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Standing Data Disproves Biomechanical Mechanism for Balance-Based Torso-Weighting

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Abstract

Objective—To test a proposed mechanism for the effect of Balance-Based Torso-Weighting (BBTW) in people with multiple sclerosis and healthy controls. The application of light weights to the trunk may result in a biomechanical shift of postural sway in the direction of weighting, mechanically facilitating maintenance of center of mass over the base of support.

Design—Non-randomized controlled trial

Setting—motion analysis laboratory

Participants—20 participants with multiple sclerosis (average EDSS 4.1) and 18 sex-, age-, height- and weight-matched controls

Intervention—Light weights strategically placed according to the BBTW protocol were applied to all participants following at least three walking trials and 10 seconds of quiet standing with feet together eyes open (EO) and eyes closed (EC). Measures were repeated after weighting.

Main Outcome Measure—Force plate center of pressure (COP) changes greater than one standard error of measurement (SEM).

Results—With BBTW, people with MS had larger maximum changes in COP than healthy controls in the left-right direction but not in the anterior-posterior direction. COP changes greater than one SEM occurred in the same direction of weighting 20% of the time (95% confidence interval 5%, 34%), ranging from 10% to 28% across conditions and directions of postural sway. Direction of greatest weight placement did not match the direction of change in average COP in the majority of participants with multiple sclerosis or the healthy controls in EO or EC conditions ($p < .0001$).

Conclusions—If BBTW worked via a biomechanical shift of the center of mass, COP changes should match the direction of greatest weighting with BBTW. Our data allowed us to reject this

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hypothesis. Future research may explore alternative mechanisms of action underlying this intervention.

Keywords

Multiple sclerosis; rehabilitation; balance; theory

Multiple sclerosis (MS) is a neurodegenerative disease affecting approximately 2.5 million people worldwide. Each year, 10,000 new cases are identified in the United States, usually in people between the ages of 20 and 50, making MS the most common progressive neurologic disease in young adults.¹ MS results in demyelination and destruction of central nervous system axons, thus slowing or halting the conduction of neural impulses, frequently affecting postural control during upright movement. Between 87% and 94% of those with MS report impaired balance and mobility.^{2, 3} Additionally, 52%⁴ to 54%⁵ of younger and middle-aged people with MS report having fallen recently. Many report multiple falls,⁶ and 50% of those over age 55 report falls resulting in injury.² Improving balance and mobility, therefore, is an integral component of rehabilitation for people with MS.

One rehabilitative intervention that has affected measures associated with fall reduction is balance-based torso-weighting (BBTW).⁷ Unlike previous reports of the use of weights in rehabilitation in which larger, fixed amounts of weight (3.6–10% body weight) are placed at a standardized location at the waist or shoulders,^{8, 9} BBTW begins with assessment of an individual's unassisted balance during quiet and perturbed standing, and continues with trials of resisted rotation of the trunk at the shoulders and pelvis. Light weights are then strategically placed onto a garment worn on the torso until the person can resist perturbations with greater ease and produce more symmetrical responses during resisted rotation. BBTW has resulted in immediate improvement in functional measures in people with MS^{7, 10, 11} with the potential for reducing their fall risk. However, the mechanism for the effectiveness of BBTW is unknown, thus restricting hypothesis-driven application to appropriate populations.

Multiple mechanisms have been proposed to account for the immediate improvements seen with a rehabilitative weighting protocol. Potential mechanisms include joint compression, increased inertia, increased afferent input about body segments, and improved conscious awareness.^{9, 12, 13} Many of these mechanisms imply that added weights must be substantial in order to improve mobility: by compressing joints, changing the moment of inertia, or increasing awareness of a body segment. The immediate functional improvements with the modest amount of weight (less than 1 kg) used in BBTW⁷ indicate that effectiveness for this intervention does not require substantial weight. Because the BBTW protocol results in strategic rather than symmetric weight placement, an alternative mechanism might be that weights result in a biomechanical shift in postural sway, observable as a change in location of the center of pressure (COP) on a force plate in the direction of the most weight placed. For example, adding weight to the right side of the upper body might shift COP to the right. The biomechanical shift may mechanically facilitate maintenance of the center of mass over the base of support, making balance and walking easier when weighted. Clinical observation, however, has suggested that changes in postural sway patterns with BBTW may not match the direction of weight placement. No previous studies have yet negated a strictly biomechanical mechanism for functional changes with BBTW, nor established an association between weight placement and COP shifts.

The purpose of this study was to investigate biomechanical shift as the mechanism for BBTW. We recorded COP during static standing with eyes open and eyes closed in people with MS and matched healthy controls in unweighted and weighted conditions, placing

weights using the BBTW protocol. If a biomechanical shift occurred, changes in COP would be expected to match the placement of weights on the body, with anterior placement of weights resulting in shift of COP anteriorly, for example. A non-match would be no shift or a shift in the opposite direction. To test this, we proposed a null hypothesis of no difference between the number of matches and non-matches; equal numbers of matches and non-matches would indicate a random response to the direction of weight placement. If the evidence was sufficient to reject the null hypothesis, examination of the actual proportions of matches with 95% confidence intervals would indicate the direction of our findings. If a biomechanical shift occurred, the direction of change in COP should match the direction of weight placement more than 50 percent of the time. This investigation was part of a larger study that involved motion analysis of gait in unweighted and weighted conditions.¹⁴

Methods

Participants with MS were recruited through the Northern California Chapter of the National Multiple Sclerosis Society and local neurologists' offices. Eligibility criteria included a self-reported diagnosis of MS, the ability to communicate in English, 18 years of age or older, ability to ambulate at least 25 feet (with or without an assistive device), reported balance or mobility difficulties, and sufficient endurance for up to three hours of testing with rest breaks. Individuals were excluded from this study if they reported an exacerbation of MS within the past two months, had a diagnosis of a concurrent neurological disorder (head injury, stroke, Parkinson's disease, etc.), or reported pain that could be exacerbated by external perturbations during standing or multiple trials of walking.

Healthy controls were matched to the participants with MS by sex, age, height, and weight. Individuals were recruited through personal contacts and online postings on Craigslist.org. Eligibility for control participants included the ability to communicate in English; characteristics that matched a participant with MS within a predefined range of age, height, and weight; and the absence of any known diagnoses or current pain that would affect balance or gait. All participants in this study gave informed consent. This study met the requirements for ethical research according to the Institutional Review Board of San Francisco State University.

Participants completed a medical questionnaire about symptoms, walking ability, 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 (EDSS; where 0=normal neurological function, and 10=death due to MS). Clinical measures were recorded for each participant including height, weight, number of falls, and self-reported visual or sensory dysfunction. Participants donned an unweighted BBTW garment^a adjusted to fit their trunk height, waist, and chest dimensions. Participants with MS performed three fast-speed walking trials prior to static standing on the force platform and were given rest breaks as needed. Healthy controls performed three fast-speed walking trials then performed additional walking trials to match the gait velocity of the MS participant with whom they were paired. The walking trials were part of a larger study investigating the effects of BBTW on gait temporal and spatial parameters.

COP data were collected in the anterior-posterior and left-right directions without weighting while participants stood quietly with feet together on a Kistler force plate^b (sampling at 600 Hz). Participants were instructed to stand as still as possible for a 10-second trial with their eyes open (EO) and then a trial with eyes closed (EC). A researcher stood near the

^aBalanceWear®: Motion Therapeutics, Inc., 1830 Eastman Avenue, Oxnard, CA 93030.

^bForce plates and Bioware software: Kistler Instrument Corp., 75 John Glenn Drive, Amherst, NY, 14228-2171.

participants during the testing and weighting protocols to monitor for undesired foot movement and to guard in case of an unrecoverable loss of balance.

Balance assessment was performed following the BBTW protocol.^{7, 10} Assessment of balance included observation of relative amounts and directions of sway during static standing with feet together, in EO and EC conditions. The examiner perturbed the participant with anterior, posterior, and lateral nudges to the shoulders and then pelvis, identifying the latency of responses as well as the amount and direction of balance loss.¹⁰ The examiner told participants that they would be perturbed, but did not reveal the direction of the perturbations. After the first perturbation was given, participants often readied themselves for the next nudge, but they did not know when the nudges would come. “Loss of balance” was defined as any tilting or leaning of the trunk that required an opposing parachute reaction, stepping response, or manual contact by the researcher to regain center of mass over the base of support. In addition, the examiner applied rotational forces through the shoulders and then pelvis to determine asymmetry in the participant’s ability to resist rotational force. All perturbations and rotational forces were recorded with a handheld dynamometer to help standardize perturbations before and after weight placement. Dynamometer data included amount of force, time to peak, and total time of force application. Comparisons were made between pre- and post-weighted conditions using two-tailed paired t-tests and an alpha of 0.05.

Weights were placed on the BBTW garment via Velcro attachment in 0.25 to 0.5 pound (0.11 to 0.23 kg) increments and documented on a body chart (Figure 1). The examiner confirmed the location of weights by repeating the original perturbations and adjusting weight placement until the participant showed minimal loss of balance. Minimal loss of balance with perturbations or rotational forces was defined as being able to hold the position, or minimal tilt or turn, along with a short latency return to position. One physical therapist provided all BBTW assessments and weight placement. A mandatory rest period followed determination of weight placement.

COP data were collected again with two 10-second static standing trials, feet together, on the Kistler force plate with eyes open and eyes closed while wearing the weighted BBTW garment.

Post-processing of the force plate data was performed in Bioware^b software, Cortex software^c and Microsoft Excel.^d Center of pressure graphs were created for each participant in all four conditions: EO unweighted, EC unweighted, EO weighted, and EC weighted. COP data were examined for direction of change with regard to the anterior-posterior and left-right directions.

The placement of weights as documented on individual body charts was transcribed to a spreadsheet. The position of the weights varied by individual with placement posteriorly in the left/right and upper/lower quadrants, and/or anteriorly in left, right or central regions as seen in Figure 1. In cases where the amount of weight was equal between anterior/posterior or left/right, the weights that were farther from the body’s center of mass (e.g., higher) were considered heavier than those placed closer. In some instances, the weight was equally distributed. When weights were distributed equally in anterior-posterior or left-right directions, lack of change in COP in that direction was counted as a match.

^cCortex software: Motion Analysis Corporation, 3617 Westwind Boulevard, Santa Rosa, CA 95403

^dExcel software: Microsoft, One Microsoft Way, Redmond, WA 98052-6399

COP direction and weight placement were compared. If the *average* COP changed from the unweighted condition to the weighted condition, the participant was counted as having moved in that direction. Direction of movement was then compared to the position of the greatest weight applied to the garment to determine if the direction of change of COP matched the direction of weight placement.

To minimize the chance of misinterpreting change that may have occurred because of measurement error, we calculated the standard error of measurement (SEM) using the formula $SEM = SD * (1 - r)^{1/2}$ where SD is the standard deviation of the pre-weighted trial, and r is the correlation between the pre-weighted and weighted trials.^{15 p 578} We used the one-SEM criterion^{16, 17} to determine whether an individual's average COP changed in the x or y direction more than measurement error.

Analyses were performed with χ^2 tests, where “expected” proportions were set at matches equal to non-matches, using a two-tailed alpha of 0.05. Observed proportions were then examined with 95% confidence intervals to indicate direction and precision of findings.

Results

Twenty-two people with MS met the eligibility criteria. Data from two participants were not included in analyses because of a change in diagnosis after data collection for one, and a power outage that interrupted data collection for the other. All 20 remaining participants with MS were female, with a mean (SD) EDSS score equivalent of 4.1 (1.6), where an EDSS score of 4.0 means fully ambulatory without assistance, up and about 12 hours per day despite relatively severe disability, and able to walk 500 meters without rest. Twenty healthy controls were matched one to one to the participants with MS by sex, age within seven years, height within five inches (0.127 m), and weight within 20 pounds (9 kg). Force plate data were unusable for two of the healthy controls because of mechanical difficulties, leaving 18 for analyses. Participants' demographics appear in Table 1. There were no significant differences between people with MS and controls in age, height, and weight ($p > 0.5$). The number of falls in the last year reported by participants with MS ranged from 0–15, with an average of 2.25. This was significantly greater ($p = 0.01$) than the healthy controls who reported a range of 0–2 falls and an average of 0.25. No participant had used BBTW prior to this study.

The data from the hand-held dynamometer showed no significant difference in the force used to provide perturbations, the time to peak force, or the total time of the perturbation between groups or between weighted and unweighted trials ($p > 0.05$). For the rotational forces, there were no significant differences between groups, but the force and total time held were significantly greater for the weighted versus unweighted trials for all participants ($p < 0.001$, $p = 0.01$, respectively).

The total amount of weight placed on the torso during the individualized BBTW evaluation process ranged from 0.75 to 2.75 pounds (0.34 to 1.25 kg, or 0.36–1.57% of the individual's bodyweight) with an average of 1.38 pounds and 0.9% bodyweight (Table 1). Mean (SD) weight placed was 1.54 (0.53) pounds for participants with MS and 1.19 (0.30) pounds for healthy controls. The participants with MS had significantly more weight placed than the healthy controls ($p = 0.03$). Table 2 provides an example of the location of each weight based on the responses to perturbation and rotation for a participant with MS and a healthy control.

Change in COP in the x-direction corresponded with left-right movement and change in the y-direction corresponded to anterior-posterior movement. Changes in COP were first examined visually by comparing graphs of force plate data between unweighted and

weighted conditions (Figure 2). To confirm visually apparent changes in COP and provide numeric data, the average x and y values for the eyes open and eyes closed conditions were compared from the unweighted to the weighted conditions. Change in average x and y was obtained for both participant groups. The participants with MS had a maximum change (x, y) of (2.6, 5.0 cm) while the healthy controls had a maximum change (x, y) of (1.4, 5.0 cm).

Table 3 depicts the numbers of times COP changed in the same or opposite direction of most weight applied. When the directions of weighting and change in COP were opposite, or change in the COP was less than SEM, we counted these as non-matches. Percent agreement between the direction of COP displacement and placement of weights ranged from 10% to 27.8% (Table 4). Overall, participants moved in the direction of most weight about 20% of the time. People with MS had lower percentages of agreement than healthy controls, but the difference between groups was not statistically significant (Fisher's exact test, two-tailed $p=0.15$).

We performed χ^2 tests on total MS, HS, and the two groups combined, using COP change greater than measurement error to determine agreement. The percent agreement between the direction of weight placement and the direction of change in COP with weighting was significantly less than 50% (number of matches did not equal non-matches) for participants with MS, healthy controls, and the combined groups (Table 4).

Discussion

If the mechanism behind BBTW was a biomechanical shift, COP changes would reflect changes in postural sway in the direction of the greatest weight placements, and the data would show a high percent of matches between weight placement and the direction of COP changes. We were able to reject the null hypothesis of no difference between the numbers of matches and non-matches between the directions of COP change and weight placement ($p < .0001$). Rejection of the null hypothesis left us with the possibility that the proportion of matches was either much lower or higher than 50%. The actual proportions and their 95% confidence intervals were lower than 50% (Table 4). Our findings thus opposed the alternative hypothesis associated with a biomechanical shift. While some participants did have a measurable change in COP towards the direction of most weight, a greater number in both the MS and control groups did not move in the direction of weight placement. These data imply that BBTW involves a non-biomechanical response that integrates input from the weights to modify motor output.

Prior to this study, no known research had investigated a biomechanical shift as a potential mechanism behind the immediate improvement in gait and balance parameters with weighting, perhaps because previous weighting interventions^{8, 9, 12} involved symmetric rather than strategic weight placement. Our findings indicate that a mechanism other than a pure biomechanical shift appears to underlie BBTW. Gait data from these participants revealed that weighting increased gait velocity ($p=0.002$) compared to gait without weight,¹⁴ indicating that BBTW did have an effect. Any proposed alternative mechanism must account for the apparent integration of sensory stimuli provided by these strategically placed light weights and consequent adjustment of postural sway, improvements in stability with perturbations and rotational forces, and increases in gait velocity.

From the literature on weighting as a therapeutic agent, other proposed mechanisms for immediate improvements with BBTW include joint compression, increased afferent input from body segments, and increased conscious awareness. Each of these possibilities hinges on augmented sensory stimuli. Joint compression and increased afferent input would stimulate mechanoreceptors in various tissues.¹⁸ Receptors in joint capsules, articular fat

pads, and intra- and extra-capsular ligaments respond to changes in tension, end position, and pressure allowing them to send afferent impulses from which an individual might regulate posture and movement.¹⁸ The small amount of weighting in BBTW could have augmented this afferent information. Although at least one study and a case report have reported some improvements with heavier weighting protocols,^{8, 19} mechanisms like these could still produce change with a small amount of weight.

Increased conscious attention to the position of the body and specific body segments could also effect change. Morgan¹² noted that effectiveness of weights on ataxic limbs does not seem to diminish over time, thus countering potential claims that weights, in general, increase an individual's awareness of movement over the long term. Although not specifically requested in the current study, several participants volunteered the information that they could not feel the weights or forgot they had them on, even during the short session of one to two hours. Because of these reports and similar clinical observations, increased attention does not seem likely to account for the improvements seen with BBTW. Future research might add dual tasks to divert attention and test this hypothesis further.

In this study we recorded the force used during perturbations and rotations before and after weighting during the BBTW protocol. The forces provided in the BBTW weighting process were not significantly different between people with MS and healthy controls; but participants held against a greater rotational force for a longer time with weighting than when unweighted. Such documentation helps standardize the BBTW protocol, and these data indicate that consistent forces were being applied in the weighting process. Observers have wondered if individuals appear to withstand perturbations and rotation forces after weighting because the forces have decreased. These data support the clinical observation that participants undergoing BBTW can immediately withstand forces of equal (for perturbations) or greater (for rotations) strength without the loss of balance or weakness that were observed prior to weight placement.

Study Limitations

This study contains some limitations. The sample was relatively small and no similar studies provide confirmation of these results. The order of testing unweighted and weighted conditions was not randomized because many individuals retain the effects of BBTW for several hours after the removal of weights.^{10, 11} Only the hypothesis of a mechanical shift in the direction of weight placement was examined in this study. Further research is needed to test alternative theories of the mechanisms underlying improvements in balance and gait velocity with BBTW. Studies that investigate the effectiveness of weighting may examine the hypothesis that weighting augments sensory input, perhaps most useful to people with proprioceptive deficits.¹² No trends were noted in our small sample associating response to BBTW with self-reported visual, sensory, or vestibular changes; and we did not systematically ask participants if they felt more confident or stable in the weighted condition. Future research should investigate which populations of people with balance and gait impairments respond best to BBTW, and the long-term effects of BBTW.

Conclusion

Despite the small amount of average additional weight (0.9% of body weight or about 0.63kg) in this study, participants showed changes in COP and resisted perturbations more easily when weighted. The fact that COP changes only matched the direction of weighting 20% of the time allows us to reject the hypothesis of a strictly biomechanical shift underlying the effects of BBTW. Further study may investigate other possible mechanisms for this intervention. Although the actual mechanism remains unclear, people with MS may benefit from using BBTW to improve gait and balance and consequently reduce falls.

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Abbreviations

MS	multiple sclerosis
BBTW	balance-based torso-weighting
COP	center of pressure
EDSS	Expanded Disability Status Scale
EO	eyes open
EC	eyes closed

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Figure 1. Balance-Based Torso-Weighting[®] garment and weights with sample placement: two ½ lb. weights, one anterior left, and one posterior left upper.

Figure 2.
Example graphs of center of pressure traces. In the x (left-right) direction, 0 = midline. In the y (anterior-posterior) direction, people faced towards 0, heels at -8.

Table 1

Demographic and Clinical Characteristics of Study Sample

	Participants with MS (n=20)	Healthy Controls (n= 18)	P value *
Age in years: mean (SD), range	49.4 (13.4), 24–68	47.3 (11.2), 29–69	0.615
Years since diagnosis: mean (SD)	12.8 (8.2)	-	-
EDSS score equivalent: mean (SD), range	4.1 (1.6), 2–6	-	-
Number of falls in last 12 months	2.0 (3.4)	0.3 (0.5)	0.008
Height in cm: mean (SD)	166.2 (6.0)	165.5 (7.2)	0.754
Weight in kg: mean (SD)	73.2 (15.7)	72.4 (14.8)	0.868
% Bodyweight BBTW: mean (SD), range	1.0 (0.4), 0.46–1.57	0.8 (0.3), 0.36–1.45	0.026
Type of MS (number of people)			
Primary Progressive (PP)	1	-	-
Secondary Progressive (SP)	4	-	-
Relapsing Remitting (RR)	11	-	-
Unknown (UN)	4	-	-
Vision impairment (number of people)	10	2	-
Dysesthesia (number of people)	16	2	-
Vestibular impairment (number of people)	11	0	-

MS = multiple sclerosis; SD = standard deviation; kg = kilograms;

EDSS = Expanded Disability Status Scale; BBTW = Balance-Based Torso-Weighting.

* Two-tailed t-test used

Table 2

Weight Placement for Two Participants and Whether Placement Matches Direction of Change in Center of Pressure with Balance-Based Torso-Weighting

Participant with MS	Direction of force	Response to perturbation	Location of weight placement [*]	Eyes Open		Eyes Closed	
				Ant/Post	Left/Right	Ant/Post	Left/Right
Healthy Control	Post at sternum	Mod		No	Yes	No	Yes
	Ant at L5	Min					
	Lat at R shoulder	Min					
	Rotation to R hip	Min		Yes	Yes	No	Yes
	Rotation to R shoulder	Min					
	Post at sternum	Mod					
	Ant at L5	Mod					
	Lat at R shoulder	Mod					
	Lat at R hip	Min		Yes	Yes	No	Yes
	Rotation to R hip	Min					
	Rotation to R shoulder	Min					
	Rotation to R shoulder	Min					

BBTW = Balanced-Based Torso-Weighting, MS = multiple sclerosis, Ant = anterior, Post = posterior,

Mod = moderate (loss of balance or position requiring parachute reaction but not stepping or assistance to recover),

Min = minimal (change in position in response to force applied, but still requiring only minor correction or longer latency to resume upright position), L = left, R = right, L5 = Lumbar vertebra 5;

* larger rectangles are ½ lb weights, smaller are ¼ lb

Table 3

Number of Participants for Whom the Direction of Weight Placement Matched the Direction of Change in Center of Pressure (COP) * in Anterior-Posterior and Left-Right Directions and Under Eyes Open and Eyes Closed Conditions

		Eyes Open		Eyes Closed	
		Weight placement		Weight placement	
		Anterior-posterior	Left-right	Anterior-posterior	Left-right
Total MS (n=20)	Yes	11 (4)	11 (4)	7 (0)	7 (4)
	No	9 (6)	9 (6)	13 (8)	13 (6)
Total HS (n=18)	Yes	11 (3)	9 (5)	10 (6)	9 (4)
	No	7 (5)	9 (3)	8 (3)	9 (5)

* Numbers listed according to change in numeric average COP outside of parentheses and (change in COP greater than measurement error in parentheses); Yes: match; No: COP change was in opposite direction to location of weights; MS: Participants with MS; HS: Healthy controls

Table 4
Percent of Participants with Agreement between Direction of COP Change Greater than Measurement Error and Weight Placement

	Eyes Open (x and y directions)	Eyes Closed (x and y directions)	Y Direction (EO and EC)	X Direction (EO and EC)	Total (95% CI)
MS	20%	10%	10%	20%	15% (0, 35) [*]
HS	22.2%	27.8%	25%	25%	25% (5, 45) [†]
Combined	21%	18.4%	17.1%	22.4%	19.7% (5, 34) [‡]

^{*} MS total $\chi^2 = 39.2$ (1 degree of freedom)
[†] HS total $\chi^2 = 18.0$ (1 degree of freedom)
[‡] Combined total $\chi^2 = 55.7$ (1 degree of freedom) All two-tailed $p < .0001$. MS: participants with multiple sclerosis; HS: healthy controls; EO: eyes open; EC: eyes closed; CI: confidence interval