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ORIGINAL ARTICLE

CLINICAL STUDIES

History of Mild Traumatic Brain Injury Affects Static Balance under Complex Multisensory Manipulations

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Abstract

A recent study in active-duty military in the Coast Guard suggested that lifetime experience with mild traumatic brain injury (mTBI) was associated with subtle deficits in postural control when exposed to multisensory discordance (i.e., rotating visual stimulation). The present study extended postural assessments to veterans recruited from the community. Service veterans completed the Defense Veteran Brain Injury Center TBI Screening Tool, Post-Traumatic Stress Disorder (PTSD) Checklist (PCL-5), and Neurobehavioral Symptom Inventory (NSI). Postural control was assessed using a custom-designed, virtual-reality–based device, which assessed center of pressure sway in response to six conditions designed to test sensory integration by systematically combining three visual conditions (eyes open, eyes closed, and rotating scene) with two somatosensory conditions (firm or foam surface). Veterans screening positive for lifetime experience of mTBI ($mTBI^+$) displayed similar postural sway to veterans without a lifetime experience of mTBI ($mTBI^-$) on basic assessment of eyes open or closed on a firm and foam surface. $mTBI^+$ veterans displayed greater sway than $mTBI^-$ veterans in response to rotating visual stimuli while on a foam surface. Similar to previous research, degree of sway was affected by the number of lifetime experiences of mTBI. Increased postural sway was not related to PTSD, NSI, or balance-specific symptom expression. In summary, veterans who experienced mTBI over their lifetime exhibited dysfunction in balance control as revealed by challenging conditions with multi-sensory discordance. These balance-related signs were independent of self-reported balance-related symptoms or other symptom domains measured by the NSI, which can provide a method for exposing otherwise covert dysfunction long after the experience of mTBI.

Keywords: balance; MDD; mTBI; posturography; PTSD; virtual reality

Introduction

Occupational hazards of active-duty service carry an increased risk of sustaining mild traumatic brain injury (mTBI), which compounds that of civilian risk before, during, and after service.[1,2] An understanding of the degree that sustaining mTBI negatively impacts health has long been dominated by self-reported symptoms,[3] leading to a seeming dichotomy between those expressing symptoms long after mTBI experience—otherwise known as persistent post-concussive symptoms (PPCS)—and those not expressing symptoms to an appreciable degree.[3,4] Reporting biases for each category reflect an understanding that motivational factors influence symptom reporting.[5] Thus, there are considerable efforts to

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provide objective markers of injury and recovery. With lifetime mTBI associated with an increased likelihood for motor disturbances such as Parkinsonian movements, and increased risk of falls,[6,7] detection of even subtle dysfunction affords an opportunity to intervene.

One such functional assessment is standing bipedal posture. Inherently unstable, standing balance control requires integrating visual, vestibular, and proprioceptive sensory inputs to counteract destabilizing forces.[8] Standing balance control has been extensively studied in mTBI.[9–14] Early studies concentrated on using objective measures of sway, such as center of pressure (COP), to verify subjective feelings of instability in the aftermath of mTBI[15,16] and demonstrating the value of objective measures of static balance in tracking injury trajectories.[9–12,17] For those registering difficulties in balance in the aftermath of mTBI, dysfunction in sensory integration can be apparent as an increase in sway during reduced visual confirmation (eyes closed) and with reduced somatosensory information (compliant surface).[13] Acute disturbances in balance control are more prominent with a combination of reduced visual and somatosensory input,[14] but other studies have noted residual dysfunction.

In veterans who report a lifetime of mTBI, even those whose symptoms of imbalance have long since abated still may exhibit signs of greater COP sway upon visual and somatosensory challenges.[18–20] For veterans with a history of mTBI, but without symptoms of balance dysfunction, two possibilities exist: 1) balance dysfunction completely resolved over time, or 2) balance dysfunction is otherwise covert given the sensitivity of standard assessments of postural control.

Sensitivity to balance dysfunction in mTBI may be enhanced through perturbations that increase sway, for example, through visual exposure to dynamically rotating visual motion.[21] Viewing a rotating scene induces increased sway, especially when standing on a foam surface, and can be used as a significant classifier of those with or without mTBI.[22–24] Using this model to test asymptomatic Coast Guard personnel who experienced more than one mTBI over their lifetime, COP sway area was greater than for those who never experienced mTBI.[24] Because post-traumatic stress disorder (PTSD) is often comorbid with mTBI in military populations, and they both have some overlapping symptoms that may affect postural control (e.g., dizziness and loss of balance),[18,19] it is important to consider the potential mediation of PTSD in balance control. In the Coast Guard study, there were too few suspected cases of PTSD to evaluate this.

The present study sought to assess balance control in veterans accounting for lifetime mTBI and current expression of PTSD symptoms. More generally, this study aimed to enhance our understanding of the relationship between symptom endorsement and detections of signs related to balance dysfunction. Based on previous work in active-duty military, we expected veterans with lifetime mTBI to exhibit increased sway during dynamic visual stimulation on a foam surface. We did not expect balance to be appreciably affected by expression of PTSD symptoms or major depressive disorder (MDD). Reminiscent of preliminary findings in active-duty military, we expected that balance control dysfunction would not be related to either the expression of PPCS or specifically balance-related symptoms.[24]

Methods

Participants and recruitment

Study volunteers included 51 military service veterans (18–65 years of age) at the Syracuse VA Medical Center (SVAMC; Syracuse, NY). Exclusionary criteria included history of hearing impairment and current experience of symptoms related to schizophrenia and/or bipolar mood disorder. Participants were recruited using printed advertisements posted within the SVAMC and associated community clinics. All eligible participants completed an informed consent agreement and were compensated $50 for completing the study session. The study was conducted under an approved SVAMC Institutional Review Board protocol.

Self-report measures

All participants completed a battery of self-report measures which included combat history, measures of current post-traumatic stress symptoms, current depressive symptoms, and concussion history.

Post-traumatic stress symptoms.

The PTSD Checklist for Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5; PCL-5)[25] is a 20-item survey corresponding to the current DSM-5 criteria for the diagnosis of PTSD. Respondents report the degree to which they have been bothered by post-traumatic symptoms over the past month using a 5-point Likert scale, with responses ranging from 0 = ''Not at all'' to 4 = ''Extremely.'' Determination of a provisional PTSD diagnosis was based on the recommended cutoff of 33 for the total symptom severity score corresponding to the sum of scores for each of the 20 items (range, 0–80).[25]

Depressive symptoms.

The Patient Health Questionnaire-8 (PHQ-8)[26] was used to assess how often depressive symptoms were bothersome over the past 2-week period. Occurrence was rated on a 4-point Likert scale that included responses ''Not at All,'' ''Several Days,'' ''More Than Half the Days,'' and ''Nearly Every Day.'' Screening for caseness followed aggregate scoring, which classifies MDD symptomology as: None

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(0–4), Mild (5–9), Moderate (10–14), Moderately Severe (15–20), and Severe (>20), with a score of ≥10 being indicative of clinically significant MDD.

Concussion history. The Defense Veteran Brain Injury Center TBI Screening Tool[3,27] was used to assess present/lifetime mTBI status to determine if, when, and what type of a head injury was experienced and the degree to which current symptoms are attributable to TBI. No veteran in the current study had current symptoms. A positive screen, which is defined as the confirmation of a head injury accompanied by an altered mental state, does not represent a formal diagnosis of mTBI, but does indicate further evaluation for mTBI or concussion.

Persistent post-concussive symptoms. The Neurobehavioral Symptom Inventory (NSI) compiles common, but not specific, symptoms reported by persons experiencing mTBI 3 months after injury.[4] The NSI contains 22 items, which are rated on a 5-point Likert scale (0 = None—Rarely if ever present; not a problem at all; 1 = Mild—Occasionally present, but it does not disrupt my activities; 2 = Moderate—Often present, occasionally disrupts my activities; 3 = Severe—Frequently present and disrupts activities; and 4 = Very Severe—Almost always present and I have been unable to perform at work, school or home due to this). Participants are instructed to rate the presence and intensity of the symptom within the past 2 weeks. Factor analysis of the NSI suggests discrete symptom clusters,[4,5,28–31] with common agreement on cognitive and affective clusters of symptoms. There is also common agreement that PTSD and MDD explain significant variance in NSI reporting.[28,29] Symptom over-reporting in some situations is a concern and some have suggested that excessive symptom reporting may be identified through aggregation of 10 NSI items,[5,30,32] with a score >33 on those items suggesting over-reporting.[33] No veteran in the current study exceeded those criteria.

Posturography

Virtual environment TBI screening. The Virtual Environment TBI Screening (VETS) device is a low-cost, portable postural assessment that uses custom-designed software and commercially available technology (i.e., a Wii Balance Board [WBB], 60-inch [75 cm high × 134 cm wide] television, Bluetooth USB, and desktop computer). The system and protocol have been validated as reliable for postural assessment in healthy and injured populations, and its form and function can be found described in detail in recent articles.[22,23] The test involves a progression of six conditions in a set order during which participants were instructed to look straight ahead and maintain an upright stance as stably as possible: 1) EO-Firm—eyes open with stable support surface (i.e., WBB) and static visual scene; 2) EC-Firm—eyes closed with stable support surface and dark screen; 3) DYN-Firm—eyes open with a stable support surface while viewing a scene rotating dynamically in the roll (frontoparallel) plane at 60 deg/sec; 4) EO-Foam—eyes open with unstable support (Airex foam pad placed on top of the WBB) and stable visual scene; 5) EC-Foam—eyes closed with unstable support and dark screen; and 6) DYN-Foam—eyes open with unstable support and rotating scene.

Each condition lasted 30 sec and was repeated three times before progressing to the next condition.

Statistical analysis

All statistical analyses were conducted using SPSS software (SPSS Version 22.0; IBM Corporation, Armonk, NY), with criteria for statistical significance set at $p < 0.05$. Bonferroni corrections to the alpha-level were applied as appropriate. For repeated-measures analyses, violations of sphericity were checked by Mauchly's test, and Greenhouse-Geisser corrections were applied in cases where significant violations occurred. For all analyses, the primary group comparisons were lifetime mTBI ($mTBI^+$ or $mTBI^-$).

COP sway area (cm^2) for each trial was the dependent variable measured by the VETS device and an mTBI × Surface Condition × Visual condition (2 × 2 × 3) mixed-model analysis of covariance (ANCOVA), with age and PCL-5 score entered as covariates. In addition, influence of the number of mTBI experiences was evaluated, with coding of no mTBI ($mTBI^-$), a single mTBI ($mTBI^1$) experience, and more than a single mTBI ($mTBI^{1+}$) experience, consistent with earlier work.[24] Symptom expression was analyzed with multi-variate analysis of variance, with mTBI as a grouping factor and PCL-5 and PHQ-8 entered as covariates. To establish correlations and predictive power among dependent variables, Pearson's product-moment correlations and linear regression models were used to determine relationships.

Results

Participant characteristics

Table 1 presents the demographic characteristics of the sample. Of the 51 veteran participants, 31 (61%) reported previous mTBI, with 20 reporting one or more incidents. No mTBI events were acute (<2 weeks), and all but one was >1 month ago, with most being ≥1 years ago (time post-injury analysis was not considered during data collection). Cohorts ($mTBI^+$ vs. $mTBI^-$) were similar in age, years of education, sex distribution, combat experience, and symptom scores from the PCL-5 and PHQ-8 (see Table 1).

Neurobehavioral symptom inventory

Affective symptoms were expressed to a *lesser* degree by $mTBI^+$ compared to $mTBI^-$ veterans ($F_{(1,39)} = 5.3$,

Table 1. Demographic Characteristics of the Study Sample

	mTBI⁻	*mTBI⁺*
N (females)	20 (4)	31 (7)
Age, years	48.8 ± 2.3	48.9 ± 2.0
CES		
Light	11	13
Light/moderate	5	7
Moderate	1	7
Moderate/heavy	3	1
Heavy	0	2
MDD		
None	3	11
Mild	7	7
Moderate	3	10
Moderately severe	4	1
Severe	3	1
PTSD		
PTSD⁻	8	19
PTSD⁺	12	12
NSI		
Affective	3.4 ± 0.5	2.1 ± 0.3[a]
Cognitive	1.5 ± 0.4	1.6 ± 0.3
Sensory/somatic	2.0 ± 0.5	2.2 ± 0.3
Balance	0.5 ± 0.2	0.5 ± 0.2

[a]Significant difference between groups.

CES, combat exposure scale; mTBI(+/–), history/no history of mild traumatic brain injury; MDD, major depression disorder; NSI, Neurobehavioral Symptom Inventory; PTSD, post-traumatic stress disorder.

$p = 0.03$; see Table 1). Expression of symptoms across all clusters was directly related to PCL-5 scores: cognitive ($F_{(1,\ 39)} = 22.9$, $p < 0.05$); balance ($F_{(1,\ 39)} = 4.4$, $p < 0.05$); affective ($F_{(1,\ 39)} = 12.9$, $p < 0.05$); and sensory/somatic ($F_{(1,\ 39)} = 9.4$, $p < 0.05$) clusters. The analysis of proportion of endorsed symptoms eliciting concern mirrored aggregated scoring. Pearson's correlations between NSI and VETS balance conditions ranged from $r = -0.15$ ($p = 0.18$) to $r = 0.16$ ($p = 0.17$). A linear regression with all six VETS conditions included in the NSI prediction model was not significant ($R^2 = 0.13$, $F_{(6,32)} = 0.794$, $p = 0.58$).

Virtual environment TBI screening

A mixed-model ANCOVA ($2 \times 2 \times 3$), with mTBI as a grouping factor and age and PCL-5 scores entered as covariates, showed a significant main effect between groups (mTBI⁺ vs. mTBI⁻; $F_{(1,\ 47)} = 4.27$, $p = 0.044$). A significant interaction for mTBI × Surface Condition was observed ($F_{(1,\ 47)} = 4.49$, $p = 0.039$), as well as non-significant interaction trends for the mTBI × Visual Condition ($F_{(1.1,\ 50.9)} = 3.32$, $p = 0.071$) and mTBI × Surface × Visual Condition ($F_{(1.1,\ 50.8)} = 2.79$, $p = 0.098$; see Fig. 1).

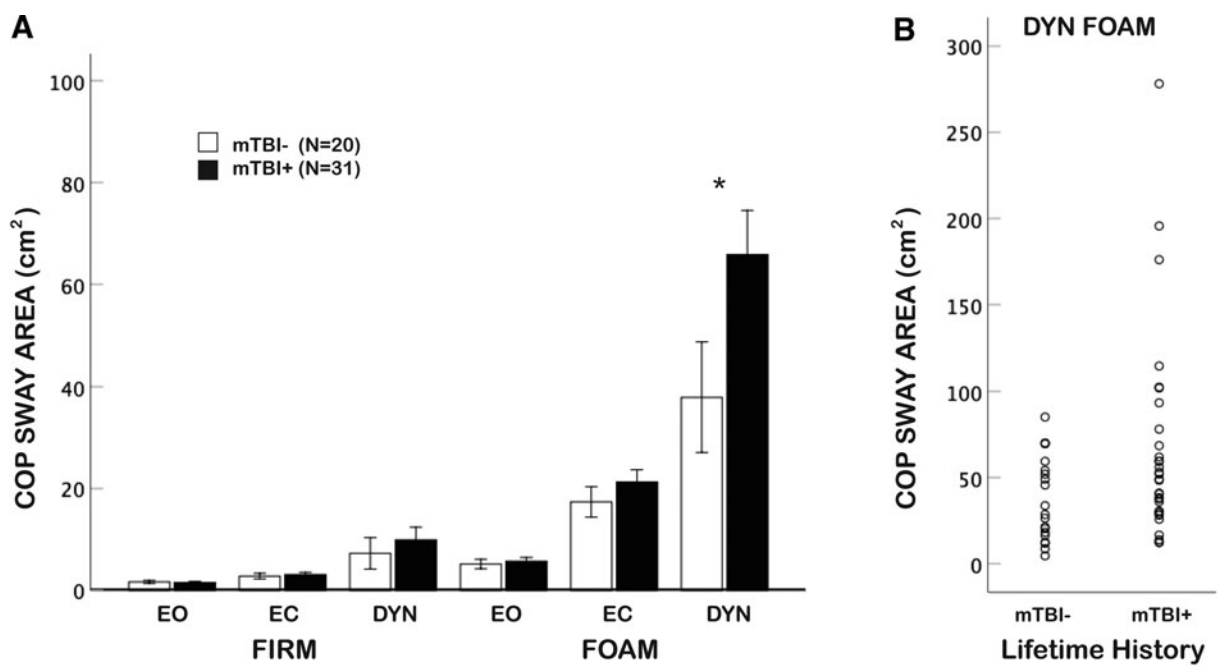

Fig. 1. (**A**) Effect of mTBI on COP sway area across postural tasks. A significant main effect between groups (history of mTBI vs. no history of mTBI) was found ($p = .044$). A significant interaction effect for the mTBI × Surface Condition was found, attributable to the DYN condition on an unstable foam surface. Neither of the covariates, age nor post-traumatic stress disorder, were significant. (**B**) Scatterplot for both mTBI groups in the DYN Foam condition, which is the source of the largest between-group mTBI difference. Error bars: ±1 SE. COP, center of pressure; EO, eyes open condition; EC, eyes closed condition; DYN, dynamically rotating visual scene condition; mTBI, mild traumatic brain injury; SE, standard error.

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Post hoc comparisons indicated that the COP sway area of $mTBI^+$ was greater than $mTBI^-$ during DYN-Foam ($p < 0.05$). Neither age nor PTSD were significant (ps > 0.10).

A secondary analysis compared $mTBI^-$ veterans to those reporting a single mTBI ($mTBI^1$, $N = 11$) and those with multiple mTBIs ($mTBI^{1+}$, $N = 20$). The $3 \times 2 \times 3$ (mTBI × Surface × Visual) mixed-model ANCOVA yielded a main effect of mTBI ($F_{(2, 45)} = 4.72$, $p = 0.014$), with the mTBI group difference attributed to $mTBI^{1+}$. A significant mTBI × Surface interaction ($F_{(2, 46)} = 3.53$, $p = 0.038$) and a non-significant trend for an mTBI × Visual interaction ($F_{(2.4, 49.8)} = 2.65$, $p = 0.070$) were found. Age was found to be a significant covariate ($F_{(1, 46)} = 4.53$, $p = 0.039$); however, PTSD was not ($p = 0.34$). Notably, the $mTBI^{1+}$ group showed greater COP sway generally across all VETS conditions compared to the $mTBI^1$ and $mTBI^-$ groups (see Fig. 2).

Discussion

Lifetime experience with mTBI in veterans was also associated with greater instability during tests of standing balance control. Dysfunction in balance control was not evident during standard test conditions, which assess sway with eyes open on a firm surface or even in combinations that removed visual or altered somatosensory input. The lack of sensitivity of these conditions to lifetime mTBI may be expected given findings that balance control dysfunction has been reported to dissipate within months after an mTBI in many, though not all,[12] studies.[11,13,14] Dysfunction was detected with conditions of displaying a dynamically rotating visual input.

In simple analyses of lifetime experience of mTBI, the DYN condition with somatosensory challenge was sensitive to $mTBI^+$ from the $mTBI^-$ group. Broader dysfunction, but still largely driven by the DYN conditions, was related to the increasing number of lifetime experiences with mTBI. This finding is reminiscent of the earlier Coast Guard study, which found that the DYN-Foam resulted in a step-wise increase in postural sway relative to the number of mTBIs.[24] Unlike that earlier study, half the current sample met aggregate score criteria for probable PTSD, allowing for an evaluation of the potential complication of PTSD. This analysis revealed that postural dysfunction was independent of PTSD.

The current findings are notable in that they add to the growing body of evidence that visual-vestibular processing is affected by mTBI,[34] sometimes long after the last injury.[24] It has been known for half a century that dynamic visual rotation in the frontoparallel plane affects

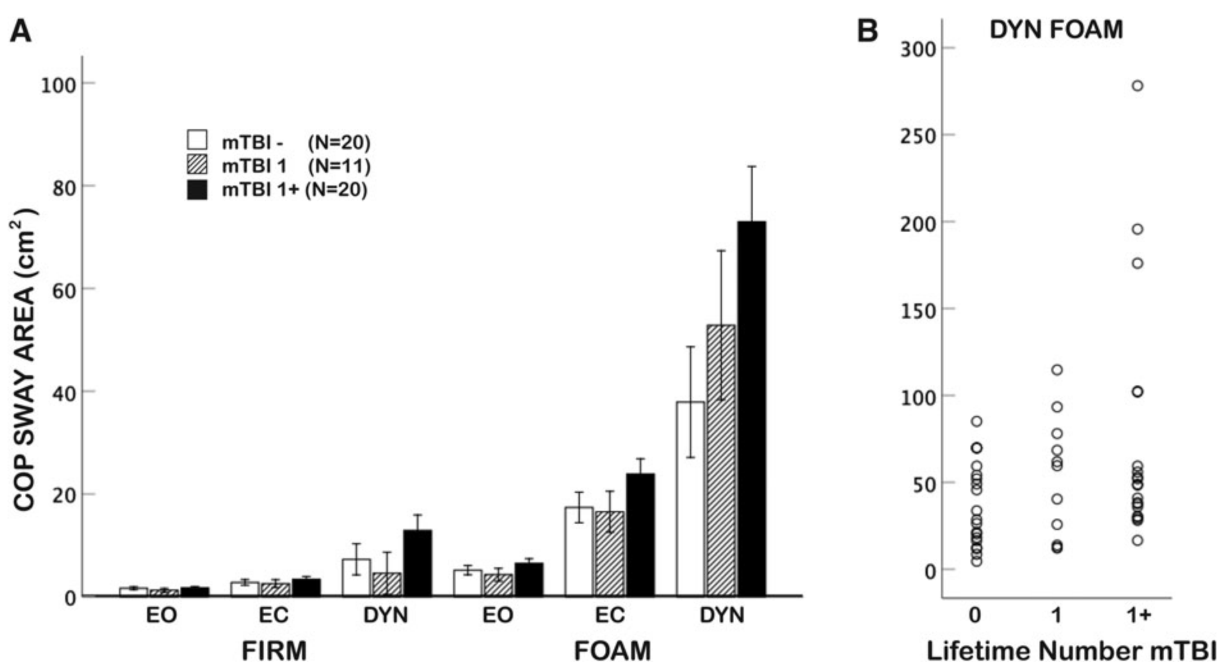

Fig. 2. (**A**) Effect of the number of previous mTBIs on postural sway area. Having a history of more than one mTBI ($mTBI^{1+}$) showed greater COP sway across all Virtual Environment TBI Screening device conditions, on average, compared to having a history of one ($mTBI^1$) and none ($mTBI^-$). (**B**) Scatterplot for each mTBI group in the DYN Foam condition, which is the source of the largest between-group mTBI differences. Error bars: ±1 SE. COP, center of pressure; EO, eyes open condition; EC, eyes closed condition; DYN, dynamically rotating visual scene condition; mTBI, mild traumatic brain injury; SE, standard error.

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balance even in healthy persons.[21,35,36] This type of full field-of-view stimulation inherently induces a visual-vestibular conflict, given that visual motion is not accompanied by inertial forces.[37,38] Accurately processing this mismatch is an integral part of spatial orientation perception and balance control.[35,39,40] Our current and previous results suggest this processing of the sensory mismatch is impaired after a mTBI. This is evident in the DYN-Foam condition; however, no deficit is observed when a subject is forced to rely on vestibular input alone (i.e., EC-Foam). Thus, the condition of visual-vestibular mismatch has proven to be highly sensitive to post-concussive deficits during balance assessments.[23,24,41,42]

Other signs that persist beyond the acute period include sensitivity to visual motion and deficits in oculomotor function.[34,43–47] Whether these specific multisensory integration issues are attributable to diffuse axonal injury in key cortical regions[48,49] or attributable to stress/strain exposure in key brainstem nuclei[50] is still unknown. However, it seems that the lingering deficit is largely covert until reliable sensory information is systematically removed or altered. Because postural control is multi-sensory, it is possible that imbalance can be compensated for under normal circumstances, given that tests of postural control have shown in other pathologies, for example, in unilateral vestibular loss, that persons may show no postural deficits over time, until they are placed in a challenging balance task such as standing on an unstable surface with eyes closed.[51] Future studies should focus on the potential cause of these long-lasting visual-vestibular processing deficits.

Much of the preceding research has been driven by symptom expression in long-term or chronic mTBI. In work with veterans, those who self-report balance difficulties also exhibit balance control difficulties during empirical tests.[19,20] In the current study, self-report NSI measures were used to probe acute mTBI symptoms in a cohort whose injury happened at least 6 months ago. As noted by others, symptoms identified by the NSI are non-specific to mTBI.[29,52] In fact, the presence of rare symptoms coupled with a high degree of endorsement to terms of disability is the basis of the V-10, which is a subscale aimed at identifying symptom over-reporting. Concern over symptom expression is heightened in veterans whose military experiences are associated with chronic stress-related psychopathology. Similar to others,[5,29,52,53] veterans endorsing PTSD also endorsed symptoms on the NSI more than those not endorsing PTSD. In contrast, those with lifetime experience of mTBI did not differentially endorse NSI symptom clusters compared to those without experience of mTBI. The usefulness of the NSI specifically in a cohort of veterans with a history of mTBI was found to be very limited here.

On the other hand, the NSI could expand understanding of PTSD and the difficulties of those with PTSD. Nonetheless, the balance dysfunction identified in this study was essentially observed in the absence of self-reported balance difficulty. The veterans recruited for the present study were community volunteers answering posted flyers; study participation was not coupled to clinical care either for mTBI or mental health. Responses to questions on the NSI related to balance symptoms did not differ between $mTBI^+$ and $mTBI^-$. Critically, these data support the contention that experience of mTBI may result in functional changes long after mTBI experience. Yet, this dysfunction remains covert, if reliance on self-report is the only means in use to identify those domains in need of rehabilitation or treatment.

We suspect that recovery from mTBI is much more complicated than either being ''asymptomatic' or part of the ''miserable minority.'' Posturography featuring visual-vestibular mismatch could contribute to identification of four groups: 1) those whose symptoms and objective markers normalize—truly recovered; 2) those whose symptoms persist, but whose objective markers normalize—emotionally affected; 3) those whose symptoms alleviated, but whose objective markers are aberrant—covert affected; and 4) those whose symptoms persist and objective markers are aberrant—pervasively affected. The emotionally affected and pervasively affected distinguish those expressing symptoms according to the degree to which they have objective signs. The covertly affected are comprised of persons who would otherwise not receive attention or treatment. This lesser-appreciated clinical group may be at greatest risk, given that motor deterioration is associated with mTBI,[7] and risk of falls related to aging[54–56] could compound fall risk, which concomitantly increases mTBI risk. Identification of otherwise covert dysfunction affords the opportunity of early intervention and development of preventive measures.

A few limitations should be considered when assessing the current findings. There was no baseline assessment before the injury, which, though not possible in the current study design, could have provided a within-subject reliable change index. We also did not have a control group with no military exposure or TBI exposure. Additionally, though we did not have a large sample size, the findings here can provide effect sizes, which will be useful for power calculations to determine sample size for a larger follow-up study.

In summary, veterans who experienced mTBI over their lifetime exhibited dysfunction in balance control as revealed through exposure to dynamic visual motion while standing on a pliant surface. Those with multiple lifetime experiences of mTBI exhibited increased sway generally across all conditions, but most notably during dynamic visual roll. Balance dysfunction in lifetime mTBI was independent of self-reported balance-related symptoms or other symptom domains measured by the

NSI. Indeed, lifetime mTBI was associated with less symptom expression in the affective cluster of the NSI. Balance-related dysfunction in lifetime mTBI was independent of PTSD. PTSD was highly influential in the degree of symptoms expressed on the NSI. Sensitivity of this population to dynamic visual motion provides a means to expose otherwise covert dysfunction long after the experience of mTBI.

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Author Disclosure Statement

No competing financial interests exist.

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