

## Variability in Postural Control With and Without Balance-Based Torso-Weighting in People With Multiple Sclerosis and Healthy Controls

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**Background.** People with multiple sclerosis (MS) have diminished postural control, and center of pressure (COP) displacement varies more in this population than in healthy controls. Balance-based torso-weighting (BBTW) can improve clinical balance and mobility in people with MS, and exploration using both linear and nonlinear measures of COP may help determine whether BBTW optimizes movement variability.

**Objective.** The aim of this study was to investigate the effects of BBTW on people with MS and healthy controls during quiet standing.

**Design.** This was a quasi-experimental study comparing COP variability between groups, between eye closure conditions, and between weighting conditions in the anterior-posterior and medial-lateral directions.

**Methods.** Twenty participants with MS and 18 healthy controls stood on a forceplate in 4 conditions: eyes open and closed and with and without BBTW. Linear measures of COP displacement included range and root mean square (RMS). Nonlinear measures included approximate entropy (ApEn) and Lyapunov exponent (LyE). Three-way repeated-measures analyses of variance compared measures across groups and conditions. The association between weighting response and baseline nonlinear variables was examined. When significant associations were found, MS subgroups were created and compared.

**Results.** The MS and control groups had significantly different range, RMS, and ApEn values. The eyes-open and eyes-closed conditions had significantly different range and RMS values. Change with weighting correlated with LyE ( $r = -.70$ ) and ApEn ( $r = -.59$ ). Two MS subgroups, with low and high baseline LyE values, responded to BBTW in opposite directions, with a significant main effect for weighting condition for the LyE variable in the medial-lateral direction.

**Limitations.** The small samples and no identification of impairments related to LyE at baseline were limitations of the study.

**Conclusions.** The LyE may help differentiate subgroups who respond differently to BBTW. In both subgroups, LyE values moved toward the average of healthy controls, suggesting that BBTW may help optimize movement variability in people with MS.

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Multiple sclerosis (MS) is the leading progressive neurologic disease in young adults, affecting 2.5 million people worldwide.<sup>1</sup> In the United States, an estimated 10,000 people are diagnosed with MS every year.<sup>2</sup> More than 90% of people living with MS report decreased mobility, frequently concurrent with a decrease in postural control.<sup>3,4</sup> Even early in the course of the disease, people with MS develop differences in mobility compared with healthy individuals.<sup>5,6</sup> Rehabilitation that addresses postural control potentially prolongs higher levels of mobility over the 20 years most people remain ambulatory after diagnosis.<sup>4</sup> One rehabilitative intervention in which small weights are strategically applied to the torso based on the direction of balance loss—balance-based torso-weighting (BBTW)—has resulted in immediate improvements in clinical measures of balance and mobility in people with MS.<sup>7-9</sup> These improvements, however, have varied across individuals, perhaps because of heterogeneous characteristics in samples.

Heterogeneity in MS occurs because patients develop different areas of demyelination, many that affect postural control. Postural control, the act of maintaining, achieving, or restoring upright posture during standing and walking, requires sensory and motor systems to work together in a complex interaction.<sup>10-13</sup> Impairment of commonly affected neural pathways associated with sensation, vision, vestibular input, sensory integration, motor control, and muscle activation<sup>14-18</sup> makes dysfunction in postural control strategies and subsequent loss of balance more likely, increasing the risk for falls.<sup>15,17,19,20</sup> More than 50% of younger and middle-aged people with MS report having fallen recently, and more than 50% of older people with MS report having injurious falls.<sup>21-23</sup> The majority of people

with MS report fear of falling, and many report curtailing their activity because of this fear.<sup>24</sup>

Assessing the component of postural control involved in maintaining the body's center of mass within the boundaries of the base of support frequently involves examining postural sway, where larger sway correlates with higher fall incidence.<sup>25</sup> Center of pressure (COP) displacement, an indicator of postural sway, has consistently diverged between people with and without MS. Karst et al<sup>5</sup> reported decreased COP displacement during reaching tasks for people with minimal impairments from MS compared with healthy controls. Huisinga et al<sup>26</sup> noted increased COP displacement in quiet standing in people with moderate impairments from MS compared with healthy controls. Daley and Swank<sup>19</sup> assessed anterior-posterior (AP) postural sway in patients with eyes open and eyes closed, noting that, with eyes closed, 8% of the 13 patients with minimal impairment but 100% of the 16 patients with severe impairments exhibited sway more than 3 standard deviations greater than the mean of age-matched controls ( $P < .03$  for differences among 4 groups with MS,  $n = 113$ ).

Traditional reports of postural sway have noted the amount of COP displacement using linear measures such as range and root mean square (RMS). Recent literature has advocated the addition of nonlinear measures to the assessment of movement over time, with proposed advantages in assessing deficits postinjury or with dysfunction.<sup>27,28</sup> Human movement occurs dynamically based on the state of the system and environment at prior moments and on the most efficient trajectory to meet the goal in succeeding moments. For example, COP displacement should indicate that the person

sways back and forward and right and left depending on the immediately preceding position toward the center or edge of the base of support, rather than swaying at random, or with the same pattern regardless of the starting position. Meeting goals efficiently means incorporating sufficient complexity into the variability of movement to adapt to environmental changes while the movement occurs. Nonlinear measures can provide insight into each individual's capability to meet movement goals in multiple environments under different conditions.<sup>27</sup>

Nonlinear measures of pattern structure include approximate entropy (ApEn, a measure of unpredictability) and Lyapunov exponent (LyE, a measure of divergence).<sup>28</sup> Invariable patterns show exact repetition with no divergence, resulting in low values for both ApEn and LyE. Highly variable movement shows randomness, lack of patterns, and highly divergent variation, resulting in higher values of ApEn and LyE. In describing the *optimal movement variability* theoretical perspective, Stergiou et al<sup>28</sup> posited that normal movement requires the right level of complexity, with structured variability but not exact repetition. Differences in nonlinear measurements in people with MS compared with healthy controls may underlie observed movement dysfunction in people with MS. Lower values of ApEn in people with MS have indicated more repetitive movement compared with healthy controls for COP displacement during quiet standing<sup>26</sup> and for stride length and width during steady gait.<sup>29</sup> The authors interpreted these differences as reduced capacity to adapt and respond to perturbations.<sup>26,29</sup> Higher values of LyE in people with MS have indicated more divergence in trunk acceleration during gait compared with healthy controls.<sup>30</sup> Huisinga et al<sup>30</sup> interpreted greater divergence

as lack of control from one gait cycle to the next, with disturbances in one gait cycle potentially affecting the next and subsequent gait cycles.

In addition to distinguishing between normal and disordered movement, nonlinear measures can show change with intervention.<sup>28,31,32</sup> Theoretically, interventions that optimize movement variability should result in an increase when baseline values are lower than optimal and in a decrease when baseline values are higher than optimal.<sup>28</sup> However, studies have not yet demonstrated differences in direction of change in nonlinear measures based on differences in preintervention values. Examining the association between preintervention variable values and the change in these variables with intervention may help discern different movement characteristics of people who respond differently to an intervention such as BBTW.

Strategic application of small weights using BBTW typically results in immediate improvement in the ability to resist or respond to a balance perturbation<sup>33</sup> and, on average, results in faster gait.<sup>7,8</sup> For patients, wearing the weights daily during exercise or activity has improved function (holding a Romberg position with eyes open and eyes closed, holding a single-leg stance, decreased dizziness and assistance needed during gait, reading while walking) both with and without weights, with better function while weighted.<sup>9</sup> The mechanism for improved function with BBTW is under investigation. Location of the weights does not directly correlate with direction of change in COP.<sup>33</sup> Furthermore, immediate BBTW results remain significant when assessors are blinded<sup>7</sup> or patients are randomized to a BBTW or placebo (standardized weight placement with 1.5% of body weight) group.<sup>8</sup> Investigating nonlin-

ear measures of COP variability with BBTW may help unmask differences in individual response and enhance future research into its mechanism.

In a previous study without an intervention, Huisinga et al,<sup>26</sup> reported measures of variability of COP displacement with eyes open and eyes closed in people with MS and healthy controls, with higher range and RMS values but lower ApEn and LyE values for people with MS. In their protocol, participants stood with feet apart for 3.5 minutes for each condition. Our protocol differs from theirs because the primary purpose of the current study was to examine the effects of a specific intervention (ie, BBTW) on the variability of COP in people with MS.

We examined ApEn, LyE, range, and RMS of COP displacement during quiet standing, with eyes open and eyes closed, in people with MS and healthy controls. We hypothesized that range, RMS, ApEn, and LyE values would differ in the medial-lateral (ML) and AP directions, between: (1) people with MS and healthy controls, (2) eyes-open and eyes-closed conditions, and (3) no-weight and weighted conditions. To test our premise that effective BBTW results in optimization of movement variability, we also examined the relationship between BBTW change and baseline variability. We hypothesized that ApEn and LyE measures would increase with BBTW if baseline values were low and decrease with BBTW if baseline values were high.

## Method

Eligibility for participants with MS included diagnosis of MS, ability to communicate in English, over 17 years of age, ability to ambulate 9.1 m (30 ft) or more (with or without a cane), self-reported balance or mobility difficulties caused by MS, and capability of tolerating up to 3

hours of testing with rest breaks. Exclusion criteria included exacerbation of MS within the previous 2 months, diagnosis of a concurrent neurological disorder, or any pain that could be exacerbated by external perturbations during standing or multiple trials of walking. Participants with MS were recruited through newsletter ads for the Northern California Chapter of the National Multiple Sclerosis Society and local neurology clinics. Eligibility criteria for control participants included the ability to communicate in English, absence of any known diagnoses or current pain that would affect balance or gait, and physical criteria that matched each participant with MS. Physical criteria to match groups included age (within 7 years), height (within 12.7 cm [5 in]), mass (within 9.1 kg [20 lb]), and sex (Tab. 1). Control participants were recruited through personal contacts and online postings on Craigslist.org. All participants provided informed consent for their participation.

Participants completed a medical questionnaire about symptoms and fall history. Responses to the medical questionnaire were used to determine approximate levels of disability, represented as equivalence scores on the Expanded Disability Status Scale<sup>34</sup> (EDSS, where 0=normal neurological function and 10=death due to MS). Clinical measures for each participant included height, weight, foot length, leg length, heart rate, and blood pressure. A BBTW garment without weights was applied and adjusted to fit the trunk. All participants wore the garment throughout testing.

Static balance without weighting was assessed while participants stood quietly with feet together, touching at heels and forefeet, and aligned with markings on a forceplate. Participants were instructed to

**Table 1.**  
Participant Demographics<sup>a</sup>

| Variable                                     | MS Group (n=20)    | Control Group (n=18) | p <sup>b</sup> |
|--|--------------------|----------------------|----------------|
| Age (y), $\bar{X}$ (SD), range               | 49.4 (13.4), 24–68 | 47.3 (11.2), 29–69   | .615           |
| Years since diagnosis, $\bar{X}$ (SD)        | 12.8 (8.2)         |                      |                |
| EDSS score equivalent, $\bar{X}$ (SD), range | 4.1 (1.6), 2–6     |                      |                |
| No. of falls in previous 12 mo               | 2.0 (3.4)          | 0.3 (0.5)            | .008           |
| Height (cm), $\bar{X}$ (SD)                  | 166.2 (6.0)        | 165.5 (7.2)          | .754           |
| Mass (kg), $\bar{X}$ (SD)                    | 73.2 (15.7)        | 72.4 (14.8)          | .868           |
| % body weight BBTW, $\bar{X}$ (SD)           | 1.0 (0.4)          | 0.8 (0.3)            | .026           |
| Type of MS (n)                               |                    |                      |                |
| Primary progressive                          | 1                  |                      |                |
| Secondary progressive                        | 4                  |                      |                |
| Relapsing remitting                          | 11                 |                      |                |
| Unknown                                      | 4                  |                      |                |
| Vision impairment (n)                        | 10                 | 2                    |                |
| Dyesthesia (n)                               | 16                 | 2                    |                |
| Vestibular impairment (n)                    | 11                 | 0                    |                |

<sup>a</sup> MS=multiple sclerosis, control group=healthy participants, EDSS=Expanded Disability Status Scale, BBTW=balance-based torso-weighting.

<sup>b</sup> Two-tailed *t* test,  $\alpha=.05$ .

stand as still as possible for 10 seconds for one trial with eyes open and for a second trial with eyes closed. We chose the 10-second time period for each trial to imitate part of the BBTW procedure for determining weight placement. Although clinically relevant, the abbreviated time period restricted the number of times COP displacement might repeat any patterns of movement, potentially limiting accurate calculation of nonlinear measures.

### BBTW Protocol

Following the baseline static standing without weights, standing balance was assessed with the BBTW protocol<sup>7–9</sup> and assessment kit (Motion Therapeutics Inc, Oxnard, California). Assessment of balance included observation of relative amount and direction of sway during static standing with eyes open and eyes closed. To control for possible interrater differences, one physical therapist performed all assessments

and weight application. Another physical therapist guarded participants during balance testing. The tester perturbed standing balance of each participant with anterior, posterior, and lateral nudges to the shoulders and pelvis and observed amount and latency of recovery and amount and direction of balance loss. *Balance loss* was defined as tilt or lean of the trunk requiring opposing parachute reaction, stepping response, or manual contact by the tester or guard to regain center of mass over the base of support. The tester also applied rotational force toward the right and left through the shoulders and then pelvis to determine asymmetry in ability to resist rotational force. Weights were strategically placed on the BBTW garment in 0.11- to 0.23-kg (0.25- to 0.5-lb) increments via Velcro attachment (Velcro USA Inc, Manchester, New Hampshire). The tester confirmed the location of weights with additional perturba-

tions and weight adjustments until the participant showed minimal loss of balance or sway latency when perturbed and showed greater symmetry of force production when rotational resistance was applied.

Once location of weights was confirmed, participants had a mandatory rest period prior to retesting static standing. Participants aligned their feet again with lines marked on the forceplate. Weighted static standing trials with eyes open and eyes closed were then performed for 10 seconds each on the forceplate.

### Data Analysis

The forceplate recorded COP displacement at 600 Hz by default (BioWare software, Kistler Instrument Corp, Amherst, New York). To determine an appropriate sampling frequency, we examined the power spectrum produced from a representative sample of the COP time series. The power spectrum showed that 99.9% of the sample frequency was contained below 3.4 Hz, indicating that the subsampling frequency should be set between 6.8 and 34 Hz (2–10 times the highest frequency present in the signal). We downsampled all of the data to 25 Hz. Each condition was examined separately for the ML and AP directions.

Data were processed using Cortex software (Motion Analysis Corp, version 1.1.4.368, Santa Rosa, California) and exported to Excel (version 2010, Microsoft Corp, Redmond, Washington). Nonlinear measures were calculated using a custom-designed program in MatLab (The Mathworks Inc, Natick, Massachusetts). Approximate entropy was calculated using the algorithm developed by Pincus and colleagues<sup>35,36</sup> ( $m$  [dimensional value]=2,  $r$  [criterion of similarity]=.2, lag=1,  $N$ =250). Lyapunov exponent was calculated using the algorithm “global false nearest neighbor” for embed-

**Table 2.**Main Effects of Mixed-Design, Repeated-Measures Analyses of Variance for 4 Measures in 2 Directions of Center of Pressure Displacement<sup>a</sup>

| Group       | Medial-Lateral Direction |      |                |      |                |      |                |      | Anterior-Posterior Direction |      |                |      |                |      |                |      |
|-------------|--------------------------|------|----------------|------|----------------|------|----------------|------|------------------------------|------|----------------|------|----------------|------|----------------|------|
|             | Range                    |      | RMS            |      | ApEn           |      | LyE            |      | Range                        |      | RMS            |      | ApEn           |      | LyE            |      |
|             | F <sup>b</sup>           | P    | F <sup>b</sup> | P    | F <sup>b</sup> | P    | F <sup>c</sup> | P    | F <sup>b</sup>               | P    | F <sup>b</sup> | P    | F <sup>b</sup> | P    | F <sup>c</sup> | P    |
| MS, control | 10.73                    | .002 | 10.84          | .002 | 8.53           | .006 | 0.69           | .413 | 13.46                        | .001 | 13.71          | .001 | 4.17           | .049 | 0.55           | .464 |
| EO, EC      | 10.20                    | .003 | 9.86           | .003 | 0.34           | .561 | 1.36           | .252 | 12.66                        | .001 | 8.94           | .005 | 1.43           | .24  | 0.79           | .381 |
| NW, W       | 0.01                     | .928 | 0.11           | .738 | 0.01           | .91  | 2.35           | .135 | 0.54                         | .469 | 0.13           | .72  | 1.27           | .267 | 2.25           | .142 |

<sup>a</sup> RMS=root mean square linear variable, ApEn=approximate entropy nonlinear variable, LyE=Lyapunov exponent nonlinear variable, MS=participants with multiple sclerosis, control group=healthy participants, EO=eyes-open condition, EC=eyes-closed condition, NW=no-weight condition, W=weighted condition.

<sup>b</sup> Degrees of freedom=1,36.

<sup>c</sup> Degrees of freedom=1,34.

ding dimension<sup>37</sup> and “average mutual information” for time delay. To determine the parameters for LyE for comparison across all participants, we calculated embedded dimension and time delay for each time series and found the average values (embedding dimension=4, time delay=4); these calculations were used to obtain LyE for all participants.

Analyses of range, RMS, ApEn, and LyE were performed in 2 directions (ML and AP, as in the study by Huisinga et al<sup>26</sup>) using mixed-design, repeated-measures analyses of variance (ANOVAs) ( $2 \times 2 \times 2$ ) for the following comparisons: (1) control group versus MS group (group), (2) eyes open versus eyes closed (EO-EC condition), and (3) no weight versus weighted (weight condition). Examination of the association between change with BBTW intervention and preintervention values of LyE and ApEn used the correlation: BBTW change (weighted minus no-weight values) versus baseline (no-weight values).

When examining correlations, we focused on the eyes-open condition as most applicable to normal activities for most individuals. We expected that if BBTW changed variability toward an optimal movement pattern, people who had baseline

values below the optimum would increase those values (with a positive number for BBTW change) and people with baseline values above the optimum would decrease those values (with a negative number for BBTW change). Where correlations were significant, the MS group was subdivided into 2 groups according to lower and higher baseline values; a 3-way ANOVA was repeated using the new subgroups ( $3 \times 2 \times 2$ ). When the main effect for subgroup was significant, pairwise analyses determined which subgroups were different. When interactions between subgroup and weight condition were significant, *t* tests revealed potential differences in effect of weighting in subgroups. Analyses were performed in Excel and SPSS (version 20.0) with level of significance set at  $\alpha=.05$ .

### Role of the Funding Source

This study was supported by Award Number R15HD066397 from the Eunice Kennedy Shriver National Institute of Child Health and Human Development.

### Results

Twenty people with MS (EDSS<sup>34</sup> range equivalent 2–6) and 20 healthy controls participated. All participants were female (prevalence in MS is generally 2–3 women:1 man); the few men who expressed interest

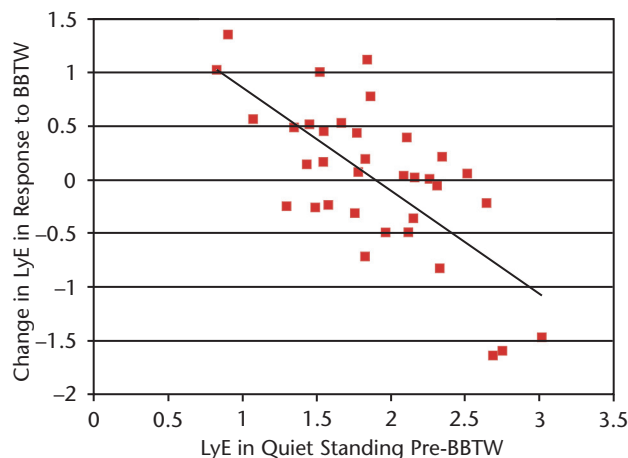
did not meet study criteria regarding timing of exacerbations and confirmed diagnosis. For 2 controls, technical difficulties with the forceplate and software made their data unusable, leaving 18 controls for most measures (Tab. 1). For 2 of the remaining control group participants, a LyE value could not be calculated for one of the EC conditions; thus, for LyE, data for only 16 controls were analyzed in the ANOVAs.

### MS and Control Groups

For the variables range, RMS, and ApEn, but not LyE, a significant main effect of group was found in both the ML and AP directions (Tab. 2). The MS group had higher range and RMS values but lower ApEn values in both ML and AP directions compared with the control group.

### EO-EC Condition

For range and RMS, the main effect of the EO-EC condition was significant (Tab. 2). Range and RMS values were higher in the eyes-closed condition than in the eyes-open condition for both ML and AP directions. For ApEn and LyE, the main effect of EO-EC condition was not significant in either direction. A group  $\times$  EO-EC condition interaction was significant for ApEn ( $F_{1,36}=4.77$ ,  $P=.036$ ) in the ML direction, with lower ApEn values for controls with eyes closed



**Figure.**

Correlation between Lyapunov exponent (LyE) at baseline and change in LyE with balance-based torso-weighting (BBTW), medial-lateral direction.

but with higher values with eyes closed for people with MS.

### Weight Condition

For all variables, the main effect of weight condition was not significant in either ML or AP direction (Tab. 2). No interaction effects were significant between weight condition and other factors.

### BBTW Change and Baseline

The correlation between BBTW change and the value of LyE at baseline with eyes open was  $r = -.70$  ( $P < .001$ ) in the ML direction (Figure) and  $r = -.75$  ( $p < .001$ ) in the AP direction. The correlation between BBTW change and value of ApEn at baseline with eyes open was  $r = -.59$  ( $P < .005$ ) in the ML direction and not significant ( $r = -.19$ ) in the AP direction.

### Subgrouping

Because the correlation between BBTW change and baseline was moderately strong for LyE and both LyE and ApEn correlated with BBTW change in the ML direction, we subdivided the group with MS based on the median LyE (2.07) for controls in the eyes-open condition in the ML direction. The resulting subgroups

had higher and lower values of LyE, respectively (MS HiLyE,  $n = 6$ : LyE average = 2.22; MS LoLyE,  $n = 14$ : LyE average = 1.54) compared with controls ( $n = 18$ : LyE average = 2.07). Although we focused on the ML direction, we noted that, in the MS HiLyE subgroup, 5 of the 6 people had LyE values greater than the control group's average for both ML and AP directions.

For LyE, a significant main effect of subgroup was found in the ML direction (3-way ANOVA,  $3 \times 2 \times 2$ ,  $F_{2,33} = 7.56$ ,  $P = .002$ ), with a pairwise difference between the MS subgroups ( $P = .002$ ), where MS LoLyE values were lower than MS HiLyE values. Also, the main effect for weight condition was significant ( $F_{1,33} = 4.26$ ,  $P = .047$ ), where LyE values generally decreased with BBTW. No interaction effects were significant.

Analyses of variance ( $2 \times 2 \times 2$ ) were repeated for each variable in the ML direction with just the MS subgroups. The interaction was significant between subgroup and weight condition in the ML direction for LyE ( $F_{1,18} = 7.153$ ,  $P = .015$ ), with LyE values increasing with BBTW for

the MS LoLyE subgroup and decreasing with BBTW for the MS HiLyE subgroup. The interaction tended toward significance for range ( $F_{1,18} = 3.168$ ,  $P = .092$ ) and RMS ( $F_{1,18} = 2.975$ ,  $P = .102$ ), with linear variability tending to decrease with BBTW for the MS LoLyE subgroup and increase with BBTW for the MS HiLyE subgroup. For ApEn in the ML direction, the interaction was significant for subgroup  $\times$  weight condition  $\times$  EO-EC condition ( $F_{1,18} = 8.184$ ,  $P = .010$ ). For the MS LoLyE subgroup, ApEn values increased in the eyes-open condition and decreased in the eyes-closed condition with BBTW. Approximate entropy values changed in the opposite direction for the MS HiLyE subgroup with BBTW.

The  $t$  tests revealed significant differences between subgroups in response to BBTW in the ML direction but not the AP direction for LyE, ApEn, and RMS (Tab. 3). The 2 MS subgroups tended to respond to BBTW in opposite ways (increasing or decreasing, as depicted in Tab. 4) for LyE, ApEn, and RMS, with differences significant for LyE ( $P < .003$ ). Range and RMS data were highly correlated across participants for all conditions ( $r = .94 - .99$ ), so only RMS is depicted in the tables.

### Discussion

We postulated that, if effective, BBTW would optimize movement variability. In these samples, weighting showed a significant effect in LyE in the ML direction when people with MS were grouped by preintervention LyE values. Furthermore, values on LyE, ApEn, and RMS in the MS subgroups changed or tended to change in opposite ways with weighting, possibly toward a more optimal pattern. The MS subgroup differences were masked when analyzing average responses to BBTW.

Analyzing data for the total groups prior to subgroup analyses tested the utility of our protocol despite the limited time series (10 seconds) for nonlinear measures. Huisinga et al<sup>26</sup> performed a similar study of linear and nonlinear variability in COP displacement for healthy controls and people with MS but used a much longer time series (3.5 minutes). Despite differences in length of time series, main effects for our first 2 hypotheses paralleled theirs for range, RMS, and ApEn; LyE results differed between the study by Huisinga et al and the current study.

### MS and Control Groups

Our data showed differences in range, RMS, and ApEn in both ML and AP directions. The 2 groups did not differ on LyE in either direction. Huisinga et al<sup>26</sup> reported the same group effects for range and RMS. In their study, ApEn differed between groups only in the ML direction, and LyE differed between groups (lower in the MS group) in both ML and AP directions.

### EO-EC Condition

Our data showed differences in range and RMS in both ML and AP directions. The eye conditions did not differ on ApEn or LyE, although we noted an interaction between group and eye condition in the ML direction for ApEn. Huisinga et al<sup>26</sup> reported significant differences for RMS but not for ApEn and LyE, no interaction effect for ApEn, and presence of interaction effects for LyE in both ML and AP directions.

Unlike Huisinga et al,<sup>26</sup> our analyses included a third factor to address the intervention, and we examined the correlation between BBTW change and baseline COP variability.

### Weight Condition

Weighting was not significant for any measure in the ML or AP direction when examining the MS and control

**Table 3.**

Mean (SD) Change in LyE, ApEn, and RMS With Weights in Each Eye Closure Condition<sup>a</sup>

| Variable and Group | EO ML         | EC ML         | EO AP         | EC AP         |
|--------------------|---------------|---------------|---------------|---------------|
| LyE                |               |               |               |               |
| Control            | -0.119 (0.85) | -0.126 (0.41) | 0.0005 (0.64) | -0.165 (0.65) |
| MS LoLyE           | 0.199 (0.55)  | -0.087 (0.50) | -0.172 (0.63) | -0.025 (0.59) |
| MS HiLyE           | -0.196 (0.46) | -0.532 (0.38) | -0.070 (0.72) | -0.246 (1.2)  |
| ApEn               |               |               |               |               |
| Control            | 0.002 (0.16)  | -0.030 (0.15) | -0.050 (0.17) | 0.002 (0.17)  |
| MS LoLyE           | 0.068 (0.14)  | -0.021 (0.08) | -0.021 (0.13) | -0.034 (0.10) |
| MS HiLyE           | -0.058 (0.07) | 0.020 (0.07)  | -0.035 (0.09) | 0.043 (0.15)  |
| RMS (cm)           |               |               |               |               |
| Control            | -0.017 (0.18) | 0.040 (0.21)  | 0.032 (0.21)  | -0.022 (0.21) |
| MS LoLyE           | -0.045 (0.28) | -0.048 (0.40) | -0.019 (0.36) | -0.065 (0.35) |
| MS HiLyE           | 0.190 (0.19)  | 0.093 (0.40)  | 0.035 (0.14)  | -0.021 (0.22) |

<sup>a</sup> LyE=Lyapunov exponent nonlinear variable, ApEn=approximate entropy nonlinear variable, RMS=root mean square linear variable, EO=eyes-open condition, EC=eyes-closed condition, ML=center of pressure movement in the medial-lateral direction, AP=center of pressure movement in the anterior-posterior direction, control=healthy participants (n=18), MS LoLyE=participants with multiple sclerosis having LyE values lower than the control group's median LyE value (2.07) recorded with eyes open in ML direction (n=14), MS HiLyE=participants with multiple sclerosis having LyE values higher than the control group's median LyE value when recorded with eyes open in ML direction (n=6). A negative change indicates that the value decreased with balance-based torso-weighting. \*t test for difference between groups: P<.05; LyE, t=2.17; ApEn, t=2.75; RMS, t=-2.19.

groups. Weighting condition was significant for LyE in the ML direction after we subdivided the MS group based on preintervention LyE values.

### BBTW Change and Baseline

Change in LyE with weighting showed a moderately strong negative correlation with LyE at baseline in both the ML and AP directions. People with lower values and higher values tended to change in opposite ways with this intervention, potentially converging on more optimal movement variability. The subgroups responded differently from each other on nonlinear and linear variables.

If BBTW optimizes movement variability,<sup>28</sup> it may help reduce the risk for falls while providing patients with greater freedom when encountering changes in their environment. However, analyzing the effectiveness of any intervention requires

accurate categorization of patients according to the type of response projected. Nonlinear variables may help to distinguish between motor control that is so random that people are unable to accomplish target tasks consistently or so rigid and predictable that they can only accomplish target tasks when the conditions stay the same. People with MS could have more random and divergent variability than normal or more rigid and repetitive patterns than normal, depending on an individual's specific symptoms, disease subtype, lesion volume, and location of lesions. For example, people with ataxia may respond differently than people with spasticity. This study supports the possibility of movement optimization with BBTW. First, both LyE ( $r=-.70$ ,  $P<.001$ ) and ApEn ( $r=-.59$ ,  $P<.005$ ) showed a negative but moderate-to-strong correlation between baseline values and change

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**Table 4.**

Variables Averaged Over Eyes-Open and Eyes-Closed Conditions in the Medial-Lateral Direction to Depict Directional Change Tendencies With Weighting<sup>a</sup>

| Variable and Group | No Weight     | Weighted      | Change With Weights |
|--------------------|---------------|---------------|---------------------|
| LyE                |               |               |                     |
| Control            | 2.03 (0.31)   | 1.91 (0.33)   | ⇐                   |
| MS LoLyE           | 1.73 (0.16)   | 1.79 (0.387)  | ⇐ }††               |
| MS HiLyE           | 2.43 (0.35)   | 2.06 (0.49)   |                     |
| ApEn               |               |               |                     |
| Control            | 0.56 (0.17)*  | 0.55 (0.12)*  | ⇐                   |
| MS LoLyE           | 0.44 (0.10)   | 0.46 (0.11)   | ⇐                   |
| MS HiLyE           | 0.47 (0.07)   | 0.45 (0.04)   | ⇐                   |
| RMS (cm)           |               |               |                     |
| Control            | 0.47 (0.19)** | 0.48 (0.15)** | ⇐                   |
| MS LoLyE           | 0.90 (0.61)   | 0.85 (0.43)   | ⇐                   |
| MS HiLyE           | 0.81 (0.41)   | 0.95 (0.54)   | ⇐                   |

<sup>a</sup> LyE=Lyapunov exponent nonlinear variable, ApEn=approximate entropy nonlinear variable, RMS=root mean square linear variable, control=healthy participants (n=18), MS LoLyE=participants with multiple sclerosis (MS) having LyE values lower than the control group's median LyE value (2.07) recorded with eyes open in the medial-lateral direction (n=14), MS HiLyE=participants with multiple sclerosis having LyE values higher than the control group's median LyE value when recorded with eyes open in the medial-lateral direction (n=6). ††t test for difference between MS groups: LyE no weight,  $t=-4.59$ ,  $P<.004$ . ††Difference between MS groups: LyE change with weights,  $t=-3.51$ ,  $P<.003$ . \*t test for difference between control and MS groups:  $P<.05$ ; ApEn no weight,  $t=2.55$ ; weighted,  $t=2.54$ . \*\*Difference between control and MS groups:  $P<.01$ ; RMS no weight,  $t=-3.05$ ; weighted,  $t=3.68$ .

that occurred with weighting. Second, BBTW resulted in changes in opposite ways (increasing versus decreasing) for the 2 MS subgroups, a significant difference for LyE, and a tendency for ApEn and RMS. If BBTW results in changes in COP variability, whether too repetitive or too random, to move the pattern toward optimal variability, application of the intervention to both groups is supported.

Although MS subgroups changed toward the mean of controls on LyE with weighting, optimization of movement variability remains uncertain. The control group had a large between-subject variance, with LyE values completely overlapping values in the 2 MS subgroups at baseline. This overlap hinders targeting a single value of LyE as the goal for “optimal” divergence. Despite the overlap in LyE values, the 2 groups

had distinctly different linear measures of variability, with larger range and RMS values in the MS group compared with the control group. Optimizing the amount of movement variability would imply that both subgroups should decrease in linear measures with weighting. However, only the MS LoLyE subgroup decreased RMS with BBTW, whereas the MS HiLyE subgroup appeared to increase RMS. Perhaps hypermetria in the MS HiLyE subgroup becomes exaggerated with the small additional inertial mass of BBTW, resulting in increased range and RMS.<sup>38</sup> The observed changes were small and only in the ML direction for either subgroup, but the MS LoLyE subgroup appeared to have the more recognizable optimization of the amount of movement variability with BBTW.

Limitations to our study include the small sample sizes and the short monitoring time (10 seconds). Sample size was further decreased for assessing LyE because for 2 control group participants, LyE could not be calculated in 1 of 8 conditions. However, these were the only 2 trials that did not yield an LyE value out of the 304 time series examined. In addition to the small sample, multiple procedures were performed without correction of alpha levels, increasing the possibility of finding spurious results in our exploratory study. Similarities between our results and those of Huisinga et al<sup>26</sup> support the conclusions of both studies, however, and support our protocol for examining differences with and without BBTW.

Another limitation was that the baseline and intervention conditions were assessed during the same session, restricting practice of alternative postural control strategies with BBTW. Previous studies indicating changes in nonlinear measures with intervention have used longer time periods. In a study by Stergiou et al,<sup>28</sup> 2 infants (1 year old) with cerebral palsy underwent a 2-month program of therapy of different types; one infant showed increased complexity of behavior, as indicated by a higher ApEn. In a study by Sethi et al,<sup>39</sup> 6 individuals poststroke underwent constraint-induced movement therapy for 2 weeks, but the higher ApEn post-intervention did not reach statistical significance. In a study by Bar-Haim et al,<sup>31</sup> individuals with hemiparesis and cerebral palsy participated in perturbation training for 12 weeks, with a resulting increase in gait complexity (higher ApEn).<sup>31</sup> Our data indicate that variability can change with intervention in this short time period, but further changes with potentially important functional effects likely require additional experience with the weighted

condition, such as wearing the weights for 30 minutes twice daily for several weeks during exercise and function.<sup>9</sup>

We collected no clinical measurements of dysmetria, spasticity, or sensory loss in this study and thus can make no definitive associations of impairments with LyE subgroup membership; we noted that EDSS scores ranged from 2 to 6 in both MS LyE subgroups. Future studies will examine possible associations such as amount of sensory dysfunction in the lower extremities. Previous studies examining the effects of restricting one sensory modality have shown that the remaining postural system compensates with a higher reliance on fewer sensory modalities to maintain balance.<sup>40,41</sup>

When sensory systems have deficits, delayed postural control may manifest in larger range and RMS before catching postural sway and moving back toward an equilibrium point. Our data showed the expected increase in COP range and RMS in the eyes-closed condition in both AP and ML directions but did not show concomitant significant decreases in ApEn or LyE that might indicate more repetitive postural sway with eye closure. On the other hand, we expected that BBTW, as a form of sensory augmentation, should decrease range and RMS; these decreases were found in the MS LoLyE subgroup. Our medical questionnaires did not reveal any patterns of self-reported sensory deficits, but more precise assessment could clarify any association. The fact that the MS subgroups showed opposing results with BBTW provides helpful guidance for future studies in identifying categories of patients showing optimized linear and nonlinear variability with weighting.

Augmented sensory signals associated with BBTW may result in

greater attention to body position. Cavanaugh et al<sup>42</sup> provided evidence refuting this contention by examining the effects of a secondary cognitive task on ApEn of COP displacement in standing for healthy individuals. Approximate entropy significantly increased during dual tasking. If weighting captures the attention of participants, ApEn should have increased, at least in the control group. The only group that tended to increase with ApEn was MS LoLyE, implying that participants in the current study were not expending attentional resources on sensory stimuli provided by BBTW. Confirmatory studies with dual tasks could help to disprove increased cognitive attention as the mechanism underlying BBTW.

In conclusion, nonlinear measures can complement traditional measures of variability. Determining whether patients have more random or more repetitive structure to movement variability can help guide expectations regarding response to an intervention. In this study, people with MS differed from healthy controls on range, RMS, and ApEn but not LyE measures of COP displacement in the ML and AP directions while standing for 10 seconds. Eyes-open and eyes-closed conditions differed on range and RMS but not ApEn or LyE. Weighting the torso using the BBTW method produced no difference in measures when analyzed in the MS and control groups. However, change with weighting correlated moderately strongly with baseline LyE and ApEn. With the MS group divided into participants with more and less divergent COP displacement (HiLyE and LoLyE subgroups), the effect of weighting was significant for LyE in the ML direction. Future analysis of postural sway variability along with sensorimotor impairments may reveal more information about the characteristics of people who respond best to BBTW

and the mechanism underlying its effects.

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## References

- 1 *Atlas: Multiple Sclerosis Resources in the World 2008*. Geneva, Switzerland: World Health Organization; 2008:15–16.
- 2 National Institute of Neurological Disorders and Stroke. Multiple sclerosis: hope through research. Last updated May 21, 2014. Available at: [http://www.ninds.nih.gov/disorders/multiple\\_sclerosis/detail\\_multiple\\_sclerosis.htm#264603215](http://www.ninds.nih.gov/disorders/multiple_sclerosis/detail_multiple_sclerosis.htm#264603215). Accessed June 16, 2014.
- 3 Peterson EW, Cho CC, von Koch L, Finlayson ML. Injurious falls among middle aged and older adults with multiple sclerosis. *Arch Phys Med Rehabil*. 2008;89:1031–1037.
- 4 Schapiro RT. *Symptom Management in Multiple Sclerosis*. 5th ed. New York, NY: Demos Health; 2007.

- 5 Karst GM, Venema DM, Roehrs TG, Tyler AE. Center of pressure measures during standing tasks in minimally impaired persons with multiple sclerosis. *J Neurol Phys Ther.* 2005;29:170-180.
- 6 Martin CL, Phillips BA, Kilpatrick TJ, et al. Gait and balance impairment in early multiple sclerosis in the absence of clinical disability. *Mult Scler.* 2006;12:620-628.
- 7 Widener GL, Allen DD, Gibson-Horn C. Balance-based torso-weighting may enhance balance in persons with multiple sclerosis: preliminary evidence. *Arch Phys Med Rehabil.* 2009;90:602-609.
- 8 Widener GL, Allen DD, Gibson-Horn C. Randomized clinical trial of balance-based torso weighting for improving upright mobility in people with multiple sclerosis. *Neurorehabil Neural Repair.* 2009;23:784-791.
- 9 Gibson-Horn C. Balance-based torso-weighting in a patient with ataxia and multiple sclerosis: a case report. *J Neurol Phys Ther.* 2008;32:139-146.
- 10 Nashner LM. Sensory, neuromuscular, and biomechanical contributions to human balance. In: Duncan PW, ed. *Balance: Proceedings of the APTA Forum, Nashville, Tennessee, June 13-15, 1989.* Alexandria, VA: American Physical Therapy Association; 1989:5-12.
- 11 Nashner LM. Vestibular postural control model. *Kybernetik.* 1972;10:106-110.
- 12 Creath R, Kiemel T, Horak FB, Jeka JJ. The role of vestibular and somatosensory systems in intersegmental control of upright stance. *J Vestib Res.* 2008;18:39-49.
- 13 Horak FB, Shupert CL. Role of the vestibular system in postural control. In: Herdman SJ, ed. *Vestibular Rehabilitation.* 2nd ed. Philadelphia, PA: FA Davis Co; 2000:25-51.
- 14 Cameron MH, Horak FB, Herndon RR, Bourdette D. Imbalance in multiple sclerosis: a result of slowed spinal somatosensory conduction. *Somatosens Mot Res.* 2008;25:113-122.
- 15 Williams NP, Roland PS, Yellin W. Vestibular evaluation in patients with early multiple sclerosis. *Am J Otol.* 1997;18:93-100.
- 16 Noseworthy JH, Lucchinetti C, Rodriguez M, Weinshenker BG. Multiple sclerosis. *N Engl J Med.* 2000;343:938-952.
- 17 Jackson RT, Epstein CM, De l'Aune WR. Abnormalities in posturography and estimations of visual vertical and horizontal in multiple sclerosis. *Am J Otol.* 1995;16:88-93.
- 18 Fjeldstad C, Pardo G, Frederiksen C, et al. Assessment of postural balance in multiple sclerosis. *Int J MS Care.* 2009;11:1-5.
- 19 Daley ML, Swank RL. Quantitative posturography: use in multiple sclerosis. *IEEE Trans Biomed Eng.* 1981;28:668-671.
- 20 Frzovic D, Morris ME, Vowels L. Clinical tests of standing balance: performance of persons with multiple sclerosis. *Arch Phys Med Rehabil.* 2000;81:215-221.
- 21 Stolze H, Klebe S, Zechlin C, et al. Falls in frequent neurological diseases: prevalence, risk factors and aetiology. *J Neurol.* 2004;251:79-84.
- 22 Cattaneo D, De Nuzzo C, Fascia T, et al. Risks of falls in subjects with multiple sclerosis. *Arch Phys Med Rehabil.* 2002;83:864-867.
- 23 Nilsagard Y, Lundholm C, Denison E, Gunnarsson LG. Predicting accidental falls in people with multiple sclerosis: a longitudinal study. *Clin Rehabil.* 2009;23:259-269.
- 24 Peterson EW, Cho CC, Finlayson ML. Fear of falling and associated activity curtailment among middle aged and older adults with multiple sclerosis. *Mult Scler.* 2007;13:1168-1175.
- 25 Prieto TE, Myklebust JB, Hoffmann RG, et al. Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans Biomed Eng.* 1996;43:956-966.
- 26 Huisinga JM, Yentes JM, Filipi ML, Stergiou NB. Postural control strategy during standing is altered in patients with multiple sclerosis. *Neurosci Lett.* 2012;524:124-128.
- 27 Harbourne RT, Stergiou NB. Movement variability and the use of nonlinear tools: principles to guide physical therapist practice. *Phys Ther.* 2009;89:267-282.
- 28 Stergiou NB, Harbourne RT, Cavanaugh JT. Optimal movement variability: a new theoretical perspective for neurologic physical therapy. *J Neurol Phys Ther.* 2006;30:120-129.
- 29 Kaipust JP, Huisinga JM, Filipi M, Stergiou NB. Gait variability measures reveal differences between multiple sclerosis patients and healthy controls. *Motor Control.* 2012;16:229-244.
- 30 Huisinga JM, Mancini M, St. George RJ, Horak FB. Accelerometry reveals differences in gait variability between patients with multiple sclerosis and healthy controls. *Ann Biomed Eng.* 2013;41:1670-1679.
- 31 Bar-Haim S, Harries N, Hutzler Y, et al. Training to walk amid uncertainty with Re-Step: measurements and changes with perturbation training for hemiparesis and cerebral palsy. *Disabil Rehabil Assist Technol.* 2013;8:417-425.
- 32 Huisinga JM, Filipi ML, Stergiou NB. Supervised resistance training results in changes in postural control in patients with multiple sclerosis. *Motor Control.* 2012;16:50-63.
- 33 Crittendon A, O'Neill D, Widener GK, Allen DD. Standing data disproves biomechanical mechanism for balance-based torso-weighting. *Arch Phys Med Rehabil.* 2014;95:43-49.
- 34 Kurtzke J. Rating neurological impairment in multiple sclerosis: an expanded disability status scale (EDSS). *Neurology.* 1983;33:1444-1452.
- 35 Pincus SM. Approximate entropy as a measure of system complexity. *Proc Natl Acad Sci U S A.* 1991;88:2297-2301.
- 36 Pincus SM, Gladstone IM, Ehrenkranz RA. A regularity statistic for medical data analysis. *J Clin Monit.* 1991;7:335-345.
- 37 Stergiou NB, Kurz MJ, Heidel J. Nonlinear tools in human movement. In: Stergiou NB, ed. *Innovative Analysis for Human Movement.* Champaign, IL: Human Kinetics; 2004:63-90.
- 38 Bastian AJ. Mechanisms of ataxia. *Phys Ther.* 1997;77:672-675.
- 39 Sethi A, Davis S, McGuirk T, et al. Effect of intense functional task training upon temporal structure of variability of upper extremity post stroke. *J Hand Ther.* 2013;26:132-137; quiz 138.
- 40 Peterka RJ. Sensorimotor integration in human postural control. *J Neurophysiol.* 2002;88:1097-1118.
- 41 Nashner LM, Black FO, Wall C III. Adaptation to altered support and visual conditions during stance: patients with vestibular deficits. *J Neurosci.* 1982;2:536-544.
- 42 Cavanaugh JT, Mercer VS, Stergiou NB. Approximate entropy detects the effect of a secondary cognitive task on postural control in healthy young adults: a methodological report. *J Neuroeng Rehabil.* 2007;4:42.