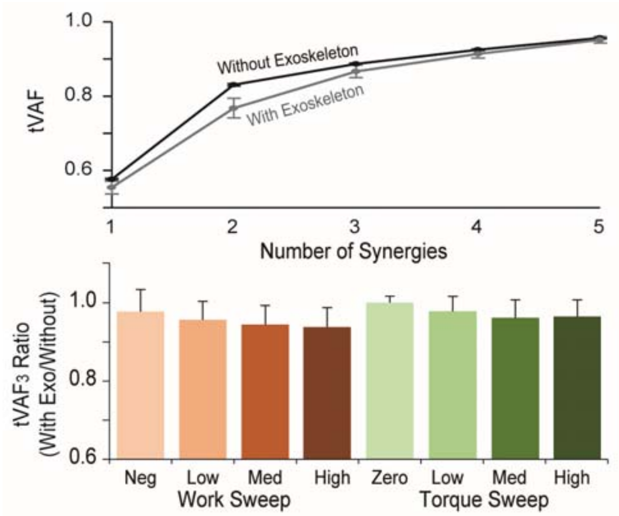

Figure 1: Total variance accounted for (tVAF) by 1-5 modules with and without the exoskeleton for Participant 4 (top). Ratio of tVAF by three modules with and without the exoskeleton for all trials and participants (bottom).

RESULTS AND DISCUSSION

The variance in EMG explained by a given number of modules decreased when participants walked with an ankle exoskeleton. Three modules explained on average 90.0±0.02% of the variance in EMG data without an exoskeleton and 86.9±0.04% with an exoskeleton (Fig. 1). Total variance accounted for by a given number of modules decreased with increasing ankle exoskeleton torque or work. These results suggest complexity of control increases with an ankle exoskeleton, where a given number of modules can describe less of the variations in muscle activity and coordination.

Module structure was similar while walking with and without an ankle exoskeleton, with no significant differences in muscle weights compared to normal walking (Fig. 2). Similar to prior analyses of unimpaired gait, the (a) quadriceps and tibialis anterior, (b) hamstrings, and (c) ankle plantarflexors were activated together during gait. Co-activation of the soleus and quadriceps increased with increasing exoskeleton work, while co-activation of the gastrocnemius and hamstrings increased with increasing exoskeleton torque. The activation of the ankle plantarflexor module decreased with increasing exoskeleton work and toque.

CONCLUSIONS

Motor module structure was largely preserved during gait with an ankle exoskeleton. However, modules described less of the variation in muscle activity with increasing ankle exoskeleton work or torque. This indicates that muscle activations and coordination have more variability when walking with an ankle exoskeleton. These results might be harnessed in the future to promote more complex coordination after neurologic injury and guide exoskeleton design.

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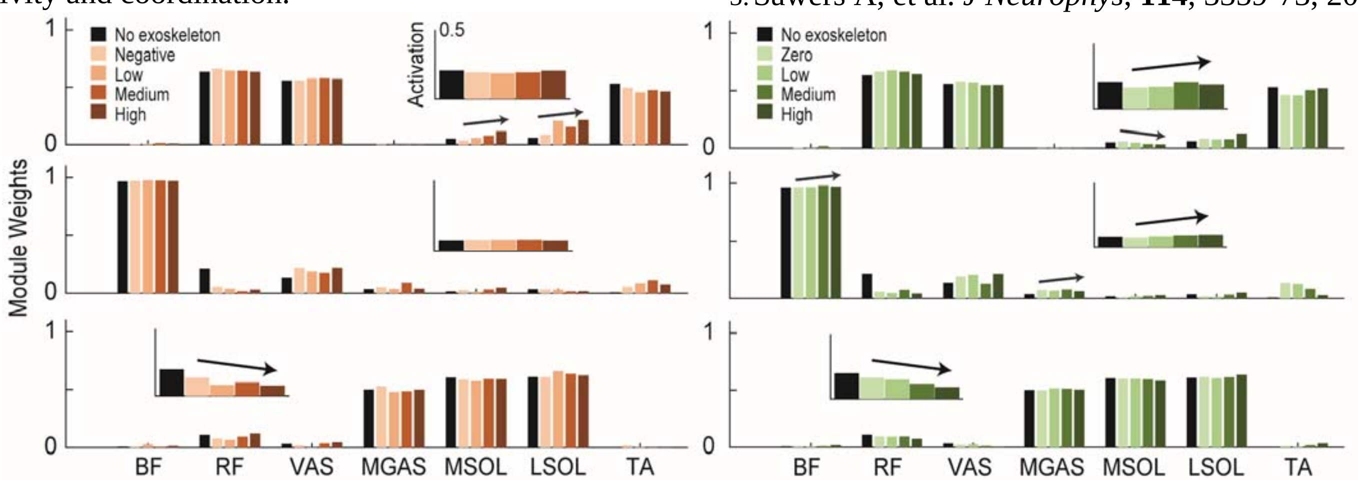

Figure 2: Module weights and average module activation level (insets) for Participant 4 with varying exoskeleton work (left) and torque (right). BF: biceps femoris, RF: rectus femoris, VAS: vastus medials, MGAS: medial gastrocnemius, MSOL/LSOL: medial/lateral soleus, TA: tibialis anterior. Participant 4 did not have EMG for the lateral gastrocnemius. Arrows show significant changes in module weights or activations with increasing work or torque from the linear mixed effects models with all participants, $p < 0.05$ and slope > 0.01.