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POSTURAL CONTROL STRATEGY DURING STANDING IS ALTERED IN PATIENTS WITH MULTIPLE SCLEROSIS

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Abstract

Disturbances in balance are one of the first reported symptoms of Multiple Sclerosis (MS), yet limited research has been performed to classify the postural control deficits in this population. This study investigated the variability present in the sway patterns during quiet standing in patients with MS (PwMS) and healthy controls. Subjects were assessed (eyes open, closed) standing on a force platform. Variability of the sway patterns was quantified using a measure of amount of variability (root mean square; RMS) and two measures of temporal structure of variability (Lyapunov Exponent – LyE; Approximate Entropy – ApEn). RMS results revealed significantly higher amount of variability in the sway patterns of PwMS. PwMS also exhibit increased regularity (decreased ApEn) and decreased divergence (decreased LyE) during standing compared to healthy controls. Removing vision resulted in significantly decreased divergence (decreased LyE) in the MS subject group. These changes in the temporal structure correspond well with the theoretical model of the optimal movement variability hypothesis and the results support using variability measures to understand the mechanisms that underline postural control in PwMS and possibly other neurodegenerative disease pathologies.

Introduction

Multiple Sclerosis (MS) is the most common disabling neurological disease among young adults, with the majority of patients diagnosed between 20 and 50 years of age [10]. The disease specific mechanisms which contribute to impaired balance and postural control likely stem from inflammation of the CNS which results in damage to axons leading to delays in conduction [13] and can block the conduction of potentials along pathways throughout the CNS [1]. Additionally, delayed somatosensory evoked potentials are related to postural response delays in persons with MS (PwMS) [4]. These delays would affect postural control under any circumstance where somatosensory information is being utilized [15], including quiet standing.

To quantify balance deficits in PwMS, sway patterns have been investigated during several tasks including quiet standing [7, 34], reaching [17, 34], and under perturbation conditions [4]. All of these studies relay information regarding only the amount of sway occurring during the task. Here, we propose to enhance the existing understanding about balance in PwMS by investigating sway variability to discern characteristics about the motor control strategies used to maintain standing balance. If posture is viewed as the dynamic stability of a continuously moving body, then the temporal structure of the sway path can provide information regarding the behavior of the moving body over time. Linear methods of examining variability within a time series provide information on the amount or magnitude of variability within the signal by employing averaging procedures which assume that variations between repetitions of a task are independent of future and past repetitions which has been proven to be false in posture tasks [11]. Assessed through nonlinear measures, variability reflects multiple options for movement, providing for adaptive strategies that are not reliant on rigid programs for each task or for each changing condition encountered [11, 12]. The optimal movement variability hypothesis contends that a healthy system exhibits an optimal state of movement variability characterized by maximum effective adaptability of the system to environmental stimuli and stresses. To acquire such insights, variability in postural control has been investigated previously in children and in Parkinson’s disease patients [14, 21] and briefly in PwMS to measure the effects of a rehabilitation intervention which showed that postural sway variability changed (RMS increased, LyE decreased) as a result of resistance training exercise [16].

The purpose of this research was to investigate upright postural control in PwMS during quiet standing with eyes open and closed. It is hypothesized that 1) PwMS will demonstrate increased amount of variability due to delayed feedback from the sensory systems and due to the previously identified exaggerated sway during perturbations [4]; 2) PwMS will demonstrate more repetitive patterns in the temporal structure of variability as compared to healthy controls since PwMS have already shown less velocity scaling and more amplitude scaling in response to a translating surface perturbation due to longer latency postural responses [4]; 3) that within PwMS, differences in both the amount and temporal structure of sway variability will be found in the eyes closed compared to the eyes open condition since postural control in PwMS has previously been shown to change with altered sensory input [5].

Methods

Participants

PwMS (n = 15, age 45.1±10.5), recruited through the University's Medical Center, and healthy controls (n = 15, age 39.4±11.7), recruited through the community, provided informed consent. PwMS and healthy controls were age, height, and weight matched (Table 1). EDSS score, the standard clinical disability scale for PwMS [18], was mean 4.5 ± 1.8 , median 5.2.The research protocol was approved by the University's Institutional Review Board.

INSERT TABLE 1 ABOUT HERE

Quiet standing protocol

Subjects stood quietly for five minutes with eyes open approximately 10 meters from a wall, while COP data was collected. Feet were placed at approximately hip width apart, toes facing forward. After a mandatory rest period of at least three minutes, subjects again stood quietly for five minutes with eyes closed. Kinetic data was collected using a force platform (Kistler Model: 9281-B11; Amherst, NY; 10 Hz) [16]. Unfiltered data was cropped to 2000 data points (approximately 3 ½ minutes) as some PwMS were unable to complete the full 5 minutes of quiet standing due to reports of discomfort and tiredness. Data was collected and analyzed unfiltered so as not to mask or remove any dynamical properties or variability present within the system [11].

Data analysis

The coordinates of the center of pressure (COP) in the medial-lateral (ML) and antero-posterior (AP) directions were calculated for each trial. Amount of sway variability was quantified using the root mean square (RMS), and was calculated from the COP time series for both directions using customized MatLab software (The Mathworks Inc., Natick, MA) [26].

Temporal structure of sway variability was also quantified from both directions using Lyapunov Exponent (LyE) and Approximate entropy (ApEn). Examining the temporal structure of the time series of the COP can provide information regarding the behavior of the moving body over time since even during quiet stance, the center of mass of a person is continuously moving. The largest LyE is a measure of the rate at which nearby trajectories in state space diverge and the system's sensitivity to initial conditions thereby [32]. Lack of divergence in the sway patterns will produce small values for the LyE and vice versa.

The LyE was calculated using the Chaos Data Analyzer Professional software [31] with an embedding dimension of 6 which was calculated using a Global False Nearest Neighbor analysis [32]. ApEn quantifies how predictable and regular are data patterns within a time series, thus evaluating the complexity of a time series [24, 25]. ApEn was calculated using customized MatLab software based upon the methodology of Pincus [24, 25] (lag = 6, m = 2, r = 0.2 were used as default parameters).

Group means for RMS, LyE, and ApEn were calculated for healthy controls and PwMS during the eyes open and eyes closed conditions. Because LyE and ApEn were computed separately for ML and AP [29], two separate 2x2 repeated measures ANOVA models were employed to test for effects of GROUP (MS v. Control) and CONDITION (eyes open v. closed). To compare the current dataset with previously published findings on COP sway in PwMS, 95% sway area, mean velocity, and range were calculated for the resultant COP time series for each group while standing with eyes open and compared using independent t-tests. Independent and dependent t-tests were used for post hoc analysis when significant group by condition interactions were identified. Statistical analysis was performed using SPSS 20.0 (SPSS, Inc., Chicago, IL) with level of significance set at 0.05.

Results

Linear Measures

PwMS had significantly greater sway area ($p = 0.002$) and greater median sway velocity ($p = 0.004$) compared to healthy controls during eyes open quiet standing. Sway range increased in PwMS as compared to controls; however this increase was not statistically significant ($p = 0.070$) (Table 1).

In the ML direction, the RMS demonstrated a significant main effect for GROUP ($F_{1,29}$: 5.91, $p = 0.022$) where PwMS had larger RMS values. There was also a significant main effect for CONDITION ($F_{1,29}$: 64.16, $p < 0.001$) where eyes closed resulted in larger RMS values. No significant interaction ($F_{1,29}$: 0.082, $p = 0.777$) was found (Figure 1A).

In the AP direction, RMS demonstrated a significant main effect for GROUP ($F_{1,29}$: 8.04, $p =0.009$) where PwMS had larger RMS values. There was also a significant main effect for CONDITION ($F_{1,29}$: 131.94, $p < 0.001$) where eyes closed resulted in larger RMS values. No significant interaction ($F_{1,29}$: 0.412, $p = 0.526$) was found (Figure 1B).

INSERT FIGURE 1 HERE

Nonlinear measures

For LyE in the ML direction, a significant main effect for GROUP was found ($F_{1,29}$: 14.98, $p = 0.001$) where PwMS had lower LyE values compared to healthy controls. No significant main effect was found for CONDITION ($F_{1,29}$: 3.57, $p = 0.070$). A significant interaction was found for GROUP x CONDITION ($F_{1,29}$: 6.52, $p = 0.017$). Post-hoc tests revealed that within the MS patient group, the LyE was significantly decreased (t: 2.50, $p = 0.026$) in the eyes closed condition compared to eyes open. Within the healthy control group, there was no difference (t: -0.66, $p = 0.516$) in the LyE values due to CONDITION. PwMS had significantly lower LyE values compared to controls during the eyes closed condition (t: 4.59, $p < 0.001$) but not during the eyes open condition (t:-1.57, $p = 0.128$) (Figure 2A).

In the AP direction, LyE analysis revealed a significant main effect for GROUP ($F_{1,29}$: 10.13, $p = 0.004$) where PwMS had significantly lower LyE values. No significant main effect was found for CONDITION ($F_{1,29}$: 0.014, $p = 0.906$). A significant interaction was found for GROUP x CONDITION ($F_{1,29}$: 7.74, $p = 0.010$). Post-hoc tests revealed that within the MS patient group, the LyE was significantly decreased (t: 2.167, $p = 0.049$) in the eyes closed condition compared to eyes open. Within the healthy control group there was no difference (t: 1.81, $p = 0.092$) in LyE values due to CONDITION. PwMS had significantly lower LyE values compared to controls during the eyes closed condition (t: 3.67, $p = 0.001$) but not during the eyes open condition (t: 0.846, $p = 0.405$) (Figure 2B).

INSERT FIGURE 2 HERE

The ApEn in the ML direction revealed a significant main effect for GROUP ($F_{1,29}$: 8.284, $p = 0.008$) where PwMS had significantly lower ApEn values. There was no significant main effect for CONDITION ($F_{1,29}$: 0.821, $p = 0.373$) and no interaction ($F_{1,29}$: 0.614, $p = 0.440$) (Figure 3A).

ApEn in the AP direction there was no significant main effect for GROUP ($F_{1,29}$: 0.591, $p = 0.449$) or for CONDITION ($F_{1,29}$: 0.837, $p = 0.368$). No significant interaction ($F_{1,29}$: 0.723, $p = 0.111$) was found (Figure 3B).

INSERT FIGURE 3 HERE

Discussion

Our results indicate that PwMS have altered COP sway variability during quiet stance in both the ML (RMS, LyE, ApEn) and AP (RMS, LyE, ApEn) directions. Results also indicate that removing vision causes changes in COP sway variability with PwMS in the ML (RMS, LyE) and AP (RMS, LyE) directions. Increased sway area and sway velocity in PwMS indicate that the current dataset is in agreement with previously published data [2, 5, 34]. These findings support our first hypothesis and agree with previous studies which reported that people with MS have increased amount of sway variability while standing quietly [7, 30, 34]. The increased RMS observed in the PwMS is possibly the result of slowed somatosensory feedback [4]. Somatosensory information has been suggested as the most critical sensory mechanism for control of posture and the increase in RMS may reflect a deficiency in the somatosensory feedback loop [28]. Adequate postural control occurs as a function of somatosensory information being integrated with vestibular information necessary for an adequate motor response to maintain control of stance [8]. In MS, it is possible that the integration of vestibular and somatosensory information is disrupted and leads to the increased amount of sway variability. The increased RMS could also be attributed to the effects of spasticity since up to 80% of PwMS report problems with spasticity, the velocity-dependent increase in tonic stretch reflexes and exaggerated tendon jerks resulting from hyper-excitability of the stretch reflex[20, 27]. While the present study did not measure spasticity, it has been reported that PwMS who have high spasticity, as measured soleus Hoffman reflex, exhibit increased COP sway area [30]. Thus, it is also possible that a combination of deficits in sensory information processing and motor impairment such as spasticity contribute to increased COP sway RMS. Fatigue is also a heavily reported symptom in PwMS [9] and because some of the subjects in the present study could not stand for the entire 5-minute trial length, it is likely that they were affected by fatigue. Chung et al [7] reported that in PwMS, reported fatigue was moderately correlated with COP variability in the ML and AP direction. Thus, it is possible that in the present study, fatigue also contributed to the increased COP sway RMS in PwMS compared to controls.

The results also support our second hypothesis since both LyE and ApEn were significantly lower in PwMS. LyE quantifies separation between continuous paths of movement and whether these paths will expand or contract within a dynamical system [32]. ApEn is a probability measure that can quantify the predictability of vectors identified within a dynamical system [32]. Decreased LyE and ApEn values of PwMS compared to controls indicate a sway pattern with less divergence and a more repeatable and predictable pattern. This direction of change for LyE and ApEn compared to controls could indicate an inability to adapt to perturbations in PwMS. Since the sway patterns of PwMS are restricted, PwMS could exhibit an increased dependence on repeatable movement patterns in order to maintain upright balance. In other words, if the task demands or environmental conditions were to change, PwMS could be less able to adapt and maintain task performance. This breakdown of task performance has been exhibited in PwMS [4]. When exposed to a surface translation during standing, PwMS responded with delayed and excessive scaling of postural response amplitude. This scaling was related to the patient’s spinal somatosensory evoked potential latencies [4], indicating a relationship between response to perturbation and somatosensory conduction speed. During quiet standing, it has been reported that the dynamics of muscle firing patterns do not necessarily map directly to the dynamics at the movement task level [25]. Thus, for PwMS, normal muscle firing patterns are likely disrupted due to delayed somatosensory information receipt and due to axonal damage which could influence the dynamics of the standing task. This conclusion is speculative but it has been reported that neural circuitry which is successful in producing a desired outcome has a higher probability of being accessed again for similar tasks [19]. This would indicate an increased reliance on past patterns of movement that have proved successful regardless of the received somatosensory information or the muscle firing activity. For PwMS, if a novel or unexpected task was necessary, reliance on past patterns of movement without the ability to adapt to the presented scenario could result in failure to maintain postural control.

Our final hypothesis was partially supported since LyE also showed a significant group by condition interaction and RMS showed an effect of condition, but ApEn was not affected by removing vision. The interaction identified for LyE indicates that when vision was removed in PwMS, the divergence of the sway trajectories decreased in PwMS only. One possible explanation for this interaction is an impaired ability to properly perform sensory re-weighing in the MS group. Control of posture requires complex integration of sensory information which is weighted based upon accuracy or availability of the information and/or environmental conditions [23]. It's possible that when vision was removed, PwMS couldn't account for the loss of sensory input by relying more heavily on somatosensory and vestibular input, so LyE decreased further in both the ML and AP directions. Previous studies have also demonstrated that PwMS have altered postural control with the alteration of one sensory input [5, 34]. To confirm the effect of sensory alteration on balance in PwMS, it is necessary to examine a variety of sensory alteration conditions and determine under which conditions the patients are most or least affected.

Employing nonlinear measures of variability to examine COP sway allowed us to gain a unique perspective on postural control in PwMS. The COP time series reflects the net motor control signal output and encompasses the position of the whole body center of gravity and the muscle activity involved in maintaining balance [6]. In PwMS, the COP time series showed decreased LyE and ApEn values which indicate less behavioral complexity in the sway paths as compared to controls. The decrease in complexity in the PwMS corresponds well with the optimal movement variability model. The theory states that optimal movement variability has a highly complex structure and is associated with healthy movement patterns which reflect a rich behavioral state allowing for diverse movement strategies [33]. Conversely, a more rigid system has reduced adaptive capability [22] which indicates that a system may be less able to produce a physiological response to a particular task or to a system perturbation [6]. Compared to healthy controls, PwMS are less complex, more rigid, and have less movement strategies available to them. Future studies should also investigate treatments that help PwMS return to a state of optimal variability, possibly by introducing variability into the process of learning a new motor task [3]. Additionally, an investigation of the relationship between postural control and specific system (sensory, pyramidal, cerebellar) disability could provide insight regarding whether there is a common source of disability which relates to postural control deficits.

References

[1] C. Bjartmar, B.D. Trapp, Axonal and neuronal degeneration in multiple sclerosis: mechanisms and functional consequences, Curr.Opin.Neurol. 14 (2001) 271.

[2] M.K. Boes, J.J. Sosnoff, M.J. Socie, B.M. Sandroff, J.H. Pula, R.W. Motl, Postural control in multiple sclerosis: Effects of disability status and dual task, J Neurol Sci 315 (2012) 44-48.

[3] L.L. Cai, G. Courtine, A.J. Fong, J.W. Burdick, R.R. Roy, V.R. Edgerton, Plasticity of functional connectivity in the adult spinal cord, Philos.Trans.R.Soc.Lond.B.Biol.Sci. 361 (2006) 1635.

[4] M.H. Cameron, F.B. Horak, R.R. Herndon, D. Bourdette, Imbalance in multiple sclerosis: a result of slowed spinal somatosensory conduction, Somatosens.Mot.Res. 25 (2008) 113.

[5] D. Cattaneo, J. Jonsdottir, Sensory impairments in quiet standing in subjects with multiple sclerosis, Mult.Scler. 15 (2009) 59.

[6] J.T. Cavanaugh, K.M. Guskiewicz, N. Stergiou, A nonlinear dynamic approach for evaluating postural control: new directions for the management of sport-related cerebral concussion, Sports Med. 35 (2005) 935.

[7] L.H. Chung, J.G. Remelius, R.E. Van Emmerik, J.A. Kent-Braun, Leg power asymmetry and postural control in women with multiple sclerosis, Med Sci Sports Exerc 40 (2008) 1717.

[8] R. Creath, T. Kiemel, F. Horak, J.J. Jeka, The role of vestibular and somatosensory systems in intersegmental control of upright stance, J.Vestib.Res. 18 (2008) 39.

[9] J.D. Fisk, A. Pontefract, P.G. Ritvo, C.J. Archibald, T.J. Murray, The impact of fatigue on patients with multiple sclerosis, Can.J.Neurol.Sci. 21 (1994) 9.

[10] E.M. Frohman, Multiple sclerosis, Med.Clin.North Am. 87 (2003) 867.

[11] R.T. Harbourne, N. Stergiou, Nonlinear analysis of the development of sitting postural control, Dev.Psychobiol. 42 (2003) 368.

[12] J.M. Hausdorff, P.L. Purdon, C.K. Peng, Z. Ladin, J.Y. Wei, A.L. Goldberger, Fractal dynamics of human gait: stability of long-range correlations in stride interval fluctuations, J.Appl.Physiol. 80 (1996) 1448.

[13] B. Hemmer, S. Nessler, D. Zhou, B. Kieseier, H.P. Hartung, Immunopathogenesis and immunotherapy of multiple sclerosis, Nat.Clin.Pract.Neurol. 2 (2006) 201.

[14] S.L. Hong, E.G. James, K.M. Newell, Age-related complexity and coupling of children's sitting posture, Dev.Psychobiol. 50 (2008) 502.

[15] F.B. Horak, Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls?, Age Ageing 35 Suppl 2 (2006) ii7.

[16] J.M. Huisinga, M. Filipi, N. Stergiou, Supervised resistance training results in changes in postural control in multiple sclerosis patients, Motor control 16 (2011) 50-63.

[17] G.M. Karst, D.M. Venema, T.G. Roehrs, A.E. Tyler, Center of pressure measures during standing tasks in minimally impaired persons with multiple sclerosis, J.Neurol.Phys.Ther. 29 (2005) 170.

[18] J.F. Kurtzke, Rating neurologic impairment in multiple sclerosis: an expanded disability status scale (EDSS), Neurology 33 (1983) 1444.

[19] M.J. Kurz, N. Stergiou, The aging human neuromuscular system expresses less certainty for selecting joint kinematics during gait, Neurosci.Lett. 348 (2003) 155.

[20] J.W. Lance, The control of muscle tone, reflexes, and movement: Robert Wartenberg Lecture, Neurology 30 (1980) 1303-1313.

[21] S. Morrison, G. Kerr, K.M. Newell, P.A. Silburn, Differential time- and frequency-dependent structure of postural sway and finger tremor in Parkinson's disease, Neurosci.Lett. 443 (2008) 123.

[22] K. Newell, Degrees of freedom and the development of postural center of pressure profiles. In: K. Newell, P. Molenaar (Eds.), Applications of non-linear dynamics to developmental process modeling, Lawrence Erlbaum Associates, Mahway, NJ, 1998, p. 80.

[23] R.J. Peterka, P.J. Loughlin, Dynamic regulation of sensorimotor integration in human postural control, J Neurophysiol 91 (2004) 410.

[24] S.M. Pincus, Approximate entropy as a measure of system complexity, Proceedings of the National Academy of Science U S A. 88 (1991) 2297.

[25] S.M. Pincus, I.M. Gladstone, R.A. Ehrenkranz, A regularity statistic for medical data analysis, J.Clin.Monit. 7 (1991) 335.

[26] T.E. Prieto, J.B. Myklebust, R.G. Hoffmann, E.G. Lovett, B.M. Myklebust, Measures of postural steadiness: differences between healthy young and elderly adults, IEEE Trans.Biomed.Eng. 43 (1996) 956.

[27] M.A. Rizzo, O.C. Hadjimichael, J. Preiningerova, T.L. Vollmer, Prevalence and treatment of spasticity reported by multiple sclerosis patients, Mult Scler 10 (2004) 589-595.

[28] L. Rocchi, L. Chiari, F.B. Horak, Effects of deep brain stimulation and levodopa on postural sway in Parkinson's disease, J.Neurol.Neurosurg.Psychiatry. 73 (2002) 267.

[29] A. Shumway-Cook, M.H. Woollacott, Motor Control: Theory and Practical Applications, Lippincott Willliams & Wilkins, New York, NY, 2001.

[30] J.J. Sosnoff, S. Shin, R.W. Motl, Multiple sclerosis and postural control: the role of spasticity, Archives of Physical Medicine and Rehabilitation 91 (2010) 93.

[31] J.C. Sprott, G. Rowlands, Chaos datas analyzer: the professional version, Physics Academic Software, Raleigh, NC, 1998.

[32] N. Stergiou, U.H. Buzzi, M.J. Kurz, J. Heidel, Nonlinear tools in human movement. In: N. Stergiou (Ed.), Innovative analyses for human movement, Human Kinetics, Champaign, IL., 2004, pp. 63-90.

[33] N. Stergiou, R. Harbourne, J. Cavanaugh, Optimal movement variability: a new theoretical perspective for neurologic physical therapy, J.Neurol.Phys.Ther. 30 (2006) 120.

[34] R.E. Van Emmerik, J.G. Remelius, M.B. Johnson, L.H. Chung, J.A. Kent-Braun, Postural control in women with multiple sclerosis: effects of task, vision and symptomatic fatigue, Gait & posture 32 (2010) 608.

Figure Legends

Figure 1A. RMS of the ML direction. Significant main effect for *GROUP ($p < 0.05$) and §CONDITION ($p < 0.05$).

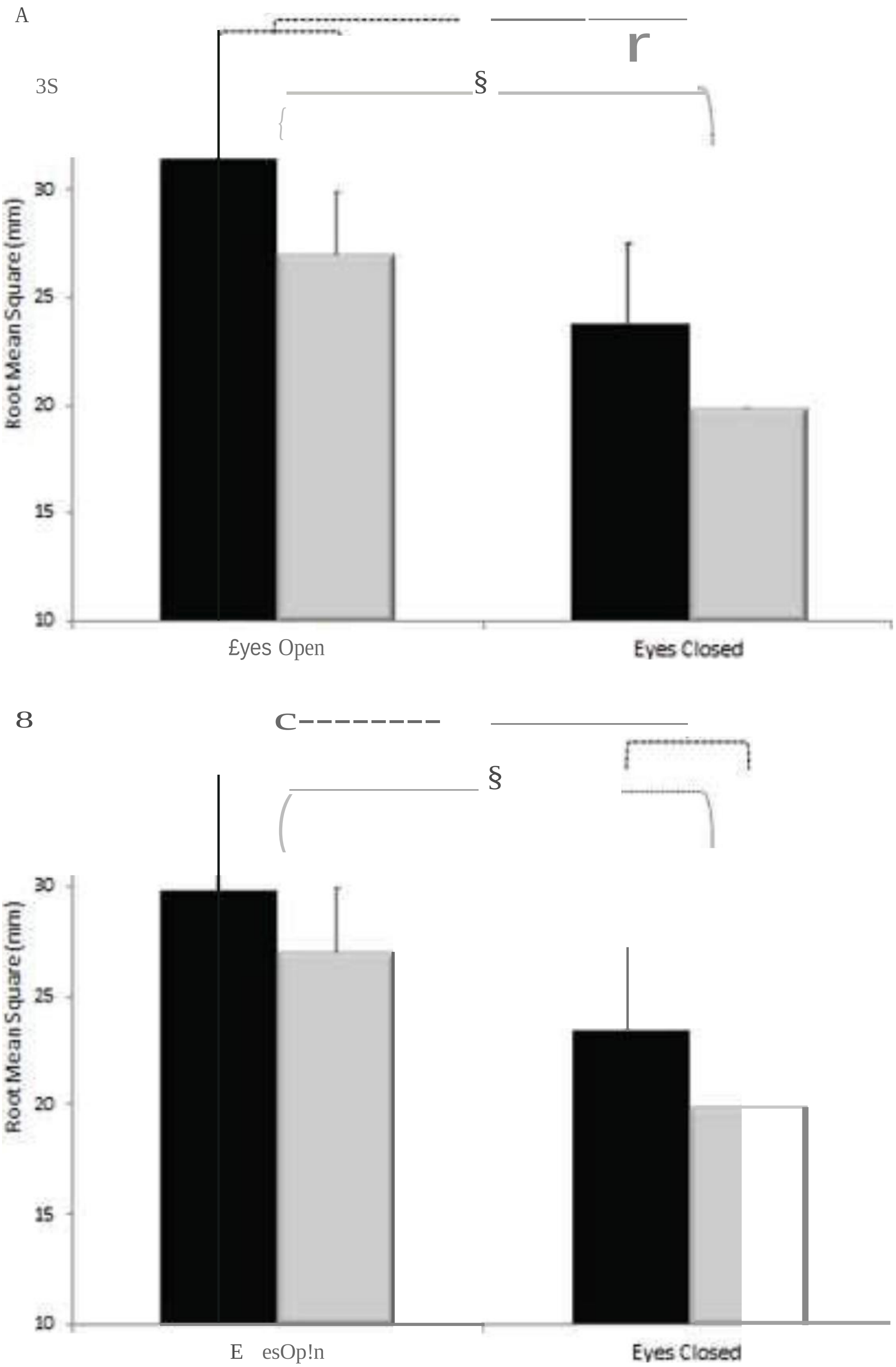
Figure 1B. RMS of the AP direction. Significant main effect for *GROUP ($p < 0.05$) and §CONDITION ($p < 0.05$).

Figure 2A. LyE for the ML direction. Significant main effect for *GROUP ($p = 0.001$). Significant interaction for CONDITION x GROUP ($p < 0.05$); †Post hoc test significant difference ($p < 0.05$).

Figure 2B. LyE for the AP direction. Significant main effect for *GROUP ($p < 0.05$). Significant interaction for CONDITION x GROUP ($p < 0.05$); †Post hoc test significant difference ($p < 0.05$).

Figure 3A. ApEn for the ML direction. Significant main effect for *GROUP ($p < 0.05$).

Figure 3B. ApEn for the AP direction.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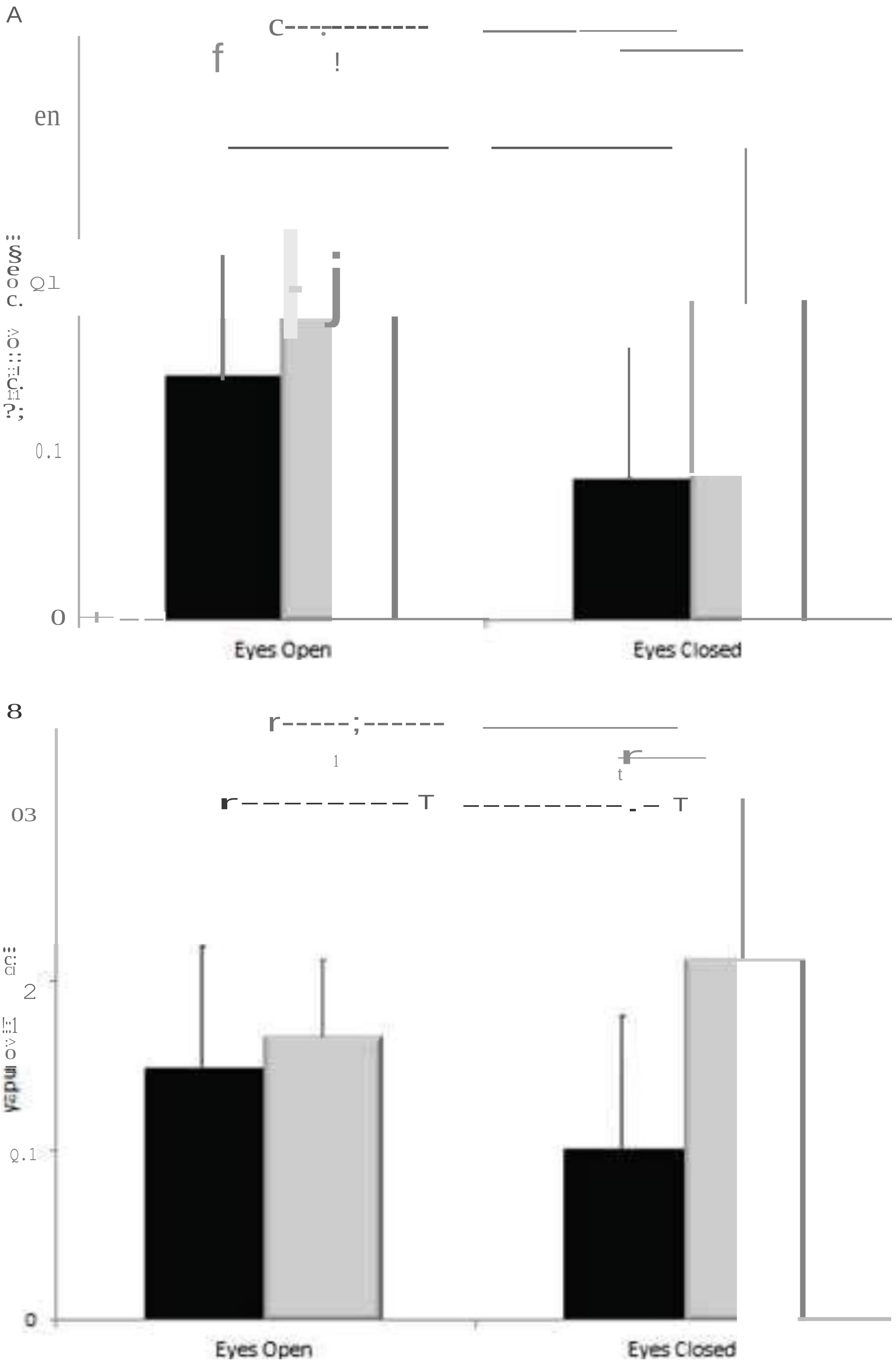
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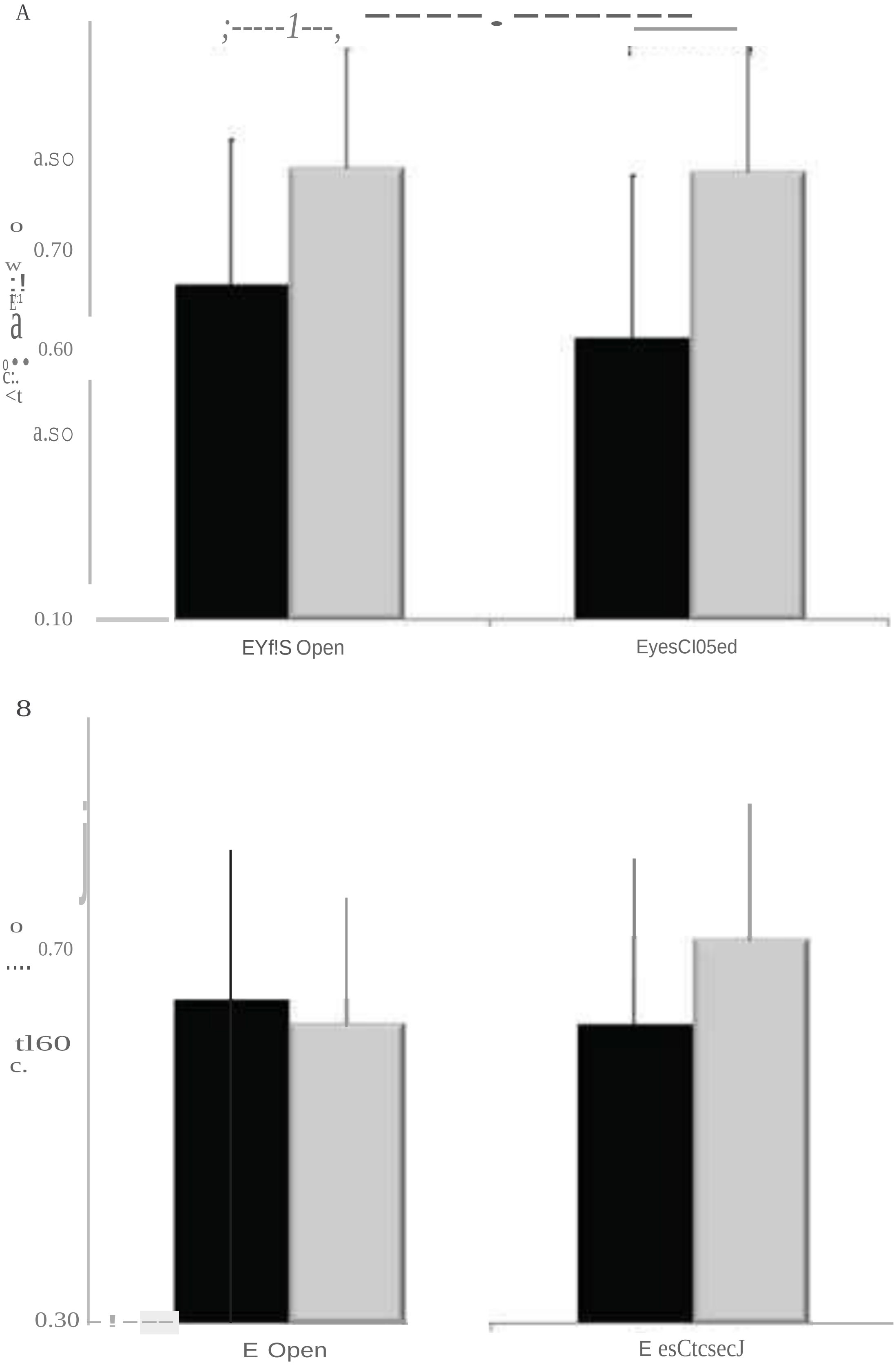
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Table 1. Demographic information (mean ± std dev) for healthy controls and MS subjects. EDSS = Expanded Disability Status Scale.

Characteristics	Control (n=15)	MS (n=15)	p-value
Age (years)	39.4 ± 11.7	45.1 ± 10.5	0.233
Height (cm)	157.4 ± 10.6	166.7 ± 8.9	0.903
Weight (kg)	66.2 ± 7.5	75.9 ± 13.1	0.104
EDSS Score Mean	-	4.5 ± 1.8	
EDSS Score Median	-	5.2	
Female/Male	12/3	13/2	
95% Sway Area (mm^2)	3.53 ± 2.92	12.23 ± 9.14	0.002*
Median Sway Velocity (mm/s)	0.98 ± 0.56	3.12 ± 2.44	0.004*
Sway Range (mm)	4.21 ± 3.64	6.91 ± 3.91	0.070

*Significant ($p < 0.05$) difference between groups