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Increased neuromuscular consistency in gait and balance after partnered, dance-based rehabilitation in Parkinson's disease

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Abstract

Here we examined changes in muscle coordination associated with improved motor performance after partnered, dance-based rehabilitation in individuals with mild-moderate idiopathic Parkinson's disease. Using motor module (a.k.a muscle synergy) analysis we identified changes in the modular control of overground walking and standing reactive balance that accompanied clinically meaningful improvements on behavioral measures of balance, gait, and disease symptoms after three-weeks of daily Adapted Tango classes. In contrast to previous studies that revealed a positive association between motor module number and motor performance, none of the six participants in this pilot study increased motor module number despite improvements in behavioral measures of balance and gait performance. Instead, motor modules were more consistently recruited and distinctly organized immediately after rehabilitation, suggesting more reliable motor output. Further, the pool of motor modules shared between walking and reactive balance increased after rehabilitation, suggesting greater generalizability of motor module function across tasks. Our work is the first to show that motor module distinctness, consistency, and generalizability are more sensitive to improvements in gait and balance function following short-term rehabilitation than motor module number. Moreover, as similar differences in motor module distinctness, consistency, and generalizability have been demonstrated previously between in healthy young adults with and without long-term motor training, our work suggest commonalities in the structure of muscle coordination associated with differences in motor performance across the spectrum from motor impairment to expertise.

Keywords: muscle coordination, muscle synergy, electromyography, dance, exercise

New and Noteworthy:

We demonstrate changes in neuromuscular control of gait and balance in individuals with Parkinson's disease after short-term, dance-based rehabilitation. Our work is the first to show that motor module distinctness, consistency, and generalizability across gait and balance are more sensitive than motor module number to improvements in motor performance following short-term rehabilitation. Our results indicate commonalities in muscle coordination improvements associated with motor skill re-acquisition due to rehabilitation and motor skill acquisition in healthy individuals.

Introduction

Features of muscle coordination associated with differences in gait and balance performance may provide important insight into neural mechanisms of motor performance, particularly in neurological disorders. Motor module (a.k.a. muscle synergy) analysis has been used to provide such insight, and has identified differences in neuromuscular control across levels of motor performance in both healthy and impaired populations (for reviews see: Bizzi and Cheung 2013; Ivanenko et al. 2013; Ting et al. 2015). Motor modules are defined as groups of coactive muscles with a fixed spatial structure that are flexibly recruited over time to transform movement goals into biomechanical outputs (Allen and Neptune 2012; Berniker et al. 2009; Chvatal et al. 2011; d'Avella and Bizzi 2005; Ting and Macpherson 2005). In an effort to advance the analysis of muscle coordination we recently developed more refined motor module-based metrics of neuromuscular control. Specifically, we identified differences in the distinctness and consistency of motor modules as a function of motor skill in healthy, young adults (Sawers et al. 2015). However, it remains unclear whether similar changes accompany improvements in motor performance following rehabilitation. Understanding general principles of neuromuscular control that underlie improvements in motor performance with rehabilitation may help improve patient screening for rehabilitation prescription and guide the development of new interventions to enhance the re-acquisition of movement skills lost through injury or disease.

The number of motor modules recruited to perform a motor task is frequently used as a measure of neuromuscular complexity, with higher complexity (i.e. more motor modules) associated with better motor performance. Increased neuromuscular complexity is observed as motor development progresses (Dominici et al. 2011) and due to long-term motor training (i.e. ballet dancers vs. non-dancers, Sawers et al. 2015). Conversely, reduced neuromuscular complexity has been identified in various populations that exhibit impaired motor performance such as individuals post-stroke (Cheung et al. 2012; Clark et al. 2010), those with spinal cord injury (Fox et al. 2013; Hayes et al. 2014; Perez-Nombela et al. 2016), cerebral palsy (Steele et al. 2015; Tang et al. 2015), and Parkinson's disease (Rodriguez et al. 2013). A single prior study has demonstrated changes in neuromuscular complexity within the same individuals due to rehabilitation where increased neuromuscular complexity, i.e. more motor modules, was associated with improved motor performance following rehabilitation (e.g., increased walking speed post-stroke; Routson et al. 2013).

However, the number of motor modules alone may be insufficiently sensitive to distinguish important and clinically-relevant impairments in motor performance and, subsequently, any improvements with rehabilitation. Individuals with neurological motor impairments who recruit the same number of motor modules can exhibit widely varying levels of motor performance (e.g., stroke, Clark et al. 2010; spinal cord injury, Hayes et al. 2014, etc.). Among stroke survivors, rehabilitation that is successful in improving motor performance does not always result in increased motor module number (Routson et al. 2013). Thus, a given number of motor modules does not directly translate to a specific level of motor performance. In the case of Parkinson's disease (PD), movement may be substantially impaired yet the number of motor modules observed during gait is comparable to that of neurotypical controls (Rodriguez et al. 2013). Further, although treatment with L-dopa has beneficial effects on gait (Smulders et al. 2016), it does not alter the number of recruited motor modules (Roemmich et al. 2014).

Whereas the number of motor modules identifies consistent features of muscle coordination underlying multiple movement observations, variation in muscle coordination within those same observations may also reflect differences in motor performance. Generating consistent and well-coordinated movements requires recruitment of motor modules that are consistently and distinctly organized around required motor output. However, increased variability in muscle recruitment (e.g., Miller et al. 1996; Robichaud et al. 2009), increased co-activation (e.g., Dietz et al. 1995; Lamontagne et al. 2000; Lunenburger et al.

2006), and less distinct motor module organization (e.g., Clark et al. 2010; Fox et al. 2013; Hayes et al. 2014) have previously been identified in individuals with motor impairment. We recently observed greater consistency and distinctness of motor modules for walking and balance among expert professional ballet dancers compared to novice non-dancers (Sawers et al. 2015). These differences may reflect greater stability of motor output across repetitions of a task (consistency) that is organized around producing more well-defined biomechanical output (distinctness), leading to superior motor performance. Whether short-term, intensive rehabilitation in motor impaired populations results in similar improvements in motor module consistency and distinctness remains unknown.

Generalization of motor modules, i.e. the ability to use the same motor modules across different motor behaviors, may also be an important feature of muscle coordination relevant to understanding the effects of rehabilitation. Animal studies suggest that shared motor modules across a range of hindlimb motor tasks may share a common neural substrates (Cheung et al. 2005; d'Avella and Bizzi 2005; d'Avella et al. 2003; Hart and Giszter 2004). Similarly in humans, shared motor modules have been identified across a range of lower-limb motor tasks, such as across gait and balance tasks (Chvatal and Ting 2013; 2012; Oliveira et al. 2012; Oliveira et al. 2013a). However, because gait and balance performance can be differently affected by aging and Parkinson's disease (Horak et al., 2016; Park et al., 2016), the same motor modules may no longer be recruited across these two motor tasks. Sharing of motor modules across motor tasks may be critical for practice of tasks during rehabilitation to generalize to other activities often performed in daily life. We previously found that long-term training over many years in professional ballet dancers leads to better motor performance on an untrained beam-walking task, which was associated with recruiting more common motor modules across motor tasks compared to non-dancers (Sawers et al., 2015). Whether increased generalization of motor modules underlies improved motor performance after rehabilitation is unknown.

Here, we hypothesized that changes in neuromuscular control similar to those associated with motor skill acquisition also underlie motor skill re-acquisition through rehabilitation. To test this hypothesis, we examined changes in neuromuscular control of gait and balance induced by an exercise-based Adapted Tango (AT) dance program. AT has previously been shown to improve clinical measures of both gait and balance performance in individuals with PD (Hackney and Earhart 2010; McKay et al., 2016; McKee and Hackney 2013). While we recently demonstrated in a small cohort of individuals with mild-moderate PD that improvements in clinical tests of gait and balance after AT were accompanied by changes in ankle muscle co-activity during automatic postural responses to anterior/posterior balance perturbations (McKay et al. 2016), we do not know how muscle activity was changed across both gait and balance Therefore, in the current study we analyzed electromyography (EMG) data from muscles across the leg and trunk during overground walking and multi-directional postural perturbations to examine whether changes in multi-muscle coordination (i.e. motor modules) would be associated with observed motor improvements in both gait and balance. We predicted that post-AT rehabilitation, these individuals would 1) recruit more consistent and distinct motor modules, and 2) increase the proportion of motor modules shared between walking and reactive balance, suggesting that generalizability of neuromuscular control across motor tasks was improved after AT.

Methods

Study population and data sources

We performed motor module analysis on EMG data collected as secondary outcome measures of a small pilot cohort study (McKay et al. 2016). Briefly, participants with a diagnosis of "definite" idiopathic PD (Racette et al. 1999) participated in a short-duration, high volume Adapted Tango rehabilitation intervention. Each participant completed fifteen 1.5-hour AT lessons taught by an experienced

professional ballroom dance instructor over the course of 3 weeks. In addition to the primary clinical outcome measures (below), a convenience sample (n=9) of the entire cohort (n=22) was allocated to additional balance and gait testing with electromyography before and after the intervention. Of these, complete EMG data suitable for motor module analysis were available for 6 participants (Table 1) due to an equipment failure at post-test for the remaining 3. All participants provided written informed consent before participating according to protocols approved by the institutional review boards at both Emory University and the Georgia Institute of Technology. All participants were prescribed and taking anti-parkinsonian medications throughout the study. All assessments occurred at a self-determined, optimal time consistent between pre- and post-tests. While we did not explicitly control for medication wear off during the experiment, the amount of wearing off should be consistent within a participant at both pre- to post-test since they were tested at the same time of day corresponding to their self-determined optimal ON state. In addition, we did not observe any deterioration in movement quality during any session. Participants were classified as either tremor-dominant (TD), postural instability / gait disability dominant (PIGD), or indeterminate based on UPDRS-III scores following the methodology of Stebbins and colleagues (Table 1, Stebbins et al. 2013). Briefly, average scores for UPDRS-III items related to tremor and UPDRS-III items related to posture and gait were calculated for each participant. The ratio between these averages was used to classify participants as TD (≥1.5), PIGD (≤1), or indeterminate otherwise.

Clinical outcomes

Clinical outcomes included motor examination of PD symptoms (Unified Parkinson Disease Rating Scale (UPDRS, Motor Subscale III; Goetz et al. 2008)) and behavioral measures of balance and gait (Berg Balance Scale (BBS; Berg et al. 1995), Fullerton Advanced Balance scale (FAB; Klein et al. 2011), Dynamic Gait Index (DGI; Shumway-Cook and Woollacott 1995), preferred gait speed, fast gait speed, and six minute walk test (6MWT; Enright 2003)).

Muscle activity assessments

During walking assessments, each participant walked overground at self-selected walking speed for approximately 7.5m. Participants were instructed to walk as they would normally while maintaining their head level. At least three trials were collected per participant.

During reactive balance assessments, we recorded postural responses to ramp-and-hold translations of the support surface during standing while participants stood on an instrumented platform that translated in 12 equally spaced directions in the horizontal plane (see Fig. 1B). Participants were instructed to maintain balance without stepping. Three trials in each of the 12 directions were collected in random order. The perturbation level was adjusted for each participant such that they could perform the set of perturbations without stepping. This level was determined at pre-test by delivering three to six initial perturbations to select the highest perturbation level a participant could reliably maintain balance without stepping among six pre-determined levels. The same perturbation level from the pre-test assessment was used in the post-test, even if the participant could withstand a higher perturbation level at post-test. All participants used level 3 (displacement 7.5 cm, velocity 15 cm/s, acceleration 0.1g) except participants PR7 and PR9 who used level 4 (10cm, 20 cm/s. 0.2g). Stance width was self-selected by each participant at the beginning of the pre-test and enforced through all trials during pre- and post-tests. In one participant (PR1), self-selected stance width was not correctly enforced and this participant used a 9.5-cm wider stance width at post-test.

Surface EMG activity was recorded at 1080 Hz from thirteen muscles of the right side leg and lower back. Muscles recorded from included: rectus abdominus (REAB), external oblique (EXOB), erector

spinae (ERSP), gluteus medius (GMED), tensor fascia lata (TFL), biceps femoris long head (BFLH), rectus femoris (RF), vastus medialis (VMED), medial gastrocnemius (MGAS), lateral gastrocnemius (LGAS), soleus (SOL), peroneus longus (PERO) and tibialis anterior (TA). Three-dimensional kinematics were also measured using an 8-camera Vicon motion analysis system at 120 Hz and a custom 25-marker set that included head-arms-trunk, thigh, shank and foot segments.

EMG data processing

All EMG data were high-pass filtered at 35 Hz, de-meaned, rectified, and low-pass filtered at 40 Hz using custom MATLAB routines. To extract motor modules, we first generated subject-specific EMG data matrices for each condition (4 conditions = 2 tasks [walking and reactive balance] x 2 time-points [pre-test and post-test]) as follows. In order to fully capture the underlying variability the EMG data matrices included the whole data set of EMG rather than averaged data (e.g., over trials for reactive balance or gait cycles for walking). Across both behaviors the EMG data matrices were normalized to the maximum activation observed during walking.

For walking, at least 5 total gait cycles per walking condition were included in the analyses. EMG data were averaged over 75 ms bins and data from the first and last two steps as identified from kinematic markers on the heels were removed in order to avoid gait initiation and termination, as in a previous study (Chvatal and Ting 2013). Trials were concatenated end to end to form an $m \times t$ data matrix, where m is the number of muscles (13) and t the number of conditions (trials × time bins). The number of datapoints in the walking data matrix varied across subjects with a minimum size of 115 points.

For reactive balance, EMG data were analyzed during four different time bins: one before the perturbation and three during the automatic postural response (APR, Fig. 1B), as in a previous study (Chvatal et al. 2011). Specifically, mean muscle activity was calculated during a 120 ms background period that ended 170 ms prior to the perturbation and during each of three 75 ms bins beginning either 120 or 150ms after perturbation onset depending on the level of the applied perturbation. Latencies of 150 and 120 ms were used for the level 3 (participants PR 1,2,3,8) and level 4 (participants PR 7,9) perturbations, respectively. These onsets are based on the earliest observed onset of muscle activity across all muscles and perturbation directions previously observed in healthy, young adults during identical levels of applied perturbations. Mean muscle activity values for each muscle during each bin during each trial were assembled to form an m x t data matrix where m is the number of muscles (13) and t the number of datapoints (3 trials x 12 directions x 4 time bins = 144).

Motor module extraction

Motor modules for each subject at each observation time point (pre-test, post-test) were extracted separately from the EMG data matrix derived from walking and from reactive balance using non-negative matrix factorization (NNMF; Lee and Seung 1999) such that EMG = W*C, where W is an $m \times n$ matrix with n modules and C is the $n \times t$ matrix of motor module activation coefficients. Each column of W represents the weights of each muscle in a module and each row of C represents how much the corresponding module was activated over all data points. To ensure equal weighting on each muscle during the extraction process, each row in the EMG data matrices (i.e. muscle vector) was scaled to unit variance before motor module extraction and rescaled to original units afterwards (Torres-Oviedo and Ting 2007).

The number of motor modules, n, per condition was chosen as follows. From each EMG data matrix 1-13 motor modules (W) were extracted and the goodness-of-fit between actual and reconstructed EMG was evaluated using variability accounted for (VAF), defined as 100 x squared uncentered Pearson's

correlation coefficient (Zar 1999). The number of motor modules was chosen such that the lower bound of the 95% confidence interval on VAF exceeded 90% (Cheung et al. 2009; Hayes et al. 2014). The 95% confidence interval was found by implementing a bootstrapping procedure where the EMG data matrix was resampled 500 times with replacement. The VAF of the reconstructed EMG was recalculated for each resampling and 95% confidence intervals were constructed from these bootstrapped VAF values at each module number (Fig. 2).

Data Analysis

Nine metrics were used to examine motor module changes with rehabilitation:

Motor module number (n_{walk}, $n_{balance}$): Motor module number was defined as the number of motor modules independently extracted for each task

Motor module co-activity ($W_{mus,walk}$, $W_{mus,balance}$): Motor module co-activity was defined as the number of significantly active muscles per module, which reflects the sparsity of motor module composition. Greater motor module sparsity has been hypothesized to reflect more efficient neuromuscular control (Hayes et al. 2014; Sawers et al. 2015). Significantly active muscles were computed by establishing 95% CIs for the contribution, i.e., the values of the elements W_{ij}, to each muscle *i* in each module *j* extracted from the previously bootstrapped version of the EMG datasets. Significantly active muscles were considered those whose 95% CI did not include zero.

Motor module generalizability ($\%_{shared}$): Motor module generalizability was defined as the percentage of motor modules recruited across both walking and reactive balance. First, the number of similar motor modules across walking and reactive balance ($n_{similar}$) was identified using Pearson's correlation coefficients (r), as in a previous study (Chvatal and Ting 2013). A pair of motor modules were considered "similar" if $r > 0.684$, which corresponds to the critical value of r^2 for 13 muscles at $p=0.01$. The amount of motor module similarity was expressed as a percentage to account for the fact that each participant recruited a different number of motor modules. The percentage of similar motor modules was calculated as $100\times[n_{similar} / (n_{walk} + n_{balance} - n_{similar})]$.

Motor module variability ($R95_{walk}$, $R95_{balance}$): Motor module variability was defined as the variability of motor module structure across different movement observations. This analysis quantifies the variability of motor module spatial structure (W) across different subsets of the EMG dataset using a multi-step process (Sawers et al. 2015). First, each EMG matrix was resampled 100 times in which 80% of the data were randomly sampled without replacement. From each resampled matrix a new set of motor modules was extracted, where the number of motor modules, *n*, was identical to the number previously identified from the entire dataset. Then, Sammon's mapping was used to map and plot each subject's set of resampled motor modules in a two dimensional space (De Marchis et al. 2013). This procedure generated a new set of 2D vectors from the set of 13D vectors (i.e., 13 muscles) while conserving the structure (point-to-point Euclidean distance) of the original dataset by minimizing differences in the distance between points from the two data sets (Sammon 1969). To allow comparison of the 2D maps across all conditions, Sammon's mapping was applied to a matrix that contained all of the resampled motor modules (i.e., all motor modules from both walking and reactive balance across all participants at both pre- and post-test). Each data point in the resulting map is a two dimensional representation of one of the resampled motor modules. Finally, the resulting 2D motor module vectors for each participant and task were organized into clusters using K-means clustering, where the number of clusters was set equal to the number of motor modules, *n*, previously identified for that task. The variability of each motor module was quantified as the radius of a circle that encompassed all of the cluster points in that module to 95% confidence (R95, Fig 4) and was then averaged across all modules within a task.

Motor module distinctness (d_{walk}, $d_{balance}$): Motor module distinctness was defined as the mean distance between the R95 circles of each module (d, Fig. 4), where the more distinct the motor modules are for a task the greater the distance.

Statistical Analyses

For preliminary analysis, changes in the number of motor modules (n_{walk}, $n_{balance}$) from pre- to post-test were compared to the null value 0 with signed-rank tests. Due to the small sample size, we considered further analyses of individual motor module outcomes unlikely to be informative. Therefore to examine changes in motor module metrics with rehabilitation, we tested whether a composite outcome measure of all motor module outcomes described above would exhibit consistent changes across all participants from pre- to post-test. We defined a "direction of expected change" for each outcome measure separately based on observed and hypothesized changes (Table 3, and see results for description). We modeled the number of the nine separate motor module outcomes that changed in the expected direction from pre- to post-test for each participant as a binomial random variable with 9 independent Bernoulli trials with probability of success 0.5 ($X \sim B(n = 9, p_0 = 0.50)$). That is, we compared the observed proportion of outcome measures that changed in the expected direction $\hat{p}$ to that which would be expected under the null hypothesis that each participant tossed nine independent, but fair coins. We compared the averaged observed proportion, $\hat{p}$, to the null value of p_0=0.5 with a Wald test.

Secondary analyses were applied to each outcome to calculate the effect size of the change induced with AT rehabilitation. Effect sizes were calculated using Cohen's d, calculated as differences in means between post-test and pre-test divided by standard deviation at pre-test.

Results

Performance on clinical outcomes in the present study are summarized in Table 2. Using effect size cutoff points suggested by Cohen (1992), at post-test medium improvements were observed in PD symptoms (UPDRS-III, d=0.55), medium to large improvements were observed in clinical balance measures (BBS, d=1.17; FAB, d=0.83; DGI, d=0.87), small to medium effects were observed on overground gait (TUG, d=0.46; 6MWT, d=0.79), and negligible effects were observed on gait speed (preferred, d=0.08; fast, d=0.11). Where effects were observed, they were consistently larger than effect sizes reported previously for the entire cohort from which these participants were sampled (cf. McKay et al., 2016, UPDRS-III, d=0.47; BBS, d=0.59; FAB, d=0.56; DGI, d=0.53; TUG, d=0.31; 6MWT, d=0.37).

In contrast with previous studies that have demonstrated that improvements in motor performance are associated with an increase in the number of recruited motor modules, no one in our study cohort increased the number of motor modules recruited in either walking or reactive balance (Fig. 2). Median (± interquartile range) changes in motor module number were -0.5±1 and -1±1 for n_{walk} and $n_{balance}$ with effect sizes of -0.82 and -1.29, respectively. Results of signed-rank tests indicated that neither of these changes could be discriminated from the null value of zero (S=-3, p=0.25; S=-5, p=0.125; for n_{walk} and $n_{balance}$, respectively). To evaluate whether this observation is robust across different criteria to determine motor module number, we performed a post-hoc analysis in which we calculated the change in motor module number using four additional criteria: (1) overall VAF > 85%, (2) overall VAF > 90%, (3) overall VAF > 95%, and (4) lower bound of the 95% confidence interval on VAF > 85%. Across all criteria, we observed no increase in the number of motor modules after rehabilitation in both walking and reactive balance in any participant.

Similarly, in contrast with our previous study that demonstrated motor module co-activity (W_{mus}) is lower in individuals with superior balance performance (Sawers et al. 2015), at least half of the participants studied here increased motor module co-activity at post-test (Fig. 3C). Three and four out of six participants increased module co-activity for walking and reactive balance, respectively. Across all participants, motor module co-activity changed from 6.18 ± 1.03 to 7.61 ± 1.77 (effect size = 1.39) for walking and from 6.23 ± 0.96 to 8.32 ± 2.03 (effect size = 2.17) for reactive balance. Post-hoc correlation analyses revealed a significant relationship between a decrease in motor module number and an increase in motor module co-activity across both walking and reactive balance ($r = -0.8523$, $p < 0.01$; Fig. 5).

Consistent with our prediction that motor modules would become more consistent and distinct after AT, most participants decreased motor module variability and increased motor module distinctness in both walking and reactive balance (Fig 4). Five and three participants decreased motor module variability at post-test in walking and reactive balance, respectively. Five and four increased motor module distinctness in walking and reactive balance, respectively. Across all participants, motor module variability decreased from 0.57 ± 0.29 to 0.33 ± 0.16 (effect size = -0.84) for walking and from 0.44 ± 0.13 to 0.34 ± 0.18 (effect size = -0.37) for reactive balance. Motor module distinctness increased from 0.50 ± 0.62 to 1.33 ± 0.45 (effect size = 1.17) for walking and from 0.35 ± 0.36 to 0.83 ± 0.56 (effect size = 0.59) for reactive balance.

Consistent with our prediction that motor module generalization across walking and balance would increase after AT, five out of six participants increased the percentage of motor modules shared between walking and reactive balance at post-test with the remaining participant having no change (Fig. 3B; 11.6 ± 10.6% to 34.0 ± 13.5%; effect size = 2.11). To examine whether this increased generalization was due to motor modules for walking becoming more like those for reactive balance, or vice versa, post-hoc analysis was performed using Pearson's correlation coefficients to examine how many of the motor modules at pre-test were similar to the ones recruited at post-test for each motor task. This analysis revealed a greater change in the motor modules recruited for walking than those recruited for reactive balance, with only 25.5 ± 25.0% of the motor modules recruited for walking in the pre-test also recruited in the post-test, compared to 46.7 ± 21.0% for reactive balance.

Overall, we found that the proportion of participants who exhibited changes in our motor module metrics in the expected direction at post-test were higher than what would be expected by chance. The directions of expected change for each motor module metric for the overall statistical test (Table 3) were chosen as follows. For motor module number, direction of expected change was defined as lack of an increase in motor module number (i.e. reduction or no change in number), which was chosen due to the observation that all participants improved motor performance after rehabilitation without an increase in motor module number. Similarly, because decrease in motor module number was associated with an increase in W_{mus}, we defined the direction of expected change for W_{mus} as an increase in value. Lastly, the direction of expected change for motor module variability (decrease), distinctness (increase), and generalizability (increase) were defined based on our hypothesized changes. Using these definitions, the average proportion of outcomes that changed in the expected direction from pre- to post-test across all participants (our composite outcome measure) was 0.78 ± 0.32% (7.0±2.9 of 9 total outcomes, Table 3), which is significantly higher than the proportion 0.50 that would be expected by chance ($Z_W = 2.00$, $p = 0.02$). As an alternative approach, we also compared the average number of outcomes that changed in the expected direction for each participant (7.0 ± 2.9 of 9 total outcomes, 0.78 ± 0.32 %) to the value that would be expected under the null hypothesis (4.5) with a t-test that yielded test statistic $t=2.11$, $p = 0.09$.

Discussion

Here we show that efficacious gait and balance rehabilitation in individuals with PD is associated with changes in neuromuscular control during walking and reactive balance responses. Our work is the first to show that motor module distinctness and consistency may act as markers of improved motor performance following rehabilitation. Further, we demonstrate that increased generalization of motor modules across gait and balance tasks that are controlled by different neural substrates may also indicate improved motor function after rehabilitation. As prior work demonstrates only a modest reduction in motor module number in PD compared to age-matched controls, the metrics of motor module consistency, distinctness, and generalizability may be more sensitive to changes in neuromuscular control underlying motor improvements with rehabilitation. Moreover, as similar differences in the distinctness, consistency, and generalization of motor modules have been demonstrated between young adults with and without long-term specialty motor training, there may be commonalities in the structure of muscle coordination associated with differences in motor performance across the spectrum ranging from impairment to expertise.

Our work demonstrates that the number of motor modules recruited for a motor task may not always be the most appropriate metric to identify changes in neuromuscular control that contribute to improvements in motor performance with rehabilitation, particularly in individuals with PD. While the number of recruited motor modules is often associated with motor performance (Cheung et al. 2012; Clark et al. 2010; Fox et al. 2013; Hayes et al. 2014; Perez-Nombela et al. 2016; Tang et al. 2015), a prior study demonstrated that many individuals with PD have reduced motor performance without exhibiting differences in motor module number (Rodriguez et al. 2013). Moreover in PD, motor module number is not affected by dopaminergic medications that improve motor function (Roemmich et al. 2014), suggesting that aspects of neuromuscular control not captured by motor module number can be affected by PD. Consistent with these prior findings, no increases in motor module number were observed in any of the participants studied here despite clinically-meaningful improvements on behavioral measures of balance, gait, and disease symptoms. Interestingly, some participants in our study actually *decreased* motor module number.

Our novel motor module analysis reveals how consistently and distinctly the structure of each motor module, and therefore its corresponding motor output, is maintained over repeated movements. In contrast to standard motor module analysis based on analysis of the entire data set, we performed multiple analyses on subsets of the data for each participant to identify variations in the structure of motor modules (Sawers et al. 2015). Each analysis identifies slightly different muscle contributions to each motor module. Consistency reflects within-module difference in motor module structure, which we showed decreased after rehabilitation. Our consistency analysis revealed that some motor modules at pre-test were highly inconsistent, and may not have represented stable neural solutions (Fig 4A); in some cases these were eliminated after rehabilitation (Fig. 4B). Distinctness reflects between-module differences in motor module structure, which we showed increased after rehabilitation. Recruiting motor modules that are more distinct in structure may result in motor modules that are organized around producing more well-defined biomechanical output, leading to better motor performance.

As a proxy for the efficiency of movement, our measure of motor module co-activation quantifies the sparsity of muscle representation within a module; the more significantly active muscles within a module the less sparse that module. Surprisingly, we found that most participants *increased* motor module co-activity after short-term rehabilitation, whereas healthy individuals who receive long-term motor training (>10 years) exhibit less muscle co-activation within their motor modules (Sawers et al. 2015). Specifically, it was those individuals who decreased motor module number that exhibited increased muscle co-activation within each module (Fig. 5). One possible interpretation is that participants prioritized the ability to reliably generate specific biomechanical output through the

consistent recruitment of a module over being more energetically efficient in their movements. It may be that once participants establish appropriate motor modules, continued rehabilitation would reduce the amount of muscle co-activation within each module, similar to what is seen after long-term training. Note that a prior analysis on the same cohort showed a decreased in the co-activation between two antagonistic ankle muscles (McKay et al. 2016); here, the increased co-activation within motor modules represents differences in the structure of multi-muscle coordination across multiple joints. Increased motor module co-activation was primarily a result of either a return toward more appropriate simultaneous activity of anatomically similar muscles (e.g., ankle plantarflexors) and/or co-activation of muscles crossing different joints.

Finally, we found motor module generalizability across tasks to be lower in individuals with PD than reported previously in healthy, young adults, and to increase in association with improved motor performance after AT rehabilitation. Prior studies of motor impaired populations have quantified motor modules within a single motor task (e.g., locomotor tasks in Clark et al. 2010; Rodriguez et al. 2013; Steele et al. 2015). However, studies in unimpaired humans and in animals show that motor modules are typically shared across multiple behaviors due to common neural substrates (e.g., Cheung et al. 2005; Chvatal and Ting 2013; 2012; d'Avella and Bizzi 2005; d'Avella et al. 2003; Hart and Giszter 2004; Oliveira et al. 2012; Oliveira et al. 2013a). For example, we previously demonstrated in healthy young adults that a common set of motor modules are used across walking and reactive balance (Chvatal and Ting 2013; 2012), which are mediated by different spinal and brainstem circuits. In contrast, the individuals with PD tested here initially exhibited little sharing of motor modules across walking and reactive balance.

Taken together with results from prior studies, the changes in module distinctness, consistency, and generalization observed after adapted tango rehabilitation in Parkinsonian patients are consistent with improved basal ganglia function. Prior studies have demonstrated that exercise can improve the trial by trial variability of fractionated EMG burst patterns observed during reaching tasks in individuals with moderate PD (David et al. 2016; Robichaud et al. 2009). Similar changes in EMG are observed with antiparkinsonian medications or stimulation of the subthalamic nucleus (Vaillancourt et al. 2004). Additionally, reduced gait variability has been reported after pallidotomy in PD patients (Siegel and Metman 2000). Thus, increased motor module consistency and distinctness could reflect changes within dopaminergic systems in the basal ganglia or their targets, perhaps by increasing the efficiency of striatal dopamine transmission through use-dependent plasticity (Petzinger et al. 2007). Further, the loss of automatic movements in favor of conscious control is a hallmark of PD (Kelly et al. 2012; Petzinger et al. 2013), and reduced cortical contributions to gait has been demonstrated in animal models of PD following exercise-based training (Petzinger et al. 2010). Successful partner dance involves concurrent performance of attention, navigation, memory, and gait tasks (Mckee and Hackney 2013). We speculate that increased generalization of motor modules across walking and reactive balance could indicate improved automatic control of gait–including dynamic balance during gait–after adapted tango. Our prior work demonstrates that reactive balance modules during standing are also used in balance responses during walking (Chvatal and Ting 2012, 2013). Increased gait automaticity is further supported by our observation that walking motor modules after AT became more similar to the reactive balance motor modules that are likely mediated by brainstem balance centers (Stapley and Drew 2009).

In this pilot study we provide evidence that the motor module metrics of consistency, distinctness, and generalizability may be related to clinically-meaningful improvements in motor performance after rehabilitation that cannot be explained by increases in motor module number. However, there are several limitations that must be addressed to identify the relationship between these metrics and motor performance. Due to our small sample size (n=6) we were unable to associate changes in our motor

module metrics with overall improvement (or lack thereof) at the level of individual participants, nor to improvements in specific clinical gait and balance measures, although the trends in these relationships are promising (e.g., Fig. 6). Further, for these metrics to be clinically-relevant they must be stable across days (i.e. demonstrate no change) in individuals who do not participate in rehabilitation and have no motor performance improvements. While we did not include a control group in the current study, some support for the stability of our motor module metrics can be seen in the highest functioning participant (PR7) who experienced little change in the clinical domain (as measured with our subset of clinical tests) and was also unchanged in the motor module domain. Nonetheless, future studies incorporating a larger cohort of individuals with appropriate control groups will be necessary to examine the repeatability/robustness of these motor module metrics. In addition, larger cohorts will be necessary to identify the specific relationship of motor module consistency, distinctness, and generalizability to clinical measures of motor performance, and whether there are particular improvements that are induced by adapted tango compared to standard of care in PD.

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Author Contributions

JLM, MEH, LHT conception and design of experiment; MEH ran the rehabilitation intervention; JLM and MEH collected data; JLA analyzed data; JLA, AS, and LHT interpreted results of experiments; JLM performed statistical analyses; JLA prepared figures; JLA and LHT drafted the manuscript; All authors edited, revised, and approved final version of the manuscript.

References

Allen JL, and Neptune RR. Three-dimensional modular control of human walking. *J Biomech* 45: 2157-2163, 2012.

Berg K, Wood-Dauphinee S, and Williams JI. The Balance Scale: reliability assessment with elderly residents and patients with an acute stroke. *Scand J Rehabil Med* 27: 27-36, 1995.

Berniker M, Jarc A, Bizzi E, and Tresch MC. Simplified and effective motor control based on muscle synergies to exploit musculoskeletal dynamics. *Proc Natl Acad Sci U S A* 106: 7601-7606, 2009.

Bizzi E, and Cheung VC. The neural origin of muscle synergies. *Front Comput Neurosci* 7: 51, 2013.

Cheung VC, d'Avella A, and Bizzi E. Adjustments of motor pattern for load compensation via modulated activations of muscle synergies during natural behaviors. *J Neurophysiol* 101: 1235-1257, 2009.

Cheung VC, d'Avella A, Tresch MC, and Bizzi E. Central and sensory contributions to the activation and organization of muscle synergies during natural motor behaviors. *J Neurosci* 25: 6419-6434, 2005.

Cheung VC, Turolla A, Agostini M, Silvoni S, Bennis C, Kasi P, Paganoni S, Bonato P, and Bizzi E. Muscle synergy patterns as physiological markers of motor cortical damage. *Proc Natl Acad Sci U S A* 109: 14652-14656, 2012.

Chvatal SA, and Ting LH. Common muscle synergies for balance and walking. *Front Comput Neurosci* 7: 48, 2013.

Chvatal SA, and Ting LH. Voluntary and reactive recruitment of locomotor muscle synergies during perturbed walking. *J Neurosci* 32: 12237-12250, 2012.
Chvatal SA, Torres-Oviedo G, Safavynia SA, and Ting LH. Common muscle synergies for control of center of mass and force in non-stepping and stepping postural behaviors. *J Neurophysiol* 106: 999-1015, 2011.
Clark DJ, Ting LH, Zajac FE, Neptune RR, and Kautz SA. Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke. *J Neurophysiol* 103: 844-857, 2010.
David FJ, Robichaud JA, Vaillancourt DE, Poon C, Kohrt WM, Comella CL, and Corcos DM. Progressive resistance exercise restores some properties of the triphasic EMG pattern and improves bradykinesia: the PRET-PD randomized clinical trial. *J Neurophysiol* 116: 2298-2311, 2016.
d'Avella A, and Bizzi E. Shared and specific muscle synergies in natural motor behaviors. *Proc Natl Acad Sci U S A* 102: 3076-3081, 2005.
d'Avella A, Saltiel P, and Bizzi E. Combinations of muscle synergies in the construction of a natural motor behavior. *Nature Neuroscience* 6: 300-308, 2003.
De Marchis C, Schmid M, Bibbo D, Castronovo AM, D'Alessio T, and Conforto S. Feedback of mechanical effectiveness induces adaptations in motor modules during cycling. *Front Comput Neurosci* 7: 35, 2013.
Dietz V, Zijlstra W, Prokop T, and Berger W. Leg muscle activation during gait in Parkinson's disease: adaptation and interlimb coordination. *Electroencephalogr Clin Neurophysiol* 97: 408-415, 1995.
Dominici N, Ivanenko YP, Cappellini G, d'Avella A, Mondi V, Cicchese M, Fabiano A, Silei T, Di Paolo A, Giannini C, Poppele RE, and Lacquaniti F. Locomotor primitives in newborn babies and their development. *Science* 334: 997-999, 2011.
Enright PL. The six-minute walk test. *Respir Care* 48: 783-785, 2003.
Fox EJ, Tester NJ, Kautz SA, Howland DR, Clark DJ, Garvan C, and Behrman AL. Modular control of varied locomotor tasks in children with incomplete spinal cord injuries. *J Neurophysiol* 110: 1415-1425, 2013.
Goetz CG, Tilley BC, Shaftman SR, Stebbins GT, Fahn S, Martinez-Martin P, Poewe W, Sampaio C, Stern MB, Dodel R, Dubois B, Holloway R, Jankovic J, Kulisevsky J, Lang AE, Lees A, Leurgans S, LeWitt PA, Nyenhuis D, Olanow CW, Rascol O, Schrag A, Teresi JA, van Hilten JJ, and LaPelle N. Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS): scale presentation and clinimetric testing results. *Mov Disord* 23: 2129-2170, 2008.
Hackney ME, and Earhart GM. Effects of dance on gait and balance in Parkinson's disease: a comparison of partnered and nonpartnered dance movement. *Neurorehabil Neural Repair* 24: 384-392, 2010.
Hart CB, and Giszter SF. Modular Premotor Drives and Unit Bursts as Primitives for Frog Motor Behaviors. *J Neurosci* 24: 5269-5282, 2004.
Hayes HB, Chvatal SA, French MA, Ting LH, and Trumbower RD. Neuromuscular constraints on muscle coordination during overground walking in persons with chronic incomplete spinal cord injury. *Clin Neurophysiol* 125: 2024-2035, 2014.
Horak FB, Mancini M, Carlson-Kuhta P, Nutt JG, and Salarian A. Balance and Gait Represent Independent Domains of Mobility in Parkinson Disease. *Phys Ther* 96: 1364-1371, 2016.
Ivanenko YP, Cappellini G, Solopova IA, Grishin AA, Maclellan MJ, Poppele RE, and Lacquaniti F. Plasticity and modular control of locomotor patterns in neurological disorders with motor deficits. *Front Comput Neurosci* 7: 123, 2013.

Kelly VE, Eusterbrock AJ, and Shumway-Cook A. A review of dual-task walking deficits in people with Parkinson's disease: motor and cognitive contributions, mechanisms, and clinical implications. *Parkinsons Dis* 2012: 918719, 2012.
Klein PJ, Fiedler RC, and Rose DJ. Rasch Analysis of the Fullerton Advanced Balance (FAB) Scale. *Physiother Can* 63: 115-125, 2011.
Lamontagne A, Richards CL, and Malouin F. Coactivation during gait as an adaptive behavior after stroke. *J Electromyogr Kinesiol* 10: 407-415, 2000.
Lee DD, and Seung HS. Learning the parts of objects by non-negative matrix factorization. *Nature* 401: 788-791, 1999.
Lunenburger L, Bolliger M, Czell D, Muller R, and Dietz V. Modulation of locomotor activity in complete spinal cord injury. *Exp Brain Res* 174: 638-646, 2006.
McKay JL, Ting LH, and Hackney ME. Balance, Body Motion, and Muscle Activity After High-Volume Short-Term Dance-Based Rehabilitation in Persons With Parkinson Disease: A Pilot Study. *J Neurol Phys Ther* 40: 257-268, 2016.
McKee KE, and Hackney ME. The effects of adapted tango on spatial cognition and disease severity in Parkinson's disease. *J Mot Behav* 45: 519-529, 2013.
Miller RA, Thaut MH, McIntosh GC, and Rice RR. Components of EMG symmetry and variability in parkinsonian and healthy elderly gait. *Electroencephalogr Clin Neurophysiol* 101: 1-7, 1996.
Oliveira AS, Gizzi L, Kersting UG, and Farina D. Modular organization of balance control following perturbations during walking. *J Neurophysiol* 108: 1895-1906, 2012.
Oliveira AS, Silva PB, Lund ME, Gizzi L, Farina D, and Kersting UG. Effects of perturbations to balance on neuromechanics of fast changes in direction during locomotion. *PLoS One* 8: e59029, 2013a.

Park JH, Mancini M, Carlson-Kuhta P, Nutt JG, and Horak FB. Quantifying effects of age on balance and gait with inertial sensors in community-dwelling healthy adults. *Exp Gerontol* 85: 48-58, 2016.
Perez-Nombela S, Barroso F, Torricelli D, de Los Reyes-Guzman A, Del-Ama AJ, Gomez-Soriano J, Pons JL, and Gil-Agudo A. Modular control of gait after incomplete spinal cord injury: differences between sides. *Spinal Cord* 55: 79-86, 2016.
Petzinger GM, Walsh JP, Akopian G, Hogg E, Abernathy A, Arevalo P, Turnquist P, Vuckovic M, Fisher BE, Togasaki DM, and Jakowec MW. Effects of treadmill exercise on dopaminergic transmission in the 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine-lesioned mouse model of basal ganglia injury. *The Journal of neuroscience : the official journal of the Society for Neuroscience* 27: 5291-5300, 2007.
Petzinger GM, Fisher BE, Van Leeuwen JE, Vukovic M, Akopian G, Meshul CK, Holschneider DP, Nacca A, Walsh JP, and Jakowec MW. Enhancing neuroplasticity in the basal ganglia: the role of exercise in Parkinson's disease. *Mov Disord* 25 Suppl 1: S141-145, 2010.
Petzinger GM, Fisher BE, McEwen S, Beeler JA, Walsh JP, and Jakowec MW. Exercise-enhanced neuroplasticity targeting motor and cognitive circuitry in Parkinson's disease. *The Lancet Neurology* 12: 716-726, 2013.
Racette BA, Rundle M, Parsian A, and Perlmutter JS. Evaluation of a screening questionnaire for genetic studies of Parkinson's disease. *Am J Med Genet* 88: 539-543, 1999.
Rikli RA and Jones CJ. Development and validation of a functional fitness test for community-residing older adults. *J Aging Phys Act* 7: 129-161, 1999.
Robichaud JA, Pfann KD, Leurgans S, Vaillancourt DE, Comella CL, and Corcos DM. Variability of EMG patterns: a potential neurophysiological marker of Parkinson's disease? *Clin Neurophysiol* 120: 390-397, 2009.
Rodriguez KL, Roemmich RT, Cam B, Fregly BJ, and Hass CJ. Persons with Parkinson's disease exhibit decreased neuromuscular complexity during gait. *Clin Neurophysiol* 124: 1390-1397, 2013.

654 **Roemmich RT, Fregly BJ, and Hass CJ**. Neuromuscular Complexity During Gait is not Responsive to
655 Medication in Persons with Parkinson's Disease. *Ann Biomed Eng* 42: 1901-1912, 2014.
656 **Routson RL, Clark DJ, Bowden MG, Kautz SA, and Neptune RR**. The influence of locomotor
657 rehabilitation on module quality and post-stroke hemiparetic walking performance. *Gait Posture* 38:
658 511-517, 2013.
659 **Sammon JW, Jr.** A Nonlinear Mapping for Data Structure Analysis. *IEEE Transactions on Computers*
660 C-18: 401-409, 1969.
661 **Sawers A, Allen JL, and Ting LH**. Long-term training modifies the modular structure and organization
662 of walking balance control. *J Neurophysiol* 114: 3359-3373, 2015.
663 **Siegel JL, and Metman LV**. Effects of bilateral posteroventral pallidotomy on gait of subjects with
664 Parkinson disease. *Arch Neurol* 57:198-204, 2000.
665 **Shumway-Cook A, and Woollacott MH**. *Motor Control: Theory and Practical Applications*.
666 Baltimore, MD: Lippincott, Williams, & Wilkins, 1995.
667 **Smulders K, Dale ML, Carlson-Kuhta P, Nutt JG, and Horak FB**. Pharmacological treatment in
668 Parkinson's disease: Effects on gait. *Parkinsonism Relat Disord* 31: 3-13, 2016.
669 **Stapley PJ, and Drew T**. The Pontomedullary Reticular Formation Contributes to the Compensatory
670 Postural Responses Observed Following Removal of the Support Surface in the Standing Cat. *J*
671 *Neurophysiol* 101: 1334-1350, 2009.
672 **Stebbins GT, Goetz CG, Burn DJ, Jankovic J, Khoo TK, and Tilley BC**. How to identify tremor
673 dominant and postural instability/gait difficulty groups with the movement disorder society unified
674 Parkinson's disease rating scale: comparison with the unified Parkinson's disease rating scale. *Mov*
675 *Disord* 28: 668-670, 2013.
676 **Steele KM, Rozumalski A, and Schwartz MH**. Muscle synergies and complexity of neuromuscular
677 control during gait in cerebral palsy. *Dev Med Child Neurol* 57: 1176-1182, 2015.
678 **Tang L, Li F, Cao S, Zhang X, Wu D, and Chen X**. Muscle synergy analysis in children with cerebral
679 palsy. *J Neural Eng* 12: 046017, 2015.
680 **Ting LH, Chiel HJ, Trumbower RD, Allen JL, McKay JL, Hackney ME, and Kesar TM**.
681 Neuromechanical principles underlying movement modularity and their implications for rehabilitation.
682 *Neuron* 86: 38-54, 2015.
683 **Ting LH, and Macpherson JM**. A limited set of muscle synergies for force control during a postural
684 task. *J Neurophysiol* 93: 609-613, 2005.
685 **Torres-Oviedo G, and Ting LH**. Muscle synergies characterizing human postural responses. *J*
686 *Neurophysiol* 98: 2144-2156, 2007.
687 **Vaillancourt DE, Prodoehl J, Verhagen Metman L, Bakay RA, and Corcos DM**. Effects of deep
688 brain stimulation and medication on bradykinesia and muscle activation in Parkinson's disease. *Brain : a*
689 *journal of neurology* 127: 491-504, 2004.
690 **Zar JH**. *Biostatistical Analysis*. Upper Saddle River, NJ: Prentice-Hall, 1999, p. 663.
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Figure captions

Figure 1: Example processed EMG from select muscles during A: overground walking and B: reactive balance. A: Muscle activity for walking was recorded while participants walked overground at their self-selected speed for at least three trials of 7.5m each. For each trial, the first and last gait cycles were removed to avoid gait initiation and termination. Dashed lines represent right heel-strikes and the shaded region represents the gait cycles analyzed for one trial. Data from all trials for a subject were concatenated prior to motor module extraction to form an m × t data matrix, where m is the number of muscles and t the number of timepoints across all trials. B: Muscle activity for reactive balance was assessed through ramp-and-hold perturbations in 12 evenly-spaced directions. *left*: Responses to backward, forward, and leftward perturbations are illustrated. EMG responses occurred approximately 120-150 ms after perturbation onset (denoted by the vertical dashed lines). Mean EMG activity was calculated during a background period prior to the perturbation, and during three 75 ms timebins during the automatic postural response (APR, shaded regions). *right:* Tuning curves of mean muscle activity from perturbation responses as a function of perturbation directions for the first APR bin. Prior to motor module extraction, the tuning curves were assembled to form an m x t data matrix where m is the number of muscles and t the number of data points (3 trials x 12 directions x 4 time bins = 144).

Figure 2: Number of motor modules and goodness of fit in A: overground walking and B: reactive balance. *Left*: The number of motor modules (mean ± SD) recruited during overground walking and reactive balance either decreased or remained the same after Adapted Tango (AT) rehabilitation. The connected circles denote the numbers of motor modules for each subject pre- and post-AT rehabilitation. *Middle*: the number of motor modules selected accounted for ≥90% of the overall variability accounted for (VAF) as depicted by plots from an example subject. *Right*: EMG signals were well reconstructed using the extracted motor modules in both walking and reactive balance as depicted in the example original vs. reconstructed EMG plots from a representative subject (light solid lines: original EMG, dark dashed lined: reconstructed EMG).

Figure 3: Motor module sharing and co-activity in overground walking and reactive balance. A: representative motor modules during *left*: walking and *right*: reactive balance. Motor modules were extracted from each behavior independently. Motor modules that were identified as similar between tasks are represented with the same color across tasks. B: The percentage of motor modules shared between walking and reactive balance increased from pre (solid red bars) to post (solid white bars) AT rehabilitation in 5 of the 6 participants. The connected circles denote the value for each participant. Shared motor modules are those pairs of motor modules across behaviors in which $r \geq 0.684$. The amount of sharing was quantified as a percentage of the total number of unique motor modules (i.e., 42.9% of the motor modules, or 3 of 7, were shared across behaviors in the representative subject in A). C: Motor module co-activity increase from pre (red bars) to post (white bars) AT rehabilitation in both walking (solid bars) and reactive balance (dashed bars) in most participants. Motor module co-activity was quantified as the average number of significantly active muscles per module (W_{mus}). Significantly active muscles represent those whose activation was consistently greater than zero, despite variations over movement repetitions and muscles were classified as significantly active if their 95% CI did not include zero, whereas nonsignificantly active muscle had 95% CIs that included zero (i.e. filled bars, solid border vs. open bars, dashed borders in the representative motor modules in A).

Figure 4: Spatial motor module variability and distinctness. Example motor modules and cluster plots for walking A: pre-rehabilitation and B: post-rehabilitation depicting motor module consistency (R95) and distinctness (d). *Left:* The colored bars for each muscle weighting represent the contribution of a muscle within a module over each of the 100 different resampled module extractions. The black bars

indicate the mean across all resampled extractions. *Middle*: Each point in a cluster is a two-dimensional representation of one of the 100 resampled motor modules as depicted to the left. C: Motor module variability decreased from pre (red bars) to post (white bars) AT rehabilitation in most participants for both walking (solid bars) and reactive balance (dashed bars). D: Motor module distinctness increased in most participants after AT rehabilitation in both walking and reactive balance. The connected circles denote the value for each participant.

Figure 5: Increased motor module co-activity was associated with a reduction in motor module number after AT rehabilitation. Motor module co-activity increased in those participants who decreased motor module number, whereas those participants who had no change in motor module number had only minor changes in motor module co-activity. Values for each participant for walking are represented by the closed circles and for reactive balance the open circles.

Figure 6: Examples of associations between clinical scores versus changes in motor module metrics. The change in walking endurance (6MWT, vertical axis) is illustrated for each subject versus the change in *Left*: motor module number for walking, *Middle*: motor module distinctness for walking, and *Right*: percentage of motor modules shared between walking and reactive balance. In general, changes in motor module number did not appear related to improvements in motor performance (e.g., 6MWT). In contrast, other motor module metrics (e.g., distinctness and percentage shared across tasks) demonstrated trends such that increases in these metrics were in general accompanied by increases in motor performance. Values for each participant are represented by the closed circles. Shaded regions denote where there is an increase in both the clinical score and the motor module metric.

766 **Table 1:** Participant demographics.

	Age (y)	Sex	Height (m)	Mass (kg)	PD duration (y)	UPDRS III	H&Y	CBF	PD Phenotype	Medications
PR1	68	M	1.8	80.6	5	26	2	24	PIGD (0.14/1.00)	C/L, Ent., Rop.
PR2	79	M	1.68	68.0	3	40	2	19	PIGD (0.57/1.00)	C/L, Ama.
PR3	64	M	1.75	79.3	11	25	2.5	20	PIGD (0.00/0.50)	C/L, Ent.
PR7	36	M	1.83	74.7	6	29	2	24	TD (1.71/0.00)	C/L
PR8	81	F	1.65	48.9	14	31	3	22	PIGD (0.00/0/50	C/L, Rop.
PR9	56	M	1.85	82.9	3	28	2	22	indet. (0.71/0.50)	C/L

767 Abbreviations: PD, Parkinson's disease; UPDRS III, Unified Parkinson's Disease Rating Motor
768 Subscale III; PIGD, postural instability / gait disability dominant; TD, tremor dominant; L/C,
769 levodopa/carbidopa; Ent., entacapone; Rop., ropinerole; Ama., amantadine; Ras., Rasagiline. Physical
770 function reported using composite physical function (Rikli and Jones, 1999). PD phenotype presented as
771 the ratio of average scores on the UPDRS III for posture and gait items / tremor items. Participant codes
772 are as in (McKay et al. 2016).
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Table 2: Clinical measures of balance and gait before and after the 3-week, high-volume Adapted Tango rehabilitation intervention.

	Participants					
Clinical Outcome	PR1	PR2	PR3	PR7	PR8	PR9
UPDRS-III						
Pretest	26	40	25	29	31	28
Posttest	26	33	26	19	30	27
Change	0	-7	+1	-10	-1	-1
BBS						
Pretest	51	52	54	56	51	54
Posttest	55	53	56	56	56	56
Change	+4	+1	+2	0	+5	+2
FAB						
Pretest	29	23	30	36	26	34
Posttest	37	28	34	35	30	38
Change	+8	+5	_4	-1	+4	+4
DGI						
Pretest	18	19	20	23	17	24
Posttest	--	22	21	24	23	23
Change	--	+3	+1	+1	+6	-1
TUG						
Pretest	10.16	8.03	6.96	5.65	7.72	7.03
Posttest	7.87	8.66	6.13	5.65	7.34	6.5
Change	-2.29	+0.63	-0.84	0	-0.38	-0.53
6MWT (m)						
Pretest	371.9	350.5	478.5	403.2	477.0	451.1
Posttest	433.4	387.1	452.6	442.0	528.0	548.6
Change	+61.5	+36.6	-25.9	38.8	51	97.5
Gait speed (m/s, preferred)						
Pretest	1.11	0.95	1.32	1.19	1.66	1.36
Posttest	1.07	0.85	1.41	1.36	1.36	1.66
Change	-0.04	-0.10	+0.09	+0.18	-0.29	+0.30
Gait speed (m/s, fast)						
Pretest	1.59	1.60	1.95	1.87	1.98	2.07
Posttest	1.57	1.31	2.19	1.95	1.93	2.24
Change	-0.02	-0.29	+0.24	+0.08	-0.04	+0.17

Abbreviations: UPDRS-III, Unified Parkinson's Disease Rating Scale, Part III: Motor Exam; BBS, Berg Balance Scale; FAB, Fullerton Advanced Balance Scale; DGI, Dynamic Gait Index; TUG, Timed Up and Go Test; 6MWT, Six Minute Walk Test. Participant codes are as in (McKay et al., 2016)

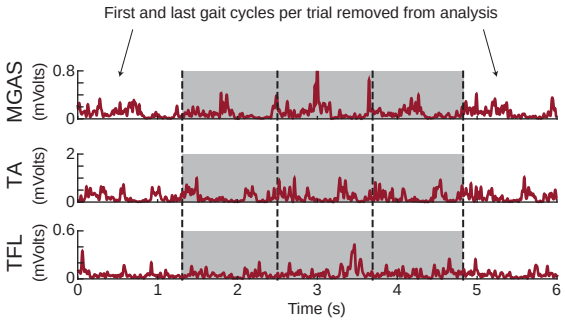
Table 3: Frequency of outcome measures that did vs. did not change in the expected direction.

Outcome Measure	Direction of expected change	# of Participants	
		Expected change	Non-expected change
n_{walk}	- or =	6	0
$n_{balance}$	- or =	6	0
$\%_{shared}$	+	5	1
d_{walk}	+	5	1
$R95_{walk}$	-	5	1
$W_{mus,walk}$	+	4	2
$d_{balance}$	+	4	2
$R95_{balance}$	-	3	3
$W_{mus,balance}$	+	4	2

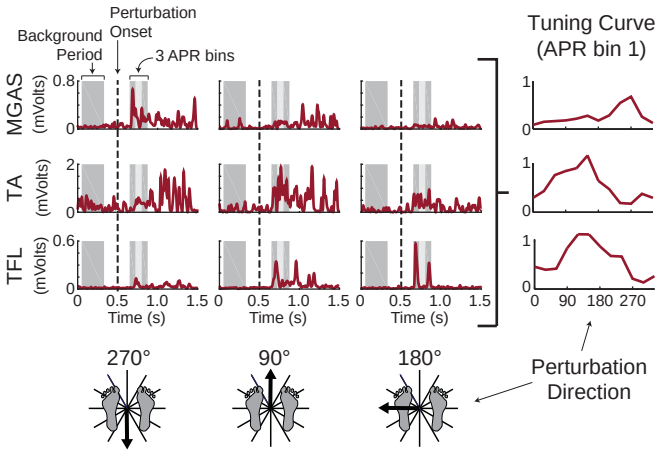
Participant	# of outcome measures	
	Expected change	Non-expected change
PR1	8	1
PR2	9	0
PR3	9	0
PR7	2	7
PR8	9	0
PR9	5	4

Abbreviations: n, motor module number (i.e. complexity); $\%_{shared}$, proportion of motor module shared across walking and reactive balance (i.e., generalizability); d, motor module distinctness, R95, motor module variability; W_{mus}, motor module co-activity. Participant codes are as in (McKay et al. 2016).

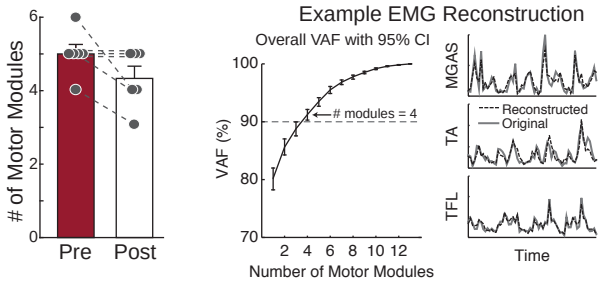
A. Overground Walking Muscle Activity



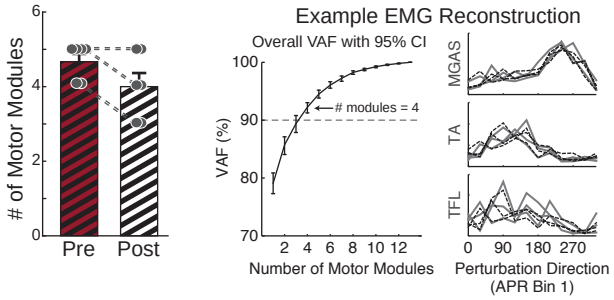
B. Reactive Balance Muscle Activity

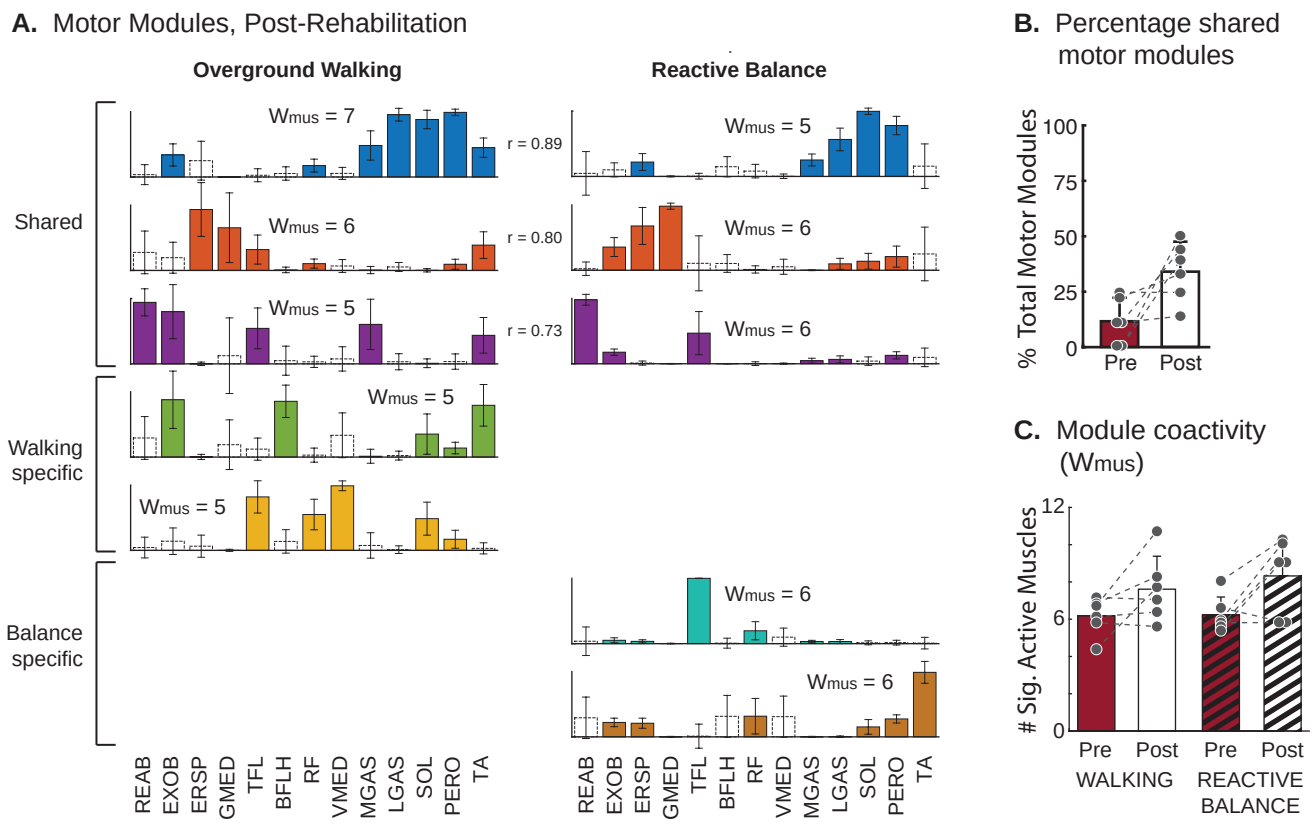


A. Overground Walking Motor Modules

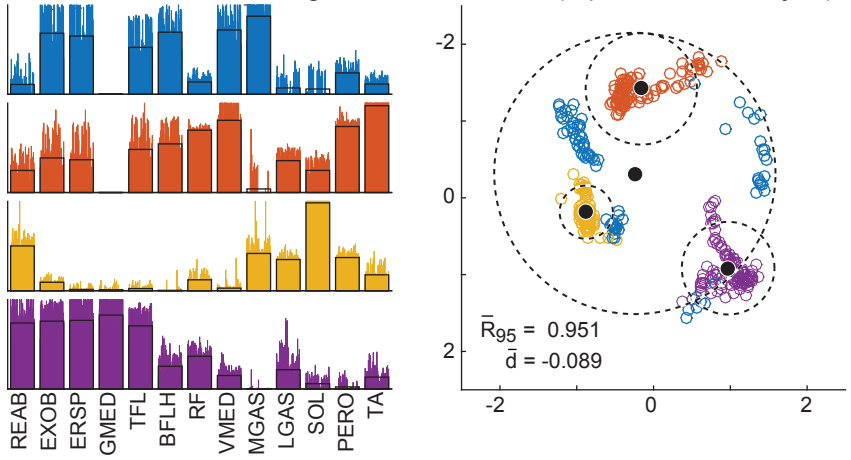


B. Reactive Balance Motor Modules

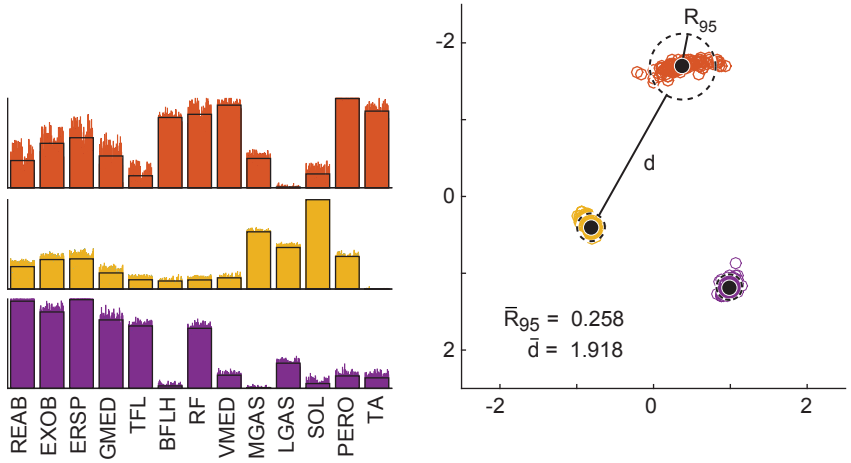



A. Motor Modules, Post-Rehabilitation
Overground Walking
Reactive Balance
Shared
Walking specific
Balance specific
Wmus = 7
Wmus = 6
Wmus = 5
Wmus = 5
Wmus = 5
Wmus = 6
Wmus = 6
Wmus = 6
r = 0.89
r = 0.80
r = 0.73
REAB
EXOB
ERSP
GMED
TFL
BFLH
RF
VMED
MGAS
LGAS
SOL
PERO
TA
B. Percentage shared motor modules
% Total Motor Modules
100
75
50
25
0
Pre
Post
C. Module coactivity (Wmus)
Sig. Active Muscles
12
6
0
Pre
Post
Pre
Post
WALKING
REACTIVE BALANCE

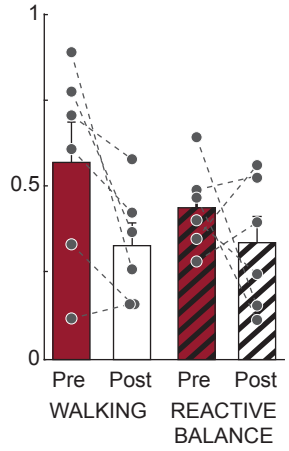
A. Motor Modules for Walking, Pre-Rehabilitation (representative subject)



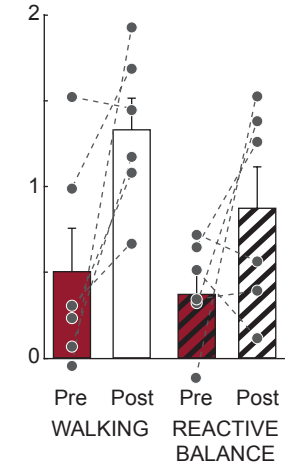
B. Motor Modules for Walking, Post-Rehabilitation (representative subject)

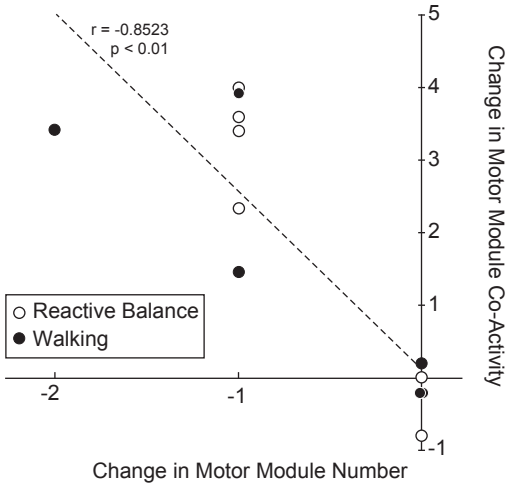


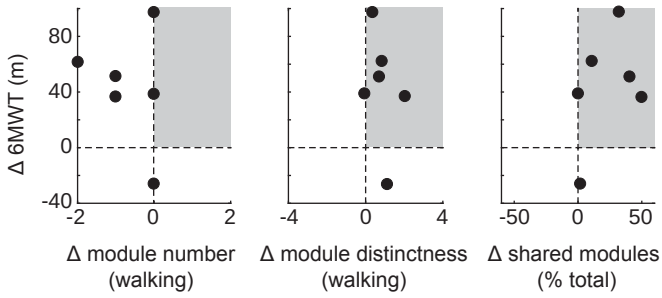
C. Spatial Variability ($\bar{R}_{95}$)



D. Spatial Distinctness ($\bar{d}$)




r = -0.8523
p < 0.01
Reactive Balance
Walking
5
4
3
2
1
-1
-2
-1
Change in Motor Module Co-Activity
Change in Motor Module Number


Δ 6MWT (m)
80
40
0
-40
-2
0
2
Δ module number
(walking)
-4
0
4
Δ module distinctness
(walking)
-50
0
50
Δ shared modules
(% total)