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Trunk Stability and Postural Stability in People with Multiple Sclerosis

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TRUNK STABILITY AND POSTURAL STABILITY IN PEOPLE WITH MULTIPLE SCLEROSIS

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Nutrition and Exercise Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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This thesis is dedicated to Catherine. Thank you for your unwavering love and support throughout my time on this project.

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CONTENTS

ABBREVIATIONS

AP	anterior/posterior
cm	centimeter
COP	center of pressure
EDSS	Kurtzke Expanded Disability Status Scale
EMG	electromyography
ES	erector spinae
ICC	intraclass correlation coefficient
ML	medial/lateral
mm	millimeter
MS	Multiple Sclerosis
MVC	maximum voluntary isometric contraction
N	newton
PwMS	People with Multiple Sclerosis
RMS	root mean square
s	second

ABSTRACT

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Multiple Sclerosis is a neurological disease which affects an estimated 2.5million people worldwide. People with Multiple Sclerosis often experience high rates of falls, which have been associated with age, disability, and increased postural sway. Additionally, people with Multiple Sclerosis often exhibit muscular weakness and poor responses to perturbations. PURPOSE: To determine if trunk stability and postural control are altered among PwMS and if trunk muscle activity is correlated with postural stability. METHODS: Ten participants with a physician's diagnosis of Multiple Sclerosis (9 female, 1 male) were included in this study. Ten healthy controls were matched for age, height, weight, and gender. To analyze postural sway, participants stood quietly on a force platform for 30s with eyes closed and 30s with eyes open. Participants were then administered anticipated and unanticipated perturbations to the trunk while in a semi-seated position. Finally, participants underwent three maximum isometric contractions. Surface electromyography was collected at the erector spinae muscle group 3cm lateral to the L3 spinous process. High speed motion capture was used to determine peak accelerations of a reflective marker placed approximately at the C7 vertebrae. RESULTS: No statistical differences were observed in trunk accelerations following perturbations. However, people with multiple sclerosis exhibit significantly greater trunk muscle

activity following anticipated perturbations ($p = 0.04$, $d = 0.98$). Additionally, numerous large significant correlations were found between trunk muscle activity and postural sway. People with Multiple Sclerosis who experience falls appear to have greater trunk muscle activity following unanticipated perturbations than non-fallers ($p = 0.07$, $d = 1.47$). However, non-fallers may be better able to anticipate perturbations than fallers ($p = 0.10$, $d = 1.29$). CONCLUSION: People with Multiple Sclerosis demonstrate greater trunk muscle activity in response to perturbations than healthy controls. Trunk muscle activity is significantly correlated to postural sway in people with multiple sclerosis. People with Multiple Sclerosis who experience falls show greater trunk muscle activity following perturbations than non-fallers. However, non-fallers may be better able to anticipate perturbations than fallers.

Introduction

Multiple Sclerosis (MS) is a chronic neurological disorder with a broad array of symptoms. Common symptoms include postural imbalance, muscular weakness, and impaired muscular coordination.(1, 2) Postural imbalance in people with MS (PwMS) typically stem from a decreased ability to maintain posture, poor control approaching limits of stability, and delayed responses to perturbations.(3) These three deficits are largely connected to delayed somatosensory feedback and impaired neuromuscular coordination.(4, 5) Cameron and colleagues have demonstrated that spinal somatosensory conduction is significantly correlated to muscular onset latencies following a perturbation in PwMS.(4) Unfortunately, impairments from MS are not limited only to feedback mechanisms. For example, when PwMS are given the ability to control when a perturbation occurs, they are unable to coordinate anticipatory muscular activity as well as non-MS controls.(6) In addition, PwMS exhibit greater contralateral displacement of the center of mass when stepping in response to a perturbation, a change that is correlated to muscle onset latency.(7) Inefficient feedback and feedforward systems in PwMS often lead to an impaired ability to make postural adjustments and return to equilibrium. Examining how individuals respond to unanticipated and anticipated perturbations can provide meaningful insight on how these individuals will respond to disturbances in activities of daily living.

A poor response to perturbations can often be attributed to greater muscle onset latencies. Greater muscle onset latencies, measured via electromyography (EMG), are observable even among minimally impaired PwMS when compared to healthy controls.(8) In addition, there is evidence of asymmetrical muscle latencies between limbs in PwMS(4) potentially contributing to the strength asymmetries commonly found in this population.(9)

The integrated EMG signal can provide information on the magnitude of muscular activation for a given period of time. This technique has been used to assess feedforward performance by assessing the magnitude of muscular activation of PwMS preparing for an anticipated perturbation.(6) While poor neuromuscular performance has frequently been observed in the lower extremities of PwMS, it is unclear how, and to what extent, neuromuscular performance of the trunk musculature affects overall postural stability.

Altered postural stability likely contributes to the high risk of falling in PwMS; over 50% of PwMS will experience a fall in a given six-month period.(10) It is well established that PwMS have increased amounts of postural sway, which increases the risk of falling.(10, 11) Furthermore, PwMS are more unstable than healthy controls in a seated position, indicating poor trunk control.(12) While it is unclear if trunk stability and overall postural stability are related, evidence suggests that a relationship does exist. Soo Han and colleagues have shown that in response to perturbations, healthy participants minimize trunk and head movements by moving primarily at the ankle and knee.(13) These findings suggest that maintaining a steady trunk and head is desirable during dynamic postural tasks.

Proprioceptive feedback is a crucial component in postural stability. However, PwMS rely heavily on visual information to maintain stability.(14) Therefore, PwMS exhibit increased postural sway in the absence of visual feedback.(14-16) With closed eyes, PwMS exhibit higher frequencies of postural sway when compared to healthy controls, indicating an impaired ability to maintain posture without vision.(14)These changes suggest that PwMS are unable to process somatosensory or proprioceptive information as well as controls. Mugge and colleagues have demonstrated that proprioceptive feedback is particularly important for muscle force control and efficient perturbation responses.(17)

Therefore, it is likely that the same neurological mechanisms contributing to increased postural sway are also contributing to the impaired ability to respond to perturbations seen in PwMS.

The primary purpose of this study is to determine if MS negatively affects the neuromuscular activation of the trunk muscles following perturbations. The secondary purpose is to determine if positive correlations exist between trunk muscle activation and overall postural stability. We hypothesize that perturbations will cause greater trunk accelerations and lower muscular activity in PwMS when compared to non-MS controls. We also hypothesize that there will be positive correlations between trunk muscle activity following perturbations and postural sway range, velocity, and variability. By understanding how MS affects neuromuscular control of the trunk, interventions can be developed which target the observed deficits. If positive correlations do exist between trunk control and postural stability, interventions that target the trunk muscles may prove beneficial for improving postural stability.

Methods

The following study has been approved by the South Dakota State University Institutional Review Board.

Participant Selection: A small pilot study was conducted to determine an appropriate sample size using three PwMS and three healthy controls. Sample size calculations were conducted on trunk accelerations to find significance at a level of 0.05 and a power of 0.8. This analysis indicated that a sample size of three to eight participants per group would be sufficient to find statistical between groups differences. Therefore, ten participants with a physician's diagnosis of Multiple Sclerosis with a Kurtzke Expanded

Disability Status Scale (EDSS; Appendix) score less than seven were recruited for the study. Participants were excluded if they were unable able to sit upright, unassisted for roughly ten minutes, had a recent history of back pain needing medical attention, scoliosis, or other orthopedic conditions that may limit their ability to complete the study. MS participants must have had no flare ups, prednisone, a change in medication, or other steroid injections within the 3-months prior to data collection. Ten non-MS controls matched for age, gender, height, and weight were recruited. Controls had no recent history of back pain needing medical attention, scoliosis, or other orthopedic conditions that may limit their ability to complete the study.

Procedures: All participants underwent one data collection session. PwMS completed the EDSS form and indicated if they had experienced any falls in the previous year. Prior research has shown an accurate predictive ability for postural sway measures and accidental falls in a 3-month period.(16) However, there were few participants who actually fell in the 3-month period of our pilot study. Therefore, we assessed falls over the previous year to increase the likelihood of identifying fallers. All participants then underwent a postural sway analysis consisting of two 30s trials (eyes open and eyes closed). Following postural sway analysis, participants underwent the trunk stability assessment. For the trunk stability assessment, a harness was used to

Figure 1: **A**: Participant is attached to the device which administers perturbations. **B:** Participant is in upright starting position. **C:** Weight used to administer perturbations

administer perturbations to the upper chest of the participants via a cable directed parallel to the floor. A magnet was used so that the peak force experienced by each participant during perturbations was approximately 90 N. After the threshold of 90 N was reached, the weight detached from the magnet consequently ending the perturbation . (Figure 1) Participants underwent two sets of five anteriorly directed perturbations in a randomized order. One set consisted of five anticipated perturbations. Participants were instructed to resist the perturbation and remain upright. The perturbation did not occur until the participant gave a countdown to the researcher to release the weight. The second set consisted of five randomized perturbations. Participants were instructed to remain relaxed and upright, and to return to upright posture following the perturbation. The load was released at randomized intervals between 30s-90s as determined by a customized computer program before data collection.

At the completion of the trunk stability assessment, participants underwent 3 sets of 3s maximum voluntary isometric contractions (MVC) while in the same semi-seated position used during the trunk stability assessment.

*Measures***:** An eight camera Qualisys motion capture system was used to capture trunk kinematics via a marker placed at the C7 vertebrae. Surface EMG was used to capture neuromuscular activity. Electrodes were placed by the same researcher at the left and right lumbar erector spinae groups (ES) 3 cm lateral to L3-L4 spinous process.(18) The skin was shaved and wiped with alcohol prior to electrode placement. Data were exported to Visual 3-D (C-Motion, Inc.; Germantown, MD) and analyzed via a custom LabVIEW (National Instruments; Austin, Texas) computer program.

*Data Analysis***:** Postural sway data was calculated from the center of pressure (COP) on the force platform using Visual 3-D. COP data was low-pass filtered at 20 Hz using a 4th-Order Butterworth Filter. For the COP analysis, anterior/posterior (AP) and medial/lateral (ML) components were analyzed separately. Range was calculated as the difference from the maximum to the minimum sway amplitudes.(19) Velocity was calculated as the total COP excursion divided by the change in time.(19) Variability was calculated as the standard deviation of the COP amplitude over the entire time series.(9)

Trunk kinematic data were low-pass filtered at 8 Hz using a 4th-Order Butterworth Filter. For the trunk stability analysis, peak acceleration following trunk perturbations was calculated. EMG data were collected during the perturbation trials and low-pass filtered at 250 Hz, high-pass filtered at 10 Hz (4th Order Butterworth). The EMG signals were then filtered using a moving root mean square filter (RMS) with a 101ms window. The maximumRMS values occurring after event onset were collected. Event onset was defined as the point at which C7 acceleration reaches 5% of its maximum.(6) Additionally, mean RMS during the 150ms following event onset was calculated This window of time has been described as the time interval that represents compensatory muscular activity following a perturbation.(6) EMG data were scaled to maximum RMS values obtained during the maximum isometric contractions. Accelerations and RMS values were averaged across 5 trials. Anticipatory adjustments were calculated by finding the differences between anticipated and unanticipated trials. Positive anticipatory adjustments indicate an increase in a variable during anticipated trials.

All data were tested for normality using the Shapiro-Wilk test. For normal data, independent sample t-tests were used to determine group differences. Cohen's *d* was calculated to determine standardized effect sizes (large > 0.8, medium > 0.5, small > 0.2).(20) Non-normal data were analyzed using the Mann-Whitney U-Test to determine group differences. Effect sizes for the non-normal data were calculated using the equation: $r = z/\sqrt{N}$ where N represents the pooled sample size of both groups and z represents the z-statistic that was calculated from the Mann-Whitney U-Test (large > 0.5, medium > 0.3, small > 0.1).(20) Spearman's rank correlations were used to determine the relationships between variables (large 0.7-0.9, medium 0.5-0.7, small 0.3-0.5).(21) Intraclass correlation coefficients (ICC) were calculated to determine the reliability of trunk accelerations following the guidelines given by Koo and Li.(22) Statistical significance was set at $p < 0.05$. As effect size has been interpreted as having important clinical implications, clinical significance was interpreted as a large effect size.(23)

Results

10 participants with a physician's diagnosis of MS (age: 48.8±21yr; height: 1.64±.08m; mass: 74.1±9kg; EDSS: 2.5, range: 1-6) and ten healthy controls (age: 46.6±21yr; height: 1.65±.04m; mass: 71.3±11kg) were included in this study. No significant differences were found between groups in age, height, or weight.

Trunk Stability: Results of the trunk stability analysis are summarized in Table 1. All trunk-related variables were determined to be normally distributed and trunk accelerations demonstrated excellent reliability (ICC > 0.96). PwMS exhibit significantly greater Left ES maxRMS values following anticipated perturbations. Additionally, a trend towards a difference in Left ES meanRMS values was also observed ($p = 0.06$), which was accompanied with a large effect size ($d = 0.89$). Similarly, large effect sizes were observed in Left ES activity following unanticipated perturbations ($d \geq 0.$); however, these did not reach statistical significance. No statistical differences were observed between groups for peak trunk accelerations during anticipated or unanticipated perturbations. Based on the clinical significance of effect sizes(23), controls may experience moderately greater accelerations following unanticipated perturbations when compared to anticipated (p = 0.42, d = 0.37). However, controls may also have greater anticipatory adjustments (p = 0.07, d = 0.85).

Table 1: Group responses to perturbations between MS and Controls

	MS	Control	*p*	Effect Size
Unanticipated				
Peak Acceleration (mm/s^2)	2.39(0.57)	2.62(0.69)	0.81	0.10
Left ES maxRMS (%MVC)	24.5(13.5)	15.7(7.43)	0.09	0.80
Left ES meanRMS (%MVC)	15.8(8.00)	10.2(5.48)	0.09	0.81
Right ES maxRMS (%MVC)	20.6(9.72)	18.9(11.8)	0.72	0.16
Right ES meanRMS (%MVC)	14.3(6.81)	12.3(8.38)	0.58	0.25
Anticipated				
Peak Acceleration (mm/s^2)	2.41(0.60)	2.47(0.65)	0.42	0.37
Left ES maxRMS (%MVC)	28.9(15.0)	17.6(6.32)	0.04*	0.98
Left ES meanRMS (%MVC)	18.8(9.12)	12.2(4.81)	0.06	0.89
Right ES maxRMS (%MVC)	27.1(18.5)	20.4(7.82)	0.30	0.47
Right ES meanRMS (%MVC)	18.0(11.2)	14.2(5.85)	0.35	0.43
Anticipatory Adjustments				
Peak Acceleration (mm/s^2)	.017(.16)	-.15(.24)	0.09	0.81
Left ES maxRMS (%MVC)	4.46(7.76)	1.94(7.63)	0.47	0.33
Left ES meanRMS (%MVC)	3.00(4.52)	2.03(5.35)	0.67	0.20
Right ES maxRMS (%MVC)	6.45(14.8)	1.49(7.32)	0.35	0.43
Right ES meanRMS (%MVC)	3.75(8.14)	1.82(5.42)	0.54	0.28

* = $p < 0.05$, ES = erector spinae, RMS = root mean square; MVC = maximum voluntary contraction

Postural Stability: Results of the postural stability analysis are summarized in Table 2. Nearly all the postural variables were determined to be non-normal, therefore non-parametric tests were used. No significant group differences were found. Only one variable, ML Peak Velocity with eyes open, approached statistical significance (p = 0.08).

Interestingly, this variable was higher in the control group. All variables were also tested within-subjects to determine if any differences were found between conditions. No statistically significant differences were found from this analysis.

Table 2: Group responses to quiet standing between MS and Controls

	MS	Control	*p*	Effect Size (*r*)
Eyes Open				
AP Range (mm)	26.8(18.0)	17.7(5.78)	0.33	0.22
AP Velocity (mm/s)	8.81(5.04)	6.63(1.49)	0.55	0.14
AP Variability (mm)	5.38(3.19)	3.53(1.42)	0.11	0.35
ML Range (mm)	16.9(17.7)	10.5(5.44)	0.65	0.10
ML Velocity (mm/s)	15.9(13.7)	9.80(1.65)	0.60	0.12
ML Variability (mm)	3.26(3.59)	1.89(0.96)	0.65	0.10
Eyes Closed				
AP Range (mm)	28.6(18.5)	22.6(5.50)	0.88	0.03
AP Velocity (mm/s)	10.5(8.51)	7.56(1.87)	0.65	0.10
AP Variability (mm)	5.50(3.54)	4.30(0.97)	0.94	0.02
ML Range (mm)	17.4(19.9)	11.2(4.10)	0.50	0.15
ML Velocity (mm/s)	19.2(18.3)	12.1(2.65)	0.94	0.02
ML Variability (mm)	2.99(3.61)	1.93(0.63)	0.36	0.20

AP = anterior/posterior, ML = medial/lateral

Fallers vs Non-Fallers: 3 fallers were identified in our sample. To determine differences between PwMS who do and do not regularly fall, we divided the MS group into Fallers and Non-Fallers. No statistical differences were observed in age, height, or weight. However, fallers had a significantly higher EDSS score than non-fallers (4.12±2.4 vs 1.79±0.86; $p = 0.04$). Group differences in trunk stability are summarized in Table 3. While no statistically significant differences were observed between groups, multiple large effect sizes were observed in the trunk muscle activity during unanticipated trials. Additionally, Non-Fallers showed greater, clinically significant, anticipatory adjustments to Left ES variables when compared to fallers. No statistical differences were found in postural stability between Fallers and Non-Fallers, however small- to moderate- effects were observed indicating greater sway velocities in Fallers.

Table 3: Group differences between Fallers and Non-Fallers

	Fallers	Non-Fallers	*p*	Effect Size
Unanticipated				
Peak Acceleration (mm/s^2)	2.46(0.31)	2.36(0.67)	0.82	0.16
Left ES maxRMS (%MVC)	36.2(16.4)	19.4(9.40)	0.07	1.45
Left ES meanRMS (%MVC)	22.3(9.01)	13.0(6.23)	0.09	1.32
Right ES maxRMS (%MVC)	27.8(11.5)	17.6(7.80)	0.13	1.15
Right ES meanRMS (%MVC)	18.9(7.82)	12.3(5.78)	0.17	1.05
Anticipated				
Peak Acceleration (mm/s^2)	2.47(0.45)	2.38(0.67)	0.85	0.14
Left ES maxRMS (%MVC)	34.4(17.3)	26.6(14.7)	0.48	0.51
Left ES meanRMS (%MVC)	22.7(10.3)	17.1(8.89)	0.41	0.60
Right ES maxRMS (%MVC)	29.3(14.0)	26.1(21.1)	0.82	0.16
Right ES meanRMS (%MVC)	19.6(9.49)	17.3(12.4)	0.79	0.19
Anticipatory Adjustments				
Peak Acceleration (mm/s^2)	0.007(0.19)	0.02(0.17)	0.92	0.07
Left ES maxRMS (%MVC)	-1.76 (4.23)	7.12(7.53)	0.10	1.29
Left ES meanRMS (%MVC)	0.39(3.08)	4.12(4.76)	0.25	0.85
Right ES maxRMS (%MVC)	1.49(10.9)	8.57(16.5)	0.52	0.46
Right ES meanRMS (%MVC)	0.67(5.49)	5.07(9.08)	0.47	0.53

* indicates $p < 0.05$, ES = erector spinae, Eyes Open and Eyes Closed variables were tested using non-parametric tests

Correlations: Results of the correlation analysis between trunk muscular activity and postural stability are summarized in Table 4. With the eyes open, numerous small- to medium- positive correlations between trunk muscle activity and postural sway were found. Additionally, Right ES variables during the anticipated trials were significantly correlated to ML Velocity for the Right ES ($p < 0.05$). With the eyes closed, numerous small- to large- positive correlations were found. Additionally, trunk muscle activity following perturbations was significantly correlated to AP Range for all variables except Right ES meanRMS following anticipated perturbations ($p < 0.05$). Right ES Mean activity during the anticipated trials was also significantly correlated to AP Variability with the eyes closed. No significant correlations were found in the control group.

Table 4: Spearman's Correlations between Trunk Muscle Activity and Postural Stability in PwMS

	Unanticipated				Anticipated			
	Left ES maxRMS	Left ES meanRMS	Right ES maxRMS	Right ES meanRMS	Left ES maxRMS	Left ES meanRMS	Right ES maxRMS	Right ES meanRMS
Eyes Open								
AP Range	0.42	0.41	0.37	0.30	0.48	0.37	0.37	0.33
AP Velocity	0.49	0.53	0.52	0.62*	0.52	0.56*	0.52	0.55*
AP Variability	0.37	0.35	0.27	0.22	0.45	0.38	0.28	0.27
ML Range	0.07	0.12	0.07	0.16	0.19	0.15	0.14	0.18
ML Velocity	0.62*	0.62*	0.64**	0.58*	0.62*	0.56*	0.64**	0.65**
ML Variability	0.27	0.26	0.22	0.21	0.37	0.33	0.30	0.31
Eyes Closed								
AP Range	0.75**	0.65**	0.72**	0.58*	0.76**	0.72**	0.77**	0.78**
AP Velocity	0.20	0.25	0.22	0.37	0.26	0.27	0.28	0.30
AP Variability	0.60*	0.53	0.55*	0.48	0.62	0.61	0.62	0.64**
ML Range	0.18	0.13	0.16	0.25	0.22	0.28	0.38	0.37
ML Velocity	0.42	0.52	0.48	0.60*	0.44	0.44	0.44	0.47
ML Variability	0.18	0.19	0.19	0.30	0.20	0.22	0.37	0.38

* indicates $p < 0.1$, ** indicates $p < 0.05$, PwMS = People with Multiple Sclerosis, AP = anterior/posterior, ML = medial/lateral

Discussion

Overall, our hypotheses are partially supported by these data. While our results do indicate altered neuromuscular control of the trunk in PwMS, it is unclear how these changes affect trunk stability. What is clear however, is that altered neuromuscular control of the trunk is positively associated with postural instability. Furthermore, the changes in trunk muscle control seem to be even greater in PwMS who exhibit falls.

Contrary to our hypothesis, PwMS exhibited greater muscular activation following perturbations than healthy controls. While no statistical differences were observed in EMG activity during the anticipated trials, large effect sizes were found in Left ES activity ($d \geq 0.80$). During the unanticipated trials, PwMS exhibit significantly greater Left ES activity when compared to controls. This is interesting given the similar peak accelerations experienced by both groups during the unanticipated perturbations. While the biomechanical outcomes are similar, the perturbation elicited

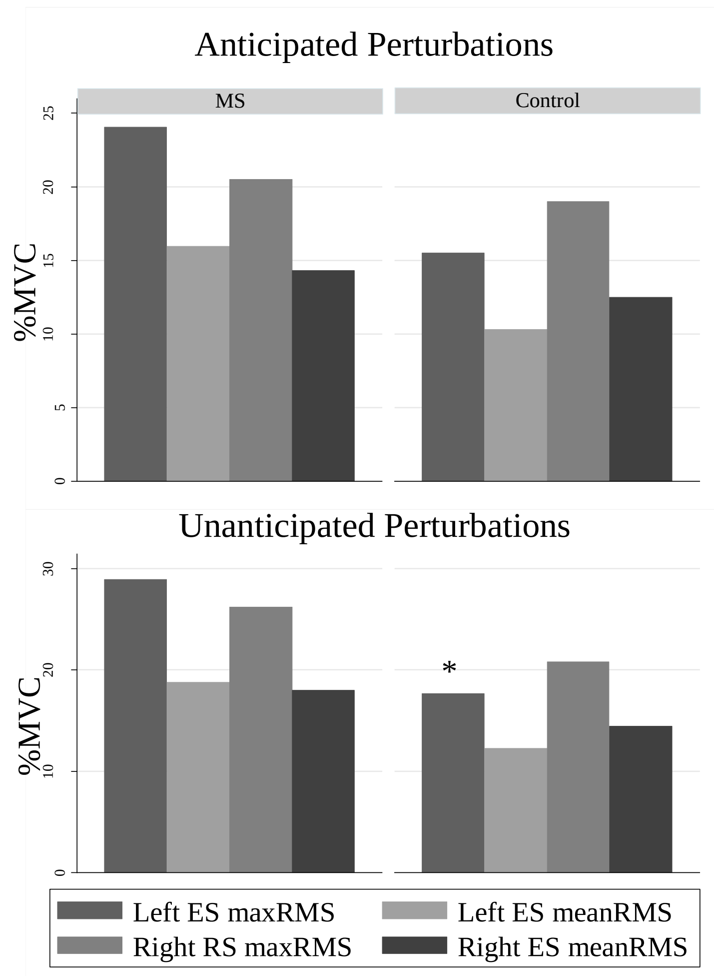

Figure 2: Neuromuscular responses to trunk perturbations between groups. * indicates $p < 0.05$

significantly greater back muscle activity in PwMS. These findings support the conclusion that the perturbation posed a greater threat to PwMS than to healthy controls. Similarly, people with chronic low back pain also show greater back muscle activation during tasks when compared to healthy controls.(24) It has been suggested that individuals with chronic low back pain exhibit greater muscle activation as a protective mechanism to compensate for spinal instability. Similarly, PwMS may be exhibiting greater muscle activation as a protective mechanism to compensate for postural instability.

We hypothesized that PwMS would exhibit greater accelerations than controls following perturbations. However, no statistical group differences were observed in peak accelerations. Interestingly, controls may have moderately greater accelerations following unanticipated accelerations (d = 0.37), although this difference was not significant. Prior research has reported mean trunk accelerations between 6 to 8 m/s^2 following similar perturbations; however, the greatest acceleration reported in the present study is 2.62 m/s^2.(25) The smaller accelerations observed in this study may partially explain the similar responses between groups. Future research should investigate the use of more challenging perturbations. Although not statistically significant, it appears controls demonstrated greater anticipatory adjustments to trunk accelerations (p

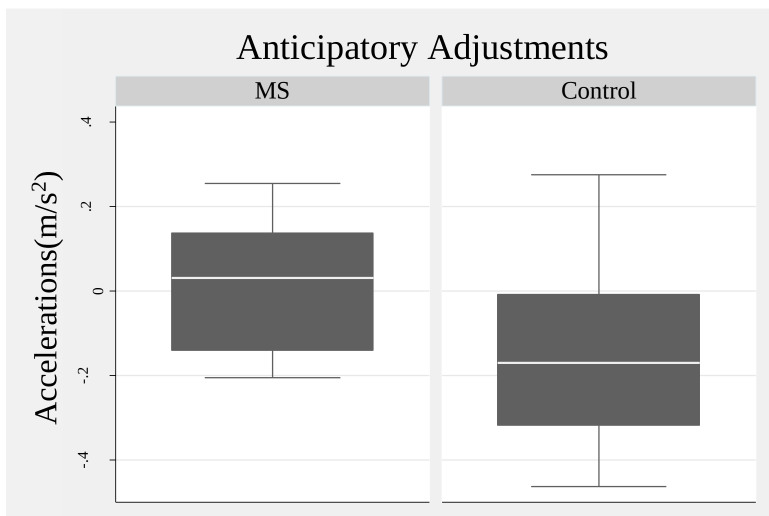

Figure 3: Differences in anticipatory adjustments to trunk accelerations between groups. Smaller values indicate a greater reduction in accelerations between trials.

= 0.07; *d* = 0.85). Greater anticipatory adjustments suggest that controls were better able to reduce their accelerations between trials when compared to PwMS. Similarly, Meharavar et al. have reported that PwMS exhibit reduced anticipatory and compensatory postural adjustments when compared to healthy controls.(6) These differences are often attributed to slower conduction velocities in the central nervous system of PwMS.(26) While we did not measure neural conduction velocities in this study, this may explain the impaired anticipatory adjustments seen in PwMS.

Group comparisons in postural stability reveal no statistical differences in postural sway. With eyes open, PwMS demonstrate moderately greater values in AP Variability ($p \leq 0.15$, $r > 0.31$). All other variables were slightly greater in PwMS ($r > 0.1$). With eyes closed, small effects sizes were observed indicating greater values in PwMS for AP Velocity, ML Range, and ML Variability ($r > 0.1$) however these are not significant. The group similarities in postural stability may be partially explained by the MS group's relatively low disability levels as postural sway has been shown to increase with disability level.(3) Additionally, we did not limit the age of our participants. Postural sway has been shown to be higher in older populations, which may make observing differences specifically from MS more difficult in older populations.(27) Finally, the control group in this study exhibited greater mean velocities than those reported previously ($p < 0.01$), while the MS group appears to have similar results.(16)

Numerous small- to medium- positive correlations were found between the trunk muscle and postural sway variables with eyes open. Additionally, significant correlations were found between ML velocity and the Right ES during anticipated trials with the eyes open variables. With the eyes closed, all EMG variables were significantly and positively associated with AP Range except for Right ES Mean during unanticipated trials. Additionally, AP Variability with the eyes closed was significantly and positively associated with Right ES Mean during anticipated trials. These data indicate that a relationship exists between neuromuscular control of the trunk and postural stability. While causality cannot be determined from these data, they support the hypothesis that PwMS exhibit greater muscle activation following perturbations as a compensatory mechanism for postural instability. The correlations between trunk muscle activity and postural stability may partially be explained by alterations in proprioceptive mechanisms. Afferent feedback, which is impaired in PwMS(4), is important for muscle force control(17). Poor muscular force control could likely contribute both to increased postural sway and increased muscular activation following perturbations. The differences in significant correlations between eyes open and eyes closed trials can likely be attributed to the change in the balance systems being utilized. It has been shown that PwMS heavily rely on the visual system to maintain balance.(14) While we found no statistically significant differences between the eyes open and eyes closed trials, the shift in correlations provides some evidence that the postural control strategy may have changed between these conditions.

The stratification of the MS group into fallers and non-fallers revealed trends that should be studied in future research. No statistical differences were found in age, height, or weight; however, disability levels were statistically significantly higher in fallers (p = 0.04). This is consistent with prior research which has shown an elevated risk of falls in PwMS at higher disability levels.(3) During the unanticipated trials, all EMG variables were greater in the fallers ($p < 0.17$, $d > 1.0$) as demonstrated by their clinical significance.

Additionally, both Left ES variables approached statistical significance ($p \leq 0.1$). During anticipated trials, moderate effect sizes were observed in the Left ES variables ($d > 0.5$) however these were accompanied with relatively high p-values ($p \geq 0.41$). PwMS who fall may respond to trunk perturbations with greater muscle activation that non-fallers, perhaps as a protective mechanism to compensate for postural instability.

While both fallers and non-fallers had similar trunk accelerations, it appears the non-fallers were better able to make anticipatory adjustments. Although the fallers showed greater muscular activity, the non-fallers showed small- to large- effect sizes for anticipatory adjustments in the trunk muscles. These data suggest that fallers are unable to activate their trunk muscles in anticipation as well as non-fallers, likely contributing to the greater incidence of falls. These findings are similar to the differences seen between PwMS and healthy controls. PwMS exhibit poor anticipatory and compensatory responses to perturbations(6), and these differences appear even greater in PwMS who exhibit falls. Finally, a similar trend can be observed in postural sway between fallers and non-fallers.(16)

This study is limited based on the small sample size, the low disability of the MS participants, and the small magnitude of the perturbations. While the small sample increases the likelihood of type II error, the inclusion of effect sizes may have revealed meaningful trends in our data. Future research should include larger samples, greater diversity of disability levels, and explore challenging perturbations. Additionally, intervention studies should investigate the use of perturbation-based therapy to improve trunk stability and ultimately postural stability in PwMS. A randomized trial utilizing trunk perturbation therapy in patients with low back pain was effective at reducing low back pain symptoms, improving muscle strength, and increasing trunk stiffness.(28) Based on the correlations between trunk muscle activity and postural stability, a similar intervention may prove beneficial for PwMS.

Conclusion

PwMS exhibit altered trunk stability and trunk muscle activation when compared to age- gender- height- and weight-matched controls. Additionally, trunk muscle activation is significantly correlated to postural sway in PwMS. The greater amounts of back muscle activation seen in PwMS following perturbations are like those found in patients with chronic low back pain. Additionally, PwMS who experience falls may not be able to anticipate perturbations as well as those who do not experience falls. Future interventions should investigate if trunk strengthening and perturbation therapy is effective in improving trunk and postural stability in PwMS.

Literature Review

The literature review consists of four sections: Trunk Stability and Balance, Stability and Balance in Persons with Multiple Sclerosis, Pathology and Symptoms of Multiple Sclerosis, and Methods for Analyzing Trunk Kinematics, Postural Stability and Neuromuscular Performance. The intention of the first three sections is to provide an overview of the factors involved in these focus areas. In some studies, only those procedures/results that are most pertinent to the study are discussed in the table. Table 1, Trunk Stability and Balance, is different from Table 2 in that it provides a general mechanical overview of trunk stability and balance. Table 2, Stability and Balance in Persons with Multiple Sclerosis, identifies the specific effects that Multiple Sclerosis has on stability and balance. Table 3 takes a broader look at Multiple Sclerosis and the common symptoms experienced by those with the disease. This table also briefly touches on the effects that training interventions can have on persons with Multiple Sclerosis. Table 4 serves as a brief review of the current methods used to analyze or calculate the variables of interest. Many of these studies are from diverse fields, and the methods presented may not be included in the final study. However, they are included in the final table as an indication that there are multiple ways to find the data we are interested in.

Table 1: Trunk Stability and Balance

Study	n	Sample Characteristics	Type	Procedures	Results	Impact	PEDro Scale
Cholewicki et al. (1996)(29)	n = 3	-Male -Age 24.3 ± 2.6y	CSA	-7 Lifting tasks -EMG -3D Motion Capture -Lumbar spine model developed by McGill et al.	Spinal stability appears to be lowest during the lifting both very low and very high loads	Muscular activation and coordination are necessary for spinal stability	4
Ishida et al. (2016)(25)	n = 15	-Physical therapy students -Age = 21.2 ± .04y	CSA	-Trunk perturbations with various breathing/bracing techniques -Surface EMG -Accelerometry	Expiration and bracing maneuvers both reduced lumbar accelerations following sudden loading (p-value <0.05)	L3 Erector Spinae, internal oblique, and external oblique activation increased with lumbar stiffness	6
Krajcarski et al. (1999)(30)	n = 8	-Male -Age = 20.4 ± 1.5y	CSA	-Anterior thoracic perturbations -MVC of back extensors -Surface EMG	Increased preload resulted in reduced peak lumbar flexion angles following perturbation (p-value <0.01)	Increased muscular activity prior to a trunk perturbation reduces the displacement caused by the perturbation	6
Shahvarpour et al. (2014)(31)	n = 12	-Male -Young -No history of LBP	CSA	-Surface EMG -Anteriorly directed perturbations	Increased preload reduced peak trunk velocity, acceleration, and increased back muscular activity (p < 0.05)	Increased back extensor activation reduces the effects of anterior perturbations	6

Colebatch et al. (2016)(32)	n = 14 (female = 5)	-Age = 26 ± 9	CSA	-Accelerometry -Surface EMG -CoP analysis -Perturbations during standing	Posterior perturbations produced greater magnitude of acceleration at sacrum ($p = 0.027$) and earlier tibial accelerations ($p < 0.001$) than anterior perturbations	Anterior perturbations show increased activation of soleus, hamstrings, and paraspinal muscles	5
Pozo-Cruz et al. (2014)(33)	LBP = 118 (female = 71) CON = 72 (female = 42)	-Office workers	CSA	-Trunk flexion/extension endurance tests -The Roland Questionnaire -The Oswestry Questionnaire for disability levels	Trunk flexion/extension endurance were correlated with functional disability from LBP (Oswestry score, $p < 0.001$)	Endurance of the trunk musculature is important for proper spinal function	6
Chen et al. (2015)(34)	n = 10 (female = 5)	-Age = 28.2 ± 3.55y -Right-Handed	CSA	-Perturbations to the shoulders while standing with an object on one side of the body	APA integrated EMG showed greater reciprocal activity (coordinated inhibition of antagonists) on the right-hand side when holding the object and greater co-contraction activity on the left side	Postural asymmetries result in neuromuscular asymmetries observable in EMG data	5

Kim et al. (2013)(35)	LBP = 31 (female = 11) CON = 16 (female = 7)	-LBP classified into: -flexion-rotation syndrome -extension-rotation syndrome	CSA	-3D motion capture -EMG of ES and HAM during a standing flexion exercise	No kinematic differences were observed in standing ($p = 0.99$) but significant rotational differences and EMG asymmetries were observed in full flexion between groups ($p < 0.05$)	Lumbopelvic asymmetries may not be observable during erect postures/movements, but are observable during lumbar flexion	5
Cholewicki et al. (1991)(36)	n = 57 (female = 13)	-Canadian national powerlifters	CSA	-2D Sagittal plane video capture -WATBAK computer model	L4/L5 compressive forces were estimated up to 8019N for women, and 18,449N for men	Intra-abdominal pressure, muscular forces, and ligamentous forces all contribute to in vivo stiffness of the lumbar spine	3
Mueller et al. (2016)(37)	n = 13 (female = 5)	-Physical activity > 2h/week	CSA	-Split-treadmill perturbations while walking -EMG of dorsal and ventral trunk musculature	Regardless of the type of perturbation, significant increases in trunk EMG were seen for both ventral and dorsal muscles ($p < 0.05$) specific muscle activity showed significant variability depending on the direction of perturbation ($p < 0.05$)	Trunk stability and neuromuscular coordination are required to adapt to perturbations when walking	3

Soo Han et al. (2014)(13)	n = 15	-Healthy -Age = 25.8±1.3y	CSA	-Anteroposterior platform perturbations at various frequencies (0.1, 1.0, 2.0 Hz) - 3D Motion Capture	As frequency increased, correlations between lower extremities (ankle and knee) and superior extremities (hip, trunk, and head) decreased	As the frequency of perturbations increased to 2.0Hz, greater neural coordination was likely required as joints took on less correlated patterns	6

Legend: CSA = Cross-Sectional Analysis, EMG = Electromyography, CON = Control, LBP = Low-Back Pain, CoP = Center of pressure, AP = anterior/posterior, ML = medial/lateral, LO = Lumbar Osteoarthritis, NPS = neuropathy pain scale, SF-36 = 36-Item Short Form Health Assessment, APA = Anticipatory, ES = erector spinae muscle group

Table 2: Stability and Balance in Persons with Multiple Sclerosis

Study	n	Sample Characteristics	Type	Procedures	Results	Impact	PEDro Scale
Chung et al. (2008)(9)	MS = 12 CON = 12	-Female -Age- and gender - matched healthy controls	CSA	- Leg Muscle Strength via dynamometer -Postural Stability via 20s stand on force plate, 25ft unaided walk	MS = similar peak torque (p-value = 0.96) but less peak power in knee extension (p-value = 0.02); greater CoP in AP (p-value = 0.005), only modestly greater CoP in ML (p-value = 0.07)	AP CoP variability correlates with walk times, knee extensor asymmetry, and loading asymmetry	4
Finlayson et al. (2006)(10)	n = 1089	-MS	Retrospective Case Control	-At-home survey	Falls associated with sex (Male; OR = 1.50, p = .009) a deteriorating MS status (OR = 2.05, p < .001) fear of falling (OR = 1.74, p = .001)	Deteriorating MS conditions and a fear of falling increase one's risk of falling	4

Van Emmerik et al. (2010)(38)	MS = 12 CON = 12	-Female -Age- and gender-matched healthy controls	CSA	-Postural stability during various tasks (multi-directional leaning, eyes open and closed)	MS-related fatigue impairs ability to anteriorly displace CoP ($p < 0.05$) MS impairs ability to anteriorly displace CoP to control ($p < 0.05$)	MS may impact postural stability, especially in the sagittal plane. Fatigue may worsen these symptoms	7
Giannì et al. (2013)(11)	Studies = 15 Participants = 2425	-MS	Meta-Analysis	-OR and SMD to compare impact of a given factor with falling	Falls are associated with longer disease durations (SMD = 0.14, $p = 0.02$) use of assisted device (OR = 3.16, p = <0.0001) postural sway (Eyes open, SMD = 0.71, $p = 0.006$) (Eyes closed, SMD = 0.83, $p = 0.01$)	Many common symptoms associated with MS impact how likely that individual is to fall	-

Huisinga et al. (2012)(15)	MS = 15 CON = 15	-MS -Age-matched Control	CSA	-Postural assessment with eyes open and eyes closed	MS had greater sway area ($p = 0.002$) greater sway velocity ($p = 0.004$) greater sway variability ($p < 0.05$) less sway divergence as shown by LyE ($p < 0.05$) less sway entropy in ML ($p < 0.05$)	A lack of divergence/entropy may indicate an impaired ability to adapt to perturbations	5
Corporaal et al. (2013)(39)	MS = 37 CON = 76	-MS (female = 29, age = 37 ± 10y) -Age- and gender-matched healthy controls	CSA	-DHI -EDSS -14 gait and stability tests with various conditions (solid vs foam surface, one vs two legs, eyes open vs closed)	Correlations were found between DHI, EDSS severity, and performance during tests Highest correlation was with standing on foam, both legs, eyes closed (0.63-0.69 depending on variable, $p < 0.003$)	Functional performance seems to decline as the severity of the disease increases	5

Ganesan et al. (2015)(40)	MS = 18 CON = 18	-MS -Age- and gender-matched healthy controls	CSA	-Participants had to shift their COM to various positions as shown on a computer screen using the EquiTest device -BBS	MS movement velocity was slower in all directions, endpoint excursion was smaller, directional control was impaired ($p < 0.001$)	Patients with MS have a reduced ability to control their posture, especially in backwards- left/right directions and left directions	5
Karst et al. (2005)(41)	MS = 21 CON = 21	-MS > 48/56 on BBS -Age/Gender-Matched Healthy Controls	CSA	-CoP analysis in sagittal plane during various reaching movements -BBS	MS group had smaller LoS ($p = 0.008$) during max leaning trials but not when expressed as a percentage of maximum CoP displacement	PwMS adapt a LoS strategy that is similar to healthy controls when evaluated as a percentage of their total possible displacement	6

McLoughlin et al. (2014)(42)	MS = 34 (female = 26) CON = 10 (female = 7)	-MS (Mean EDSS = 3.5)	Intervention	-Postural sway with eyes open/closed -Knee extension and dorsiflexion strength -Fatigue via VAS-F	A 6MWT elicited significant increases in postural sway ($p<0.05$) Significant decreases in peak force ($p<0.01$), and significant increases in fatigue ($p<0.01$)	MS patients are extremely sensitive to fatigue, this affects strength, balance, and stability	6
Mehravar et al. (2015)(6)	MS = 12 CON = 12	-Female (EDSS = 1.9 ± 0.94) -Healthy female controls	CSA	-EMG of RA, ES, TA, SOL, RF, BF -Self-released posterior perturbations	Prior to load release, EMG activity of RA, TA, and BF was lowered while SOL, BF, and ES was increased. MS could anticipate muscle activity to perturbations, but not as well as CON ($p<0.05$)	MS patients are unable to anticipate a perturbation as well as controls, and have an impaired ability to compensate after the perturbation has occurred	5

Peterson et al. (2016)(8)	MS = 19 (female = 17) CON = 12 (female = 9)	-MS -Age- and sex-matched healthy controls	CSA	-Postural Assessment: 20 backwards surface translations (4 sets of 5 at varying amplitude) -MRI assessment -EMG of TA and MG	Latency of antagonist (TA) was significantly greater for PwMS ($p = 0.012$) Pedunculopontine nucleus radial diffusivity was larger (worse) in PwMS ($p = 0.004$)	Structural integrity of the Pedunculopontine nucleus-balance-locomotion network is associated with improved postural control	5
Fling et al. (2015)(43)	MS = 24 (female = 21) CON = 14 (female = 11)	-MS -Age-matched controls	CSA	-Postural Assessment: 5 sets of 5 surface translations at varying amplitudes, after 24 hours, 2 sets of 5 were completed to test learning -fMRI	Both groups improved in short-term and long-term perturbation response ($p < 0.001$) Cortico-cerebellar connectivity was strongly related to baseline performance ($p = 0.013$) but not short/long-term learning in PwMS	PwMS were better able to adapt to perturbations than CON when considering the impaired initial performance	5

Cavallari et al. (2014)(44)	MS = 30 (female = 18) CON = 10 (female = 7)	-MS -Healthy controls	CSA	Timed 25-Foot Walk MRI	Fractional anisotropy was positively associated with EDSS (r = 0.424, p = 0.022) and gait assessment via the ambulation index (r = 0.388, p = 0.037) but no associations with a timed 25-foot walk test	Changes in basal ganglia and thalamus may contribute to ambulatory deficits in PwMS	7
Lanzetta et al. (2004)(12)	MS = 10 CON = 10	-MS, must use a wheelchair	CSA	-Seated postural analyses during a static trial, with head movements, and while reaching for objects with the hands	Many significant differences were observed between MS and controls for angular displacements and velocities in both sagittal and frontal planes (p < 0.01)	PwMS show altered stability at the trunk, indicating neuromuscular deficits are not limited to the lower extremities	5

Huisinga et al. (2012)(45)	MS = 15 CON = 15	-MS	Intervention	-5-minute quiet-standing postural assessment -3-month biweekly strength training intervention	Pre-training RMS values were significantly higher in MS group ($p = 0.002$) but not post-training ($p = 0.298$)	3-months of supervised strength training may be beneficial for improving balance in PwMS	5
Davies et al. (2017)(46)	MS = 15 CON = 15	-MS -Age- and gender-matched healthy controls	CSA	-Gait analysis at self-selected speeds -Dynamic isometric ankle force control task	MS had short step length, lower step frequencies, velocity, and peak ankle moments ($p < 0.05$) Negative rank order correlations were found between RMS (error during control task) and various gait variables ($p < 0.05$)	Neuromuscular control of the ankle is impaired in PwMS and is associated with impaired walking performance	5

Kanekar et al. (2015)(14)	MS = 10 (female = 8) CON = 10	-MS -Age- and gender-matched healthy controls	CSA	-4 sets of 30s standing postural assessment -2 EO -2 EC -Frequency analysis of postural sway	-MS had greater sway velocity in ML direction ($p < 0.05$) -MS had less power in the ML low frequency band with EC ($p < 0.05$)	While CON seemed unaffected by the EC condition, MS showed a greater reliance on vestibular/proprioceptive systems. This strategy seemed to be insufficient as MS showed a greater sway velocity.	6

Legend: MS = Multiple Sclerosis, CON = control, CSA = Cross-sectional analysis, PR = progressive relapsing, SP = secondary progressive, RR = relapsing remitting, CoP = center of pressure, AP = anterior/posterior, ML = medial/lateral, PwMS = Persons with MS, OR = odd's ratio, SMD = standard mean difference, LyE = Lyapunov exponent, DHI = Dizziness Handicap Inventory, EDSS = Expanded Disability Status Scale, BBS = Berg Balance Scale, LoS = Limits of Stability, VAS-F = Visual Analog Scale for Fatigue, 6MWT = 6 Minute Walk Test, RA = Rectus abdominis, ES = Erector spinae, TA = Transversus abdominis, SOL = Soleus, RF = Rectus femoris, BF = Biceps femoris, MRI = Magnetic resonance imaging, MG = Medial-head of the gastrocnemius, fMRI = Functional MRI, EO = eyes open, EC = eyes closed

Table 3: Pathology and Symptoms of Multiple Sclerosis

Study	n	Sample Characteristics	Type	Procedures	Results	Impact	PEDro Scale
Harrison et al. (2015)(2)	MS = 25 (female = 19)	MS (PR = 3, SP = 6, RR = 16)	Retrospective Case Control	Telephone Interviews	92% report fatigue, 92% report balance disruption, 80% report stiffness or spasms in muscles	MS has a wide variety of symptoms, most commonly fatigue, poor balance, and muscular issues	3
Heckman et al. (2001)(47)	MS = 83 (female = 71)	MS (RR = 46, SP = 13, PP = 11, PR = 3)	Retrospective Case Control	Take Home Survey	Medication was reported as the most and least effective treatment (45% and 48% respectively)	MS pain management differs greatly between patients. Medication, Manipulation, and Exercise are most common	3

Kratz et al. (2016)(1)	MS = 180	78% Women, 97% Caucasian, MS (RR = 56%, PP = 21%, SP = 14%, PR = 9%)	Retrospective Case Control	Mailed-in Survey	Fatigue, weakness, and balance are most commonly reported symptoms and are shown to increase with disease severity ($p < 0.05$)	The most commonly reported symptoms of MS all have biomechanical consequences	4
Heitmann et al. (2016)(48)	MS = 377 (female = 252)	Early MS (RR = 96.8%) (mean disease duration = 4.2 ± 5.6 years)	Prospective Case Control	-PainDETECT for neuropathic pain -Fatigue Scale for Motor and Cognitive Functions -Paced Auditory Serial Addition Test for cognitive function	Neuropathic pain only found in 4.2% of patients, most closely correlated with EDSS, fatigue, and depression	Particularly in early MS, pain symptoms may be more related to “normal” causes rather than neurological consequences of MS	5

Cameron et al. (2008)(4)	MS = 10 CON = 10	MS	CSA	-Somatosensory evoked potentials measured in response to sudden rearward ground shifts	MS patients had significantly longer postural latencies, peripheral somatosensory conduction times were normal, but central/spinal somatosensory times were significantly slower ($p < 0.01$)	Impaired spinal somatosensory feedback interferes with the information conduction needed to stabilize the body	5
Kiylioglu et al. (2015)(5)	MS = 26 CON = 26 Myelopathy = 13	-MS (RR) -Myelopathy	CSA	-Somatosensory evoked potentials -Motor evoked potentials -EDSS	Summed SEP and MEP values were correlated with EDSS motor function score ($p < 0.05$)	Motor function in MS is correlated with both afferent and efferent neural performance	5
Wilski et al. (2015)(49)	MS = 257 (female = 172)	MS	CSA	A 29-item Multiple Sclerosis Impact Scale to measure quality of life	General self-efficacy was the only correlate of the multi regression model ($p <0.05$)	Maintaining a good self-image is necessary to maintaining a healthy quality of life for PwMS	4

Raimo et al. (2016)(50)	MS = 160	MS	CSA	-Clinical neuropsychological assessment -Psychiatric assessment	Apathy is present in 37.6% of patients, “pure” apathy (without depression) found in 16% of patients, those with apathy and depression were significantly older, less educated, had longer disease duration, and higher EDSS scores	Negative psychological conditions are associated with disease progression in MS	4
Bogenschutz et al. (2016)(51)	MS = 55	MS	Descriptive survey	Focus-group based phone survey	PwMS have three major concerns with regards to employment, future uncertainty, feeling a sense of loss, and navigating the workplace	Maintenance of mobility is crucial for maintaining quality of life in PwMS	2

Broekmans et al. (2011)(52)	CON = 14 RES = 11 RESe = 11	MS	RCT	-Strength testing -TUG -T25FW -TMWT -20-week resistance training intervention -RESe group also received electrical stimulation during their training sessions	RES and RESe both experienced significant increases in strength from baseline ($p < 0.05$) while there were no significant changes in TUG, T25FW, or TWMT	Resistance training alone may not be sufficient to improve functional performance, despite increases in strength	8
Kjolhede et al. (2015)(53)	n = 25	MS	Randomized Cross-over	-T25MW -TMWT -STS -Ascending stair climb test -24-week PRT/24-week break.	Significant changes were seen in all functional measurements and were maintained after a 24-week follow-up ($p < 0.05$)	Higher intensity exercise and longer training durations seem to have greater effects on functional performance for PwMS	6

Legend: MS = Multiple Sclerosis, LBP = Low Back Pain, TENS = Transcutaneous electrical nerve stimulation, PR = progressive relapsing, SP = secondary progressive, RR = relapsing remitting, SEP = Somatosensory evoked potential, MEP = Motor evoked potential, MEG = magnetoencephelography, MRI = magnetic resonance imaging, FA = fractional anisotropy, CON = control, RES = resistance training group, RESe = resistance training and electrical stimulation, RCT = randomized control trial

Table 4: Methods for Analyzing Trunk Kinematics, Postural Stability and Neuromuscular Performance

Study	n	Population	Type	Methods of Interest	Results	Take Away	PEDro Scale
McGill et al. (1996)(54)	Male = 5 Female = 3	University Students, aged 26 ± 1.3	CSA	Surface EMG	Quadratus lumborum and external oblique can be estimated within ~10% for most activities, psoas within ~10-20%	Surface EMG can be used to predict deep muscular activity within a given margin of error	5
Huebner et al. (2014)(55)	n = 15	Male, Healthy, no LBP, aged 30 ± 10	CSA	Surface EMG	RA- sensitive to lateral displacements at low intensities IO- sensitive to lateral shifts (inguinal ligament) EO- Medial displacements show small changes at low intensities MF- Sensitive to lateral shift LO- Sensitive to lateral shift	Surface EMG placement is critical to ensure consistent data from one group to the next	5

Fry et al. (2014)(56)	MS (female = 16)	Ambulatory MS patients	Test-Retest	-Modified ACSM Curl-Up Test	Curl-up test had excellent test-retest reliability (ICC = 0.995, p <0.001) with a minimum detectable change value of 3.40	A modified ACSM Curl-Up Test is a simple but effective abdominal endurance test for PwMS	-
Singh et al. (2013)(57)	n = 52	Young = 26 (Aged 20-35 years) Old = 26 (Aged 65 to 84)	CSA	-Lumbar extensor strength via load cell applied to upper trunk, 3 sets of 5 second MVC	The difference between lumbar strengths of men and women increases with age	The use of a load cell attached to the upper trunk during MVC is a good measure of extensor strength	5
Prosperini et al. (2015)(16)	MS = 100 (female = 64) CON = 50 (female = 32)	MS, EDSS < 5.5	Test-Retest	-BBS -Static posturography; EO 30s, EC 30s -3-month prospective fall analysis	Greater sway velocities for fallers in AP and ML directions with EO and EC (p < 0.0001)	30s EO condition was the best predictor of fall rates and had greatest test-retest reliability	6

Fling et al. (2015)(43)	MS = 24 (female = 21) CON = 14 (female = 11)	MS Age-matched controls	CSA	-Postural Assessment: 5 sets of 5 surface translations at varying amplitudes, after 24 hours, 2 sets of 5 were completed to test learning -fMRI	Both groups improved in short-term and long-term perturbation response ($p < 0.001$) Cortico-cerebellar connectivity was strongly related to baseline performance ($p = 0.013$) but not short/long-term learning in PwMS	Sets of 5 perturbations were sufficient for testing PwMS	5
Peterson et al. (2016)(8)	MS = 19 (female = 17) CON = 12 (female = 9)	MS Age and sex-matched healthy controls	CSA	-Postural Assessment: 20 backwards surface translations (4 sets of 5 at varying amplitude) -MRI assessment -Surface EMG of TA and MG	Latency of antagonist (TA) was significantly greater with MS ($p = 0.012$) Pedunculopontine nucleus was larger (worse) in PwMS ($p = 0.004$)	Muscle onset latency can be measured via surface EMG by setting a threshold at 2SD above resting for greater than 25ms	5

Chen et al. (2015)(34)	n = 10 (female = 5)	Young (age = 28.2±3.55) Right-Handed	CSA	APA and CPA calculations via integrated EMG activity from -150ms to 49ms and 50ms to 250ms respectively	APA integrated EMG showed greater reciprocal activity (coordinated inhibition of antagonists) on the right-hand side when holding the object and greater co-contraction activity on the left side	Integrated EMG is an effective method for evaluating neuromuscular asymmetries	5
Singh et al. (2011)(57)	Young = 26 (female = 16) Old = 26 (female = 16)	Young = Aged 20-35 years Old = Aged 65 to 84	CSA	-Standing lumbar extension MVC -Lumbar extension fatigue test at 60% MVC for 120s -Using 40% of the distance between PSIS midpoint and ASIS midpoint for L5/S1 joint approximation -Analysis of EMG in the frequency domain for changes with age	Decline of lumbar extensor moment of 46% in old group (p = 0.001), lumbar extensor EMG signals occurred mostly in lower frequency domains (~45-50% power at 20-100Hz)	Frequency domain analysis of EMG may provide insight into altered neuromuscular recruitment strategies	5

Griffioen et al. (2016)(18)	-CON = 13 (female = 7) -LBP = 18 (female = 8)	-Healthy = aged 22-28 -LBP = aged 29-69 years	CSA	-Pseudorandom trunk perturbations -test of validity	Admittance gain (lumbar translation, p-value = 0.164) was more reliable than Reflex gain (EMG, p-value = 0.992)	-Demonstrates validity of test protocol -Trunk perturbations can safely be used with patients with low back pain	5
Kanekar et al. (2015)(14)	MS = 10 (female = 8) CON = 10	-MS -Age- and gender-matched healthy controls	CSA	-4 sets of 30s standing postural assessment -2 EO -2 EC -Frequency analysis of postural sway	-MS had greater sway velocity in ML direction ($p < 0.05$) -MS had less power in the ML low frequency band with EC ($p < 0.05$)	Using a frequency analysis approach to COP data provides insight to the balance strategy being utilized by the subjects	6

Legend: CSA = Cross-sectional analysis, EMG = Electromyography, LBP = Low-back pain, RA = Rectus abdominis, IO = Internal oblique, EO = External oblique, MF = Multifidus, LO = Longissimus, ACSM = American College of Sports Medicine, ICC = Intraclass correlation coefficient, MVC = Maximum voluntary contraction, CON = Control, EDSS = Expanded Disability Status Scale, EO = Eyes open, EC = Eyes closed, AP = Anterior/posterior, ML = Medial/lateral, Fmri = Functional magnetic resonance imaging, PwMS = Persons with MS, TA = Transversus abdominis, MG = Medial-head of the gastrocnemius, PSIS= Posterior superior iliac spine, ASIS = Anterior superior iliac spine, T25MW = Timed 25-Foot Walk Test, TMWT = Two-minute Walk Test, STS = Sit-to-Stand Test, PRT = Progressive resistance training

APPENDIX

Kurtzke Expanded Disability Status Scale

- The 10-point Kurtzke Expanded Disability Status Scale (EDSS) is the most widely accepted clinical disability scale. [1]
- The EDSS is considered the standard for monitoring patients with multiple sclerosis (MS), including those in MS clinical research, although MS is difficult to assess because of the differences in signs and symptoms. [2]
- The EDSS assigns a severity score to the patient's clinical status that ranges from 0-10 in increments of 0.5. The scores from grades 0-4 are determined using functional systems (FS) scales that evaluate dysfunction in the following 8 neurologic systems: Pyramidal, Cerebellar, Brainstem, Sensory, Bladder and bowel, Vision, Cerebral

EDSS grades are as follows:

0 - Normal neurologic examination (all grade 0 in FS, cerebral grade 1 acceptable)

1.0 - No disability, minimal signs in 1 FS (ie, grade 1 excluding cerebral grade 1)

1.5 - No disability, minimal signs in more than 1 FS (more than 1 grade 1 excluding cerebral grade 1)

2.0 - Minimal disability in 1 FS (1 FS grade 2, others 0 or 1)

2.5 - Minimal disability in 2 FS (2 FS grade 2, others 0 or 1)

3.0 - Moderate disability in 1 FS (1 FS grade 3, others 0 or 1) or mild disability in 3 or 4 FS (3/4 FS grade 2, others 0 or 1) though fully ambulatory

3.5 - Fully ambulatory but with moderate disability in 1 FS (1 grade 3) and 1 or 2 FS grade 2, or 2 FS grade 3, or 5 FS grade 2 (others 0 or 1)

4.0 - Fully ambulatory without aid; self-sufficient; up and about some 12 hours a day despite relatively severe disability, consisting of 1 FS grade 4 (others 0 or 1) or combinations of lesser grades exceeding limits of previous steps; able to walk approximately 500 m without aid or resting

4.5 - Fully ambulatory without aid; up and about much of the day; able to work a full day; may otherwise have some limitation of full activity or require minimal assistance; characterized by relatively severe disability, usually consisting of 1 FS grade 4 (others 0 or 1) or combinations of lesser grades exceeding limits of previous steps; able to walk approximately 300 m without aid or rest

5.0 - Ambulatory without aid or rest for approximately 200 m; disability severe enough to impair full daily activities (eg, to work full day without special provisions; usual FS equivalents are 1 grade 5 alone, others 0 or 1; or combinations of lesser grades usually exceeding specifications for step 4.0)

5.5 - Ambulatory without aid or rest for approximately 100 m; disability severe enough to preclude full daily activities (usual FS equivalents are 1 grade 5 alone; others 0 or 1; or combinations of lesser grades usually exceeding those for step 4.0)

6.0 - Intermittent or unilateral constant assistance (cane, crutch, or brace) required to walk approximately 100 m with or without resting (usual FS equivalents are combinations with more than 2 FS grade 3+)

6.5 - Constant bilateral assistance (canes, crutches, or braces) required to walk approximately 20 m without resting (usual FS equivalents are combinations with more than 2 FS grade 3+)

7.0 - Unable to walk beyond approximately 5 m even with aid; essentially restricted to wheelchair; wheels self in standard wheelchair and transfers alone; up and about approximately 12 hr/day (usual FS equivalents are combinations with more than 1 FS grade 4+; very rarely, pyramidal grade 5 alone)

7.5 - Unable to take more than a few steps; restricted to wheelchair; may need aid in transfer; wheels self but cannot carry on in standard wheelchair a full day; may require motorized wheelchair (usual FS equivalents are combinations with more than 1 FS grade 4+)

8.0 - Essentially restricted to bed or chair or perambulated in wheelchair but may be out of bed itself much of the day, retains many self-care functions; generally, has effective use of arms (usual FS equivalents are combinations, generally grade 4+ in several systems)

8.5 - Essentially restricted to bed much of the day; has some effective use of arms; retains some self-care functions (usual FS equivalents are combinations, generally 4+ in several systems)

9.0 - Helpless bedridden patient; can communicate and eat (usual FS equivalents are combinations, mostly grade 4+)

9.5 - Totally helpless bedridden patient; unable to communicate effectively or eat/swallow (usual FS equivalents are combinations, almost all grade 4+)

10.0 - Death due to MS

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