Head Stabilization During Standing in People with Persisting Symptoms after Mild Traumatic Brain Injury

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ABSTRACT

Increased postural sway is often observed in people with mild traumatic brain injury (mTBI), but our understanding of how individuals with mTBI control their head during stance is limited. The purpose of this study was to determine if people with mTBI exhibit increased sway at the head compared with healthy controls. People with persisting symptoms after mTBI (*n* = 59, 41 women) and control participants (*n* = 63, 38 women) stood quietly for one minute in four conditions: eyes open on a firm surface (EO-firm), eyes closed on a firm surface (EC-firm), eyes open on a foam pad (EO-foam), and eyes closed on foam (EC-foam). Inertial sensors at the head, sternum, and lumbar region collected tri-axial accelerations. Root-mean-square (RMS) accelerations in anteroposterior (AP) and mediolateral (ML) directions, and sway ratios between the head and sternum, head and lumbar, and sternum and lumbar region, were compared between groups. People with mTBI predominantly demonstrated greater sway than controls across conditions and directions. During foam-surface conditions, the control group, but not the mTBI group, reduced ML sway at their head and trunk relative to their lumbar. These results are consistent with suggestions of inflexible postural control in people with mTBI.

KEY TERMS: Posture, Balance, Sway, Sensory Integration, Concussion, Stability

INTRODUCTION

Considerable work has demonstrated the importance of head stabilization for whole-body postural control during stance [8, 19, 26, 31] and locomotion [9, 16, 33, 34]. Objective assessments of postural sway in people with mild traumatic brain injury (mTBI) often reveal increased sway of the center of mass (CoM) or center of pressure (CoP) compared with healthy controls [15, 17, 20, 24], but these results do not inform us about head stabilization. While there is some evidence that head stabilization may be impaired while walking in those with mTBI [39], we are unaware of studies that specifically examine the sway of the head in individuals with mTBI during standing.

The lack of knowledge about head stability during standing in those with mTBI likely stems from two sources: 1) the predominant use of force plates or sensors at the waist to quantify postural sway; and 2) the reliance on single-link inverted pendulum mechanics to understand postural control. Force plates are ideal for quantifying the center-of-pressure (CoP) and reflective of CoM sway measured with inertial sensors at the waist[27]. However, the motion of the CoP and CoM does not match the motion of the head [36] because upright postural control is not strictly determined by single-link inverted pendulum mechanics. While a single-link inverted pendulum representation can account for some aspects of body motion during stance in controlled and unperturbed conditions [14], a multi-link representation of body mechanics provides a larger feasible control manifold [22, 25]. Multi-link postural control can also facilitate adaptations to situational demands [21] and sensory integration [28, 42] through in-phase and anti-phase motion between the upper and lower body [6]. Torque generated at the hip joint can stabilize superior body segments such as the head to optimize the sensitivity of sensory inputs to

vestibular and visual signals [9, 35]. In addition to the ankle and hip joint, multi-link postural control models can include a joint at the neck [30]. Neck afferent signals are involved in perceptual functions of self-motion [32] and reflex responses such as the cervico-spinal and cervico-ocular reflex, suggesting somatosensory cervical input converges with vestibular input to mediate multisensory control of orientation, gaze, and posture [2]. Head stabilization could therefore be achieved by applying joint torques at the hip, neck, or both.

While numerous studies have investigated postural stability during standing in people with mTBI [3, 10, 15, 17, 41], the control of head stability after mTBI remains unclear. Thus, we conducted an ancillary analysis of a larger study [11] to address two pertinent questions: 1) Do individuals with mTBI exhibit greater sway at the head compared with healthy controls when standing under various sensory conditions?, and 2) Does the relationship between sway at the lumbar spine level (approximate CoM), sternum, and head differ between those with mTBI and healthy controls as sensory conditions change? In accordance with previous reports of larger CoP and CoM sway after mTBI, we hypothesized that individuals with mTBI would sway more at the head compared with controls. We did not have a direction-specific *a priori* hypothesis for the second exploratory question, but we anticipated that segmental sway patterns in people with mTBI would differ from controls under more challenging sensory conditions. For example, if normalized to anthropometry, smaller sway at the head relative to the sternum would indicate more active neck control, and smaller sway at the sternum relative to the lumbar would indicate more active hip control.

MATERIALs and METHODS

Participants

Fifty-nine individuals with chronic (>3 months) balance complaints after a clinically diagnosed mTBI and 63 healthy controls (Table 1) were recruited as part of a larger study (ClinicalTrials.gov Identifier NCT02748109) in people with chronic mTBI (detailed elsewhere; see [11]). Briefly, participants were recruited through posters in athletic facilities, physical therapy clinics, hospitals, concussion clinics, community notice boards and cafes in and around the Portland, Oregon metropolitan area. Participants were included if they were: >3 months post-mTBI and reporting a nonzero symptom score on the Sport Concussion Assessment Tool 3 (SCAT3)[18] balance problems symptom, or had no history of brain injury in the past year for the control group; zero to minimal cognitive deficits as determined by the Short Blessed Test [23] (score ≤8); and were between the ages of 18 and 60 years. For the purposes of this study, mTBI was defined and classified using the criteria from the United States Department of Defense: no CT scan, or a normal CT scan if obtained; loss of consciousness not exceeding 30 min; alteration of consciousness/mental state up to 24 h; and post-traumatic amnesia not exceeding one day [43]. The mechanism of injury was not restricted. Exclusion criteria for both groups consisted of: musculoskeletal injury in the previous year that could have seriously impacted gait or balance; current moderate or severe substance abuse; any past peripheral vestibular or oculomotor pathology from before their reported mTBI; or refusal to abstain from medications that could impact their mobility for the duration of testing. Participants were asked to abstain from medications that could impact their mobility starting 24 hours prior to their first testing date. These medications included sedatives, benzodiazepines, narcotics pain

medications and alcohol. All recruitment procedures were approved by the Oregon Health & Science University and Veterans Affairs Portland Health Care System joint institutional review board and participants provided written informed consent prior to commencing the study.

Table 1

Procedures

Subjects completed demographic and symptom-related questionnaires (Neurobehavioral Symptom Inventory, NSI[5]) and an assessment of postural control for 60 seconds standing under four different sensory conditions: (1) firm ground with eyes open (EO-Firm), (2) firm ground with eyes closed (EC-Firm), (3) foam surface with eyes open (EO-Foam), (4) and foam surface with eyes closed (EC-Foam)[11, 12, 15, 40]. For all conditions, participants were instructed to stand with their feet together with their hands on their hips, and to hold that position for 60 seconds. The duration of 60 seconds was chosen to ensure a long enough period to capture reliable sway data after removing transient effects [38]. If the participant lost balance or deviated from the starting position (e.g., opening eyes during an eyes closed condition) before the completion of the 60 seconds, the trial was stopped. Trials that were stopped early were not repeated, and these trials were excluded from future analysis. Trials were always presented in the same order: EO-Firm, EC-Firm, EO-Foam, EC-Foam, and rest breaks were provided between each condition as needed.

Data Analysis

Data were collected at 128 Hz using wearable inertial sensors (Opal, APDM Inc.) affixed over the lumbar spine region (approximate CoM), sternum, forehead, and bilaterally on the dorsum of the feet using elastic straps. Each sensor provided tri-axial acceleration, angular velocity, and magnetometer data. For this ancillary analysis, only data from the head, sternum, and lumbar sensors were analyzed.

For each condition, the sensors' axes were rotated to align with the global coordinate system [29]. Acceleration data were low-pass filtered using a phaseless 4th order, 10 Hz low pass Butterworth filter. After filtering, the first and last 10 seconds of each trial were removed to reduce the influence of transient effects from the start of the trial, movement coincident with the end of the trial, or end distortion from filtering. The middle 40 seconds of each trial were retained for analysis. For each condition, the root mean square (RMS) of AP and ML accelerations were calculated for the head, sternum, and lumbar sensors. To examine the sway at the head relative to the sway at the lumbar, the ratio of head sway over lumbar sway was calculated in each direction for all trials. To account for the effect of pendulum length on linear accelerations, acceleration sway ratios were normalized based on the height of the sensor. For example, the head-to-lumbar sway ratio was multiplied by the ratio of the height of the lumbar sensor over the height of the head sensor,

$$SwayRatio_{Head2Lumbar} = \frac{RMS_{Head}}{RMS_{Lumbar}} \times \frac{h_{Lumbar}}{h_{Head}} \quad (1)$$

where h_{Head} *and* h_{Lumbar} *are* the height of the head and lumbar sensors, respectively and RMS is the RMS of acceleration at each segment. Similarly, the ratio of head-to-sternum and sternum-to-lumbar sway was also calculated to determine if the neck

played a significant role in attenuating acceleration between the lumbar and head. The height of each sensor was estimated based on the percentage of total height based on standard anthropometric data: h_{Head} = 0.96, $h_{Sternum}$ = 0.76, h_{Lumbar} = 0.59 [7]. Sway ratios equal to one indicate single-link sway about the ankle, sway ratios less than 1 indicate multi-link sway where the superior segment is stabilized relative to the inferior segment, and sway ratios greater than one indicate multi-link sway where the inferior segment is stabilized relative to the superior segment.

Statistical Analysis

To examine whether individuals with mTBI and healthy controls had similar rates of failure (e.g., loss of balance before 60 seconds), Chi-squared proportions tests compared the number of failed trials in each condition using a 0.05 significance level. To assess differences between groups across conditions, linear mixed models were fit for RMS sway at each body segment in each direction. Outcomes were first assessed for normality; all segments and directions exhibited skewed distributions for RMS sway and were therefore log-transformed. Each linear mixed model contained fixed effects of group, condition, the group×condition interaction, and random intercepts to account for the within-subject correlations. Condition was modeled as a categorical variable with EO-Firm serving as the reference condition. The control group served as the reference condition for group. Post-hoc pairwise comparisons were performed using independent sample t-tests to further investigate group×condition interactions for any sway ratio outcome. All significance values were corrected for multiple comparisons using a false discovery rate (FDR) correction [1] and a significance level of 0.05. All statistical analysis was performed in MATLAB (r2018a, The MathWorks Inc.).

RESULTS

Task Completion

No participants in the control group failed to complete the 60 seconds during any of the trials. Comparatively, mTBI subjects failed to complete a total of 23 trials (EO-firm: n = 2 (3%), p = 0.447, EC-firm: n = 8 (14%), p = 0.008, EO-foam: n = 3 (5%), p = 0.220, EC-foam: n = 10 (17%), p = 0.002). Compared with controls, more mTBI subjects failed during EC trials, but did not have significantly higher failure rates during EO trials.

Head Sway

Participants with mTBI swayed more at the head for all conditions and directions relative to controls (Tables 2,3). Relative to the baseline EO-Firm condition, RMS head sway increased in both AP and ML directions for every condition in control participants (main condition effects, Table 3). Compared with the between-condition changes in the control group, the mTBI group exhibited larger increases in head sway in both directions and all conditions except for EO-Foam in the ML direction (group×condition interactions, Table 3).

Table 2

Table 3

Sternum Sway

Participants with mTBI exhibited greater RMS sway at the sternum for all conditions in the ML direction only (Tables 2,4). Relative to the baseline EO-Firm condition, RMS sternum sway increased in both AP and ML directions for all other

conditions in control participants except for EC-Firm in the AP direction (condition effects, Table 4). Compared with the between-condition changes in the control group, the mTBI group had larger increases in AP sternum sway in all conditions and larger changes in ML sternum sway in the EC-Foam condition (group×condition interactions, Table 4).

Table 4

Lumbar Sway

Similar to sway at the head, participants with mTBI exhibited greater RMS sway at the lumbar for all conditions and directions (Tables 2,5). Relative to the baseline EO-Firm condition, RMS lumbar sway increased in both directions for all other conditions in control participants except for EC-Firm in the AP direction (condition effects, Table 5). Compared to the between-condition changes relative to the baseline EO-Firm condition in the control group, the mTBI group had larger increases in AP lumbar sway in EC-Firm and EC-Foam conditions (group×condition interactions, Table 5).

Table 5

Head to Lumbar Sway Ratio

In foam conditions, control participants decreased the ML head-to-lumbar sway ratio relative to the baseline EO-Firm condition (condition effects, Table 6, Figure 1F). Comparatively, the mTBI group exhibited little change in the ML head-to-lumbar sway ratio in foam conditions (EO-Foam, EC-Foam) relative to the EO-Firm condition (group×condition interactions, Table 6, Figure 1F). Post-hoc t-tests revealed the mTBI group had significantly greater sway ratios than the control group during foam

conditions (*adjusted p* < 0.001). No effects of group, condition, or interactions were detected for the head-to-lumbar sway ratio in the AP direction.

Table 6

Head to Sternum Sway Ratio

The head-to-sternum sway ratio did not differ by group or condition in the AP direction. In the ML direction, the head-to-sternum sway ratio decreased in the EC-Foam condition only (condition effects, Table 7); no other group, condition, or group×condition effects were found.

Table 7

Sternum to Lumbar Sway Ratio

In foam conditions, control participants decreased the ML sternum-to-lumbar sway ratio relative to the baseline EO-Firm condition (condition effects, Table 8). Comparatively, the mTBI group exhibited increased ML sternum-to-lumbar sway ratio in foam conditions (EO-Foam, EC-Foam) (group×condition interactions, Table 8). Post-hoc t-tests revealed the mTBI group had significantly greater sway ratios than the control group during foam conditions (*adjusted p* < 0.001). No effects of group, condition, or interactions were found for the sternum-to-lumbar sway ratio in the AP direction.

Table 8

Figure 1

DISCUSSION

Our primary objective was to compare postural sway at the head between individuals with mTBI and healthy control subjects under varying sensory conditions. Additionally, we sought to examine the relationship between stabilization of the head and stabilization of inferior locations (sternum and lumbar) to understand potential postural control strategies. We found individuals with mTBI swayed more at the head, sternum, and lumbar spine, extending previous results indicating postural sway of the CoM or CoP is greater in people with mTBI [15, 17, 24]. Between-group differences in RMS sway, however, were greatest at the head location. Additionally, the largest between-group differences were observed in the ML direction, agreeing with previous studies suggesting the importance of ML sway in differentiating acute, symptomatic mTBI from healthy controls [24].

We found healthy control subjects tended to stabilize the head when standing on foam, while individuals with mTBI did not exhibit the same degree of head stabilization. Fujisawa et al. [13] represented body mechanics as a double inverted pendulum that allowed joint rotations at the ankles and hip while assuming a rigid head-on-trunk coupling and showed that balance control shifted toward greater use of hip joint torques compared to ankle joint torques when the surface was narrowed. With double pendulum body mechanics, proprioceptors at the ankle determines the ankle angle, proprioceptors at the hip determines the hip angle, and the visual and vestibular sensors determine the angle of the head and trunk relative to vertical. The head stabilization demonstrated by controls may have been a strategy that places greater reliance on hip proprioceptors and visual/vestibular information at the head to estimate body position due to compromised ankle proprioceptive cues during stance on foam.

That the mTBI group did not demonstrate this same adaptation speculatively suggests an inflexible postural control system that was unable or unwilling to shift towards a head-stabilization strategy. This interpretation agrees with studies using entropic measures of sway; individuals with mTBI, at various times since injury, have greater regularity and less complexity in their postural sway that are typically indicative of inflexible postural control [3, 4, 10, 37, 41].

Our results also suggest the head stabilization exhibited by control subjects during foam conditions was achieved primarily through torque at the hip, rather than the neck. While ankle and hip strategies are traditionally defined in the sagittal plane [21], similar control mechanisms exist in the frontal plane [44] - we only detected this head stabilization and increased hip strategy during foam conditions in the ML direction. The ML sternum-to-lumbar sway ratio was less than one for all conditions in healthy controls, with lower sway ratios in foam conditions (see Fig 1E). These results are consistent with the idea that a continuum exists between ankle and hip strategies [6]; here, healthy subjects increased their expression of a ML hip strategy when the ankle strategy was compromised by the foam surface. Conversely, the ML head-to-sternum ratios were greater than or equal to one for all conditions, indicating a lack of active neck torque in both healthy control and mTBI groups (see Fig 1D). These results suggest that the stiffness of the neck joint increased in the EC-Foam trial, but no active stabilization was observed at the neck. Pozzo et al. noted head stabilization in the frontal plane during complex balance tasks tended to occur at the neck, but small oscillations were compensated with a rigid head-trunk unit with minimal actuation at the neck [35]. Our results suggesting both groups increased the head-to-trunk coupling during

EC-Foam conditions are consistent with the small oscillation condition reported by Pozzo et al. [35]. It is possible that complex balance tasks with larger frontal plane angular displacements than those examined here may elicit compensation utilizing head-on-trunk stabilization that reveals differences between individuals with mTBI and healthy controls. Nevertheless, the lack of a between-group difference in the head-to-sternum sway ratio suggests that neck problems in mTBI subjects, such as neck pain or whiplash, did not influence our results.

Several limitations should be acknowledged and considered. First, participants were tested with their shoes on. Traditionally, postural sway would be assessed barefoot to remove any confounding factor of footwear. However, out of concern for safety and other aspects of the larger study, balance assessments were performed with shoes. Therefore, some heterogeneity in our data may stem from differences in footwear. Second, our interpretations rely on a single summary metric (RMS sway) that does not capture temporal correlations. The quiet standing protocol lacks a driving stimulus, and because the placement of the sensors were superior to the hip, we were unable to directly assess the cross-covariance of upper and lower body motion. Future studies should further examine the expression of ankle and hip strategies in mTBI by directly assessing upper and lower body motion and quantifying the phase angle. Finally, we excluded trials in which individuals lost balance before the end of the trial, removing 17% of our mTBI subjects from the EC-Foam condition and potentially leading to a bias in our sample. However, excluding incomplete trials was a conservative approach. A loss of balance creates extremely large RMS values. Since these trials only occurred in our mTBI groups, removing these trials with a loss of balance likely led to

smaller sway in the mTBI group and may have biased our results toward smaller between-group effects. Our results should therefore be interpreted as the conservative estimate of the difference in head stability between mTBI and controls.

CONCLUSIONS

Using inertial sensors on the head, sternum, and lumbar, we found that people with persisting balance complaints following mTBI exhibited greater sway at each location compared with healthy control subjects. Further, control subjects reduced the sway at the head relative to sway at the lumbar when on foam, while those with mTBI did not change postural control strategies. The attenuation of sway predominantly occurred over the trunk segment, suggestive of a shift towards increasing expression of a hip strategy. Speculatively, these results suggest healthy control subjects are more capable, or more willing, to shift control into head-centric postural control using hip torque, while people with persisting symptoms after mTBI may continue to use the same strategy regardless of sensory information.

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Table 1. Demographic information for each group of participants. Data are presented as mean (SD) unless otherwise noted.

	mTBI	Control
N	59	63
Age (yrs)	39.3 (10.9)	37.7 (12.8)
Gender (F / M)	41/18	38/25
Height (cm)	170.8 (9.4)	171.5 (9.5)
Mass (kg)	79.8 (19.7)	75.2 (19.0)
NSI Symptom Score*	37.0 (23.0)	3.0 (5.0)
One or more lifetime mTBI (n)	59	5
Time Since Most Recent mTBI (yrs)*	1.12 (1.95)	13.28 (11.10)

* Shown as median (interquartile range)
NSI: Neurobehavioral Symptom Inventory

Table 2. Descriptive statistics of median and inter-quartile range (IQR) for RMS sway at the head, trunk, and lumbar spine in mTBI and control groups.

Location	**Head**				**Trunk**				**Lumbar**			
Group	mTBI		Control		mTBI		Control		mTBI		Control	
Statistic	*Median*	*IQR*	*Median*	*IQR*	*Median*	*IQR*	*Median*	*IQR*	*Median*	*IQR*	*Median*	*IQR*
A/P direction												
EO-Firm	0.18	0.12	0.12	0.08	0.13	0.06	0.11	0.06	0.11	0.05	0.08	0.05
EC-Firm	0.24	0.22	0.14	0.08	0.15	0.12	0.11	0.04	0.13	0.10	0.09	0.05
EO-Foam	0.24	0.17	0.15	0.07	0.16	0.10	0.13	0.06	0.14	0.08	0.11	0.03
EC-Foam	0.40	0.23	0.22	0.12	0.27	0.23	0.17	0.07	0.22	0.16	0.13	0.06
M/L direction												
EO-Firm	0.12	0.08	0.08	0.03	0.08	0.06	0.05	0.02	0.06	0.04	0.05	0.02
EC-Firm	0.15	0.13	0.08	0.03	0.09	0.10	0.06	0.02	0.08	0.06	0.05	0.02
EO-Foam	0.18	0.19	0.12	0.05	0.14	0.12	0.09	0.04	0.12	0.08	0.10	0.03
EC-Foam	0.32	0.22	0.17	0.05	0.25	0.21	0.14	0.05	0.20	0.12	0.15	0.06

Note: All values given in units of m/s^2

Table 3. Mixed effect regression model fit and parameters for head acceleration

Fixed-Effects	*β*	*SE*	*t*	*p*	*Adjusted p*
AP direction					
Intercept	-2.07	0.06	-34.32	**< 0.001**	**< 0.001**
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	0.15	0.06	2.62	**0.008**	**0.019**
Condition: EO-Foam	0.17	0.06	3.04	**0.003**	**0.006**
Condition: EC-Foam	0.59	0.06	10.62	**< 0.001**	**< 0.001**
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	0.29	0.09	3.43	**< 0.001**	**0.002**
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	0.25	0.08	2.96	**0.003**	**0.008**
Condition: EO-Foam × Group	0.21	0.08	2.61	**0.009**	**0.019**
Condition: EC-Foam × Group	0.27	0.08	3.20	**0.001**	**0.004**
ML direction					
Intercept	-2.55	0.05	-48.37	**< 0.001**	**< 0.001**
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	0.08	0.04	2.25	**0.025**	**0.048**
Condition: EO-Foam	0.44	0.04	10.10	**< 0.001**	**< 0.001**
Condition: EC-Foam	0.81	0.04	18.57	**< 0.001**	**< 0.001**
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	0.43	0.08	5.61	**< 0.001**	**< 0.001**
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	0.17	0.06	2.68	**0.007**	**0.016**
Condition: EO-Foam × Group	0.09	0.06	1.36	0.174	0.259
Condition: EC-Foam × Group	0.16	0.07	2.50	**0.012**	**0.025**

Note: Degrees of freedom = 456 for all effects. Significance denoted by bolded *p*-value. Parameter estimates: slope estimate (*β*), standard error (*SE*), t-value (*t*), and *p*-value (*p*).

Table 4. Mixed effect regression model fit and parameters for sternum accelerations

Fixed-Effects	*β*	*SE*	*t*	*p*	*Adjusted p*
A/P direction					
Intercept	-2.26	0.06	-38.37	**< 0.001**	**< 0.001**
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	0.09	0.06	1.56	0.119	0.191
Condition: EO-Foam	0.19	0.06	3.34	**< 0.001**	**0.003**
Condition: EC-Foam	0.53	0.06	9.48	**< 0.001**	**< 0.001**
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	0.19	0.09	2.21	0.028	0.051
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	0.19	0.08	2.31	**0.021**	**0.041**
Condition: EO-Foam × Group	0.18	0.08	2.23	**0.026**	**0.049**
Condition: EC-Foam × Group	0.30	0.08	3.61	**< 0.001**	**0.001**
M/L direction					
Intercept	-2.99	0.06	-49.35	**< 0.001**	**< 0.001**
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	0.18	0.05	3.31	**0.001**	**0.003**
Condition: EO-Foam	0.54	0.05	10.13	**< 0.001**	**< 0.001**
Condition: EC-Foam	1.02	0.05	19.00	**< 0.001**	**< 0.001**
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	0.48	0.09	5.49	**< 0.001**	**< 0.001**
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	0.13	0.08	1.57	0.117	0.189
Condition: EO-Foam × Group	0.12	0.08	1.53	0.126	0.199
Condition: EC-Foam × Group	0.19	0.08	2.40	**0.016**	**0.033**

Note: Degrees of freedom = 456 for all effects. Significance denoted by bolded *p*-value. Parameter estimates: slope estimate (*β*), standard error (*SE*), t-value (*t*), and *p*-value (*p*).

Table 5. Mixed effect regression model fit and parameters for lumbar accelerations

Fixed-Effects	*β*	*SE*	*t*	*p*	*Adjusted p*
A/P direction					
Intercept	-2.49	0.05	-48.35	**< 0.001**	**< 0.001**
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	0.04	0.05	0.87	0.385	0.463
Condition: EO-Foam	0.26	0.05	4.96	**< 0.001**	**< 0.001**
Condition: EC-Foam	0.54	0.05	10.41	**< 0.001**	**< 0.001**
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	0.25	0.07	3.40	**< 0.001**	**0.002**
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	0.25	0.08	3.23	**0.001**	**0.004**
Condition: EO-Foam × Group	0.11	0.08	1.41	0.159	0.244
Condition: EC-Foam × Group	0.21	0.08	2.64	**0.008**	**0.018**
M/L direction					
Intercept	-3.04	0.05	-62.85	**< 0.001**	**< 0.001**
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	0.14	0.04	3.31	**< 0.001**	**0.003**
Condition: EO-Foam	0.67	0.04	15.47	**< 0.001**	**< 0.001**
Condition: EC-Foam	1.15	0.04	26.41	**< 0.001**	**< 0.001**
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	0.38	0.07	5.45	**< 0.001**	**< 0.001**
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	0.08	0.06	1.23	0.218	0.302
Condition: EO-Foam × Group	-0.09	0.06	-1.47	0.141	0.220
Condition: EC-Foam × Group	-0.03	0.07	-0.40	0.687	0.722

Note: Degrees of freedom = 456 for all effects. Significance denoted by bolded *p*-value. Parameter estimates: slope estimate (*β*), standard error (*SE*), t-value (*t*), and *p*-value (*p*).

Table 6. Mixed effect regression model fit and parameters for head to lumbar sway ratio

Fixed-Effects	*β*	*SE*	*t*	*p*	*Adjusted p*
A/P direction					
Intercept	-0.07	0.05	-1.25	0.213	0.299
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	0.10	0.06	1.65	0.100	0.168
Condition: EO-Foam	-0.09	0.06	-1.38	0.167	0.253
Condition: EC-Foam	0.05	0.06	0.94	0.350	0.434
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	0.05	0.08	0.60	0.547	0.617
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	-0.01	0.09	-0.06	0.949	0.949
Condition: EO-Foam × Group	0.10	0.09	1.14	0.254	0.339
Condition: EC-Foam × Group	0.05	0.09	0.59	0.555	0.615
M/L direction					
Intercept	0.01	0.04	-0.13	0.893	0.911
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	-0.05	0.04	-1.16	0.248	0.336
Condition: EO-Foam	-0.23	0.04	-5.82	**< 0.001**	**< 0.001**
Condition: EC-Foam	-0.34	0.04	-8.47	**< 0.001**	**< 0.001**
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	0.05	0.06	0.83	0.406	0.475
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	0.09	0.06	1.61	0.108	0.179
Condition: EO-Foam × Group	0.18	0.06	3.09	**0.002**	**0.005**
Condition: EC-Foam × Group	0.19	0.06	3.19	**0.002**	**0.004**

Note: Degrees of freedom = 456 for all effects. Significance denoted by bolded *p*-value. Parameter estimates: slope estimate (*β*), standard error (*SE*), t-value (*t*), and *p*-value (*p*)

Table 7. Mixed effect regression model fit and parameters for head to sternum sway ratio

Fixed-Effects	*β*	*SE*	*t*	*p*	*Adjusted p*
A/P Direction					
Intercept	-0.04	0.05	-0.69	0.330	0.414
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	0.06	0.05	1.11	0.268	0.354
Condition: EO-Foam	-0.01	0.05	-0.32	0.752	0.775
Condition: EC-Foam	0.06	0.05	1.18	0.237	0.325
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	0.11	0.07	1.74	0.083	0.144
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	0.05	0.08	0.63	0.528	0.597
Condition: EO-Foam × Group	0.03	0.08	0.34	0.732	0.761
Condition: EC-Foam × Group	-0.04	0.08	-0.53	0.598	0.648
M/L Direction					
Intercept	0.21	0.03	6.70	**< 0.001**	**< 0.001**
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	-0.08	0.03	-2.01	0.045	0.081
Condition: EO-Foam	-0.10	0.04	-2.61	0.009	0.019
Condition: EC-Foam	-0.21	0.04	-5.29	**< 0.001**	**< 0.001**
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	-0.05	0.05	-1.08	0.283	0.368
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	0.05	0.06	0.87	0.387	0.463
Condition: EO-Foam × Group	-0.03	0.06	-0.56	0.578	0.633
Condition: EC-Foam × Group	-0.03	0.06	-0.45	0.656	0.696

Note: Degrees of freedom = 456 for all effects. Significance denoted by bolded *p*-value. Parameter estimates: slope estimate (*β*), standard error (*SE*), t-value (*t*), and *p*-value (*p*)

Table 8. Mixed effect regression model fit and parameters for sternum to lumbar sway ratio

Fixed-Effects	*β*	*SE*	*t*	*p*	*Adjusted p*
A/P Direction					
Intercept	-0.02	0.04	-0.80	0.422	0.653
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	0.04	0.05	0.83	0.404	0.475
Condition: EO-Foam	-0.07	0.05	-1.35	0.179	0.262
Condition: EC-Foam	-0.01	0.05	-0.11	0.912	0.921
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	-0.07	0.06	-1.03	0.305	0.392
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	-0.05	0.08	-0.75	0.454	0.519
Condition: EO-Foam × Group	0.07	0.07	1.01	0.310	0.394
Condition: EC-Foam × Group	0.10	0.08	1.26	0.209	0.298
M/L Direction					
Intercept	-0.20	0.04	-6.17	**< 0.001**	**< 0.001**
Condition: EO-Firm	**reference**	--	--	**--**	**--**
Condition: EC-Firm	0.03	0.04	0.89	0.378	0.461
Condition: EO-Foam	-0.13	0.04	-3.30	**0.001**	**0.003**
Condition: EC-Foam	-0.13	0.04	-3.26	**0.001**	**0.003**
Group: Control	**reference**	--	--	**--**	**--**
Group: mTBI	0.10	0.05	1.95	0.051	0.092
Condition: EO-Firm × Group	**reference**	--	--	**--**	**--**
Condition: EC-Firm × Group	0.04	0.06	0.82	0.414	0.479
Condition: EO-Foam × Group	0.21	0.06	3.80	**< 0.001**	**< 0.001**
Condition: EC-Foam × Group	0.22	0.06	3.83	**< 0.001**	**< 0.001**

Note: Degrees of freedom = 456 for all effects. Significance denoted by bolded *p*-value. Parameter estimates: slope estimate (*β*), standard error (*SE*), t-value (*t*), and *p*-value (*p*)

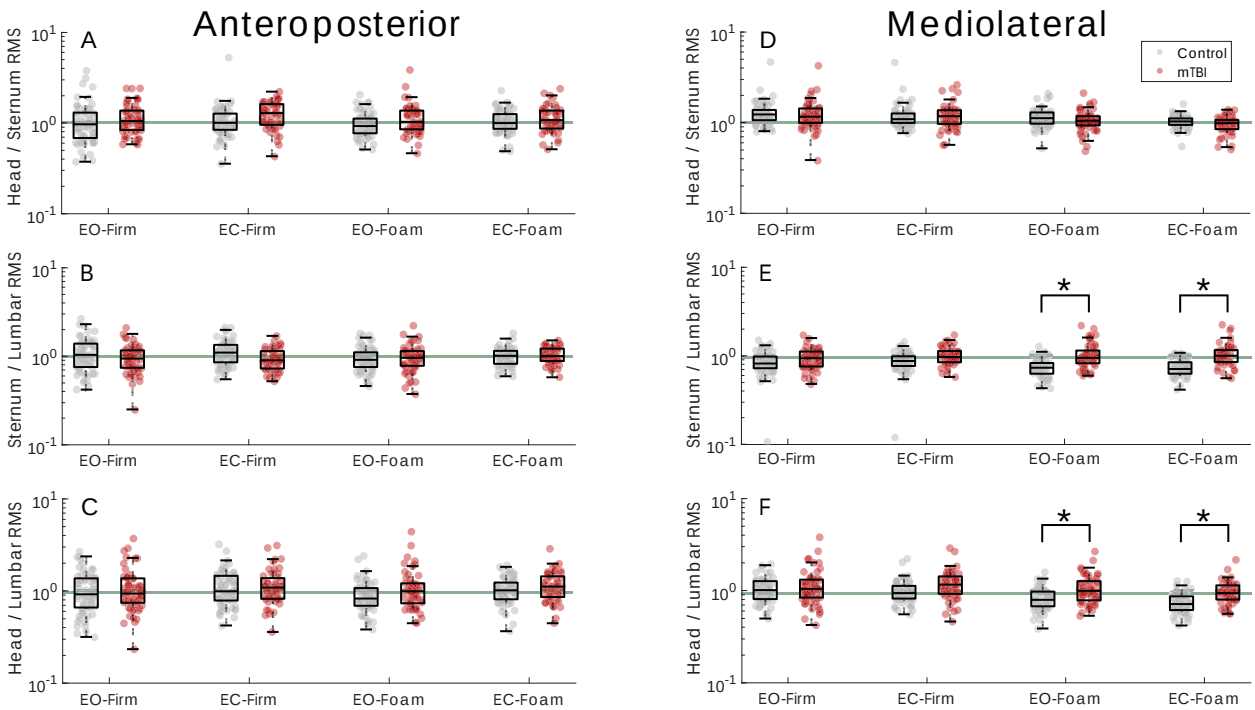

Figure 1. Sway ratios for each direction and condition. A-C) Sway ratios for the head-to-sternum, sternum-to-lumbar, and head-to-lumbar sway ratios in the anteroposterior direction. D-F) Sway ratios for the head-to-sternum, sternum-to-lumbar, and head-to-lumbar sway ratios in the mediolateral direction. Across all figures, the horizontal green line indicates a sway ratio equal to one. In E and F, * indicates significant between-group differences based on post-hoc pairwise t-tests.