

AWARD NUMBER: W81XWH-15-1-0620

TITLE: Assessment and Rehabilitation of Central Sensory Impairments for Balance in mTBI

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REPORT DATE: December 2020

TYPE OF REPORT: Final Technical Report

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
Distribution Unlimited

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REPORT DOCUMENTATION PAGE		<i>Form Approved</i> <i>OMB No. 0704-0188</i>	
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1. REPORT DATE December 2020	2. REPORT TYPE Final report	3. DATES COVERED 30Sep2015- 29Sep2020	
4. TITLE AND SUBTITLE Assessment and Rehabilitation of Central Sensory Impairments for balance in mTBI		5a. CONTRACT NUMBER W81XWH-15-1-0620	
		5b. GRANT NUMBER MR141257	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Dr. Laurie King (PI); Dr. Lucy Parrington; Dr. Kody Campbell Ms. Shelby Martin		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES) Oregon Health & Science Veteran Affair Portland University Health Care System 3181 SW Sam Jackson Park 3710 SW US Veteran Hospital Road Rd, Portland, Oregon 97239 Portland, OR 97239		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Medical Research and Materiel Command Fort Detrick, Maryland 21702-5012		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited			
13. SUPPLEMENTARY NOTES			

14. ABSTRACT

Objectives: Control of balance requires complex integration of sensory and motor systems. Balance measurement is often over-simplified, preventing balance deficits from being identified and treated after mTBI. Our central hypothesis is that chronic balance deficits after mTBI result from impairments in central sensorimotor integration that may be helped by rehabilitation. This research has two objectives; 1) to characterize balance deficits in people with mTBI, and 2) to use a novel auditory biofeedback device to improve measures central sensorimotor integration and balance control.

Methods: Aim I) Balance Assessment: mTBI patients with non-resolving balance deficits following injury and healthy control participants with no history of mTBI are currently being recruited and tested on a battery of vestibular, neurocognitive, and balance-related tests. Aim II) Balance Rehabilitation: mTBI patients (a subgroup from Aim 1) are randomly allocated into a standard of care balance rehabilitation program either with (ABF), or without auditory biofeedback (no ABF). Both groups receive rehabilitation two times per week for six weeks. All participants are tested at baseline during Aim I testing, and are tested again following the intervention period, and again 6 weeks later to determine retention of changes.

Status: 132 subjects were enrolled out of 130 planned total (67 out of 65 mTBI, 65 out of 65 controls). 192 subjects were screened out of 170 planned total. 123 subjects completed Aim 1 testing out of 130 planned total, 10 control subjects returned for the 6-week follow up testing out of 10 planned total, 32 mTBI subjects returned for the 6- and 26 for the 12-week follow up testing out of 40 planned total.

Findings to date: Aim 1a: Instrumented sway during quiet stance with eyes closed had better diagnostic capacity than the clinical scoring alternatives for classifying chronic mTBI. Novel measures of central sensory integration and gait were not better than their clinical alternatives at classifying chronic mTBI. Aim 1b: Few people in our chronic mTBI sample had peripheral vestibular or oculomotor deficits, while over half had impaired central sensorimotor integration for balance control. Aim 1c: Sensorimotor integration factors mediated the relationship between mTBI impairment severity and balance, but did not mediate the relationship with gait. Aim 2a: Both no ABF and ABF groups improved performance on the sensory organization test (SOT) and improved sensory weighting (vestibular), while ABF group had larger improvements in motor activation and latency of responses across conditions following rehabilitation. Aim 2b: Both no ABF and ABF groups showed decreased sway and increased gait speed for dual task gait after rehabilitation. These improvements were retained 6 weeks following the conclusion of the rehabilitation intervention. Aim 2c: Improvements to SOT performance and sensory weighting remained present 6 weeks following testing, with the non-ABF group showing continued improvement in sensory weighting across all conditions at the retention stage. For motor activation measures of stiffness and damping, some improvement was maintained although this was condition dependent, and more notable in the ABF group.

15. SUBJECT TERMS

Balance, mTBI, Rehabilitation, Brain Injury, BESS, Dynamic Posturography, SOT, Inertial Sensors, Auditory Biofeedback, Central Sensory Integration, Concussion

16. SECURITY CLASSIFICATION OF:

a. REPORT

Unclassified

b. ABSTRACT

Unclassified

c. THIS PAGE

Unclassified

17. LIMITATION OF ABSTRACT

Unclassified

18. NUMBER OF PAGES

94

19a. NAME OF RESPONSIBLE PERSON USAMRMC

19b. TELEPHONE NUMBER (include area code)

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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1. INTRODUCTION:

Control of balance requires complex integration of sensory and motor systems. In the clinic or in the field, balance measurement is often over-simplified, preventing balance deficits from being identified and treated after mTBI. Our central hypothesis is that chronic balance deficits after mTBI result from impairments in central sensorimotor integration that may be helped by rehabilitation. There are two objectives of this proposal; the first objective is to characterize balance deficits in people with mTBI. The second objective is to use a novel auditory biofeedback (ABF) device to improve measures of central sensorimotor integration and balance control.

2. KEYWORDS:

mTBI, Rehabilitation, Brain Injury, BESS, Inertial Sensors, Balance, Auditory Biofeedback, Central Sensory Integration, Concussion

3. ACCOMPLISHMENTS:

What were the major goals and objectives of the project?

Goal	Target Completion Date	Percentage of Completion/ Date of Completion
Specific Aim 1 (Study 1: Assessment n=130 mTBI)		
Major Task 1: Launch Study Activities	30-Feb-2016	100%
Major Task 2: Recruitment and Testing (n=130)	30-Feb-2019	100%
Major Task 3: Data Analysis and Publications	30-Sep-2019	100%
Specific Aim 2 (Study 2: Rehabilitation n=40 mTBI)		
Major Task 1: Launch Study Activities	30-Feb-2016	100%
Major Task 2: Prepare Technology and Protocol for Intervention	30-Sep-2016	100%
Major Task 3: Randomized Interventions (n=40 mTBI)	30-Feb-2019	100%
Major Task 4: Assess Efficacy of Interventions (n=40)	30-Feb-2019	100%
Major Task 5: Data Analysis and Publications	30-Sep-2019	100%

What was accomplished under these goals?

Specific Aim 1 (Study 1: Assessment n=130)

Major task 1: Launch study activities

Subtask 1: Prepare regulatory documents and research protocol

- Set up sub award between sites; 100% complete
- Finalize consent form and human subject protocol; 100% complete
- Prepare testing protocol for both sites; 100% complete
- Prepare screening and testing forms for subject database; 100% complete
- Prepare combined OHSU/VA IRB documents; 100% complete
- Prepare FITBIR forms for data reporting; 100% complete

Subtask 2: Prepare technology for study

- Purchasing and testing software of Opals; 100% complete
- Modify SOT platform for new CSMI test; 100% complete
- Validate CSMI on commercial Neurocom SOT compared to laboratory posturography; 100% complete
- Develop new algorithm to automatically quantify head movements from Opal sensor; 100% complete
- Set up and test gait paradigm with turns and dual task; 100% complete
- Dual task; test microphone for recording cognitive task; 100% complete

Subtask 3: Hiring and training personnel

- Hire RA at the VA; 100% complete
- Staff completes research compliance training; 100% complete
- Train VA audiologist and RA in data collection; 100% complete

Subtask 4: Research essential documents

- HRPO approval for human protocol; 100% complete

Subtask 5: Study registration (Not included in original SOW)

- Complete the Clinical Trial Registry; 100% complete
- Complete registration for FITBIR; 100% complete

Major Task 2: Recruitment and testing (n=130)

Subtask 1: Recruitment (n=130)

- Prepare brochures for subject recruitment and meet with primary sources of referral; 100% complete
- Finalize recruitment strategy; 100% complete
- Phone screening of subjects; 100% complete
- Schedule vestibular/audiogram/ocular motor, CSMI, balance and gait testing; 100% complete

Subtask 2: Data collection/management (n=130)

- Schedule testing sites for data collection; 100% complete
- Data collection for the 2 days of data collection for aim 1 takes place; 100% complete
- Data back-up onto server including manual data entry; 100% complete
- Screen and verify data on server; check for accuracy; 100% complete
- Upload data to FITBIR; 100% complete

Major Task 3: Data analysis and publications

Subtask 1: Data analysis

- Perform all analysis according proposal and share all findings with investigators; 100% complete

Subtask 2: Manuscripts and presentations

- Disseminate findings (abstracts, presentations, papers, DoD); 100% complete
- Integrate new protocols and head movement metrics into APDM mobility lab system; 100% complete

Specific Aim 2 (Study 2: Rehabilitation n=40 mTBI)

Major Task 1: Launch study activities

Subtask 1: Hire and train personnel

- Hire and train physical therapists for intervention; 100% complete
- Order ABF and exercise equipment; 100% complete

Major Task 2: Prepare technology and protocol for intervention

Subtask 1:

- Finalize and prepare written protocol for PT training; 100% complete
- Test 2 ABF devices with new protocol; 100% complete
- Train ABF PT in protocol; 100% complete
- Interpretation of CSMI for each mTBI subject provided to PT to design intervention; 100% complete

Major Task 3: Randomized interventions (n=40 mTBI patients)

Subtask 1:

- Statistician prepares randomization schedule; 100% complete
- PTs call subjects to schedule intervention; 100% complete
- 6 week interventions at both sites; 100% complete
- PTs document compliance, adverse events and progression of exercise for each subject; 100% complete

Major Task 4: Assess efficacy of interventions (n=40)

Subtask 1:

- Immediate post-test after intervention; 100% complete
- Long-term assessment 6 weeks later to assess retention of improvements; 100% complete

Subtask 2:

- A subset of controls will be tested at a 6 week follow up in order to determine any natural changes in the CSMI test over 6 weeks; 100% complete

Major Task 5: Data analysis and publications

Subtask 1: Data Analysis

- Perform all analysis according proposal and share all findings with investigators; 100% complete

Subtask 2: Manuscripts and presentations

- Disseminate findings (abstracts, presentations, papers, DoD), including American Physical Therapy Association and American Congress of Rehabilitative Medicine and rehabilitation journals to share with clinicians; 100% complete
- Publish novel ABF intervention protocol; 100% complete

Significant Results/ Key Outcomes:

Aim 1: To characterize balance deficits in chronic mTBI compared w/ healthy control subjects.

Aim 1a: To determine if objective (novel) measures of central sensorimotor integration, static and dynamic balance can better distinguish between chronic mTBI and healthy controls than clinical measures.

To complete this aim, we analyzed data from 118 people (57 with mTBI and chronic balance complaints, and 61 healthy matched controls). For sensorimotor integration the clinical measure, the sensory organization test (SOT) composite score, was compared against the novel Central Sensory Motor Integration Test (CSMI) sensory weight scores (W) for three conditions (1) eyes-open, moving surface (EO, S), (2) eyes-closed, moving surface (EC, S), and (3) eyes-open, moving surface and visual surround (EO, S+V) each performed with 2 degree peak to peak rotations of the surface/ visual surround (Peterka et al., 2018). For static balance, the clinical measures included the error count for the modified Balance Error Scoring System (mBESS), and the time measured for modified Clinical Test of Sensory Interaction on Balance (mCTSIB). These were compared against an objective measure of sway (the medio-lateral component of root mean square of acceleration: ML RMS sway) derived from 60 seconds quiet stance with eyes closed instrumented with an inertial measurement unit (IMU). ML RMS sway was chosen as the objective static balance metric based on previous work from our team with mTBI populations (see King et al., 2017; Parrington et al., 2018; Parrington et al., 2019; Parrington et al., 2020). For dynamic balance, clinical single-task and dual-task gait speed were compared with single-task and dual-task gait domain scores. The domain scores of Pace, Rhythm, Variability and Turning, were determined based on our work during this study (see Stuart et al., 2020).

To determine whether the novel measures were more effective than clinical measures at classifying people with chronic mTBI and healthy controls, we computed receiver operating characteristic (ROC) curves with corresponding area under the curve (AUC) for the variables of interest. Comproc Stata routines were used with bootstrap calculations (1000 replications) were used to test for any statistically significant differences between ROC curves. A 5-fold cross-validation method was used to address overfitting. Stata version 16 (StataCorp LLC., College Station, TX) was used for all statistical analyses.

Sensorimotor integration results

We hypothesized that the CSMI sensory weight scores would be better at classifying between chronic mTBI and healthy controls. However, the SOT composite score was significantly better at classifying between chronic mTBI and healthy controls than the sensory weight score for the eyes-closed, moving surface condition and the eyes-open, moving surface and visual surround condition. The SOT composite was not significantly better at classifying chronic mTBI from controls than the eyes-open, moving surface condition.

Table 1. SOT and CSMI sensory weighting (W) for different conditions

Variable	AUC	95% CI (corrected)		z	p	interpretation
		Lower	Upper			
SOT composite	0.76	0.66	0.85	-	-	-
W (EO, S)	0.66	0.55	0.77	-1.7	0.092	No difference in diagnostic capacity
W (EC, S)	0.61	0.51	0.72	-2.5	0.011	SOT composite significantly better
W (EO, S+V)	0.55	0.45	0.67	-3.8	<0.001	SOT composite significantly better

Static balance assessment

Based on our prior work in this area, we hypothesized that the instrumented balance evaluations (postural sway) would outperform clinical scoring methods in the ability to classify chronic mTBI. Our findings

support this hypothesis and the objective measure ML RMS sway significantly outperformed the clinical mBESS total error count and the mCTSIB total time in its diagnostic capacity (Table 2).

Table 2. Comparison of clinical and instrumented static balance measures

Variable	AUC	95% CI (corrected)		z	p	interpretation
		Lower	Upper			
ML RMS sway	0.75	0.65	0.84	-	-	-
mBESS total error count	0.62	0.51	0.72	-2	0.043	ML RMS sway significantly better
mCTSIB total time	0.18	0.10	0.31	-8.3	<0.001	ML RMS sway significantly better

Dynamic balance results

We hypothesized that the dynamic balance variables would be better at classifying between chronic mTBI and healthy controls. However, there were no differences in the ability to classify between chronic mTBI and healthy controls for our clinical single-task gait speed measure (time in seconds) compared with instrumented turning, pace or rhythm single-task domain scores. Interestingly, clinical single-task gait speed was a significantly better classifier than variability. For dual-task gait, there were no differences in the ability to classify between chronic mTBI and healthy controls for our clinical dual-task gait speed measure (time in seconds) compared with instrumented pace and rhythm dual-task domain scores. Clinical single-task gait speed was a significantly better classifier than variability and turning dual-task domain scores.

Table 3. Comparison of clinical gait speed (single task) and instrumented gait measures

	95% CI (corrected)					
Measure	AUC	Lower	Upper	z	P	interpretation
<i>Single-task gait</i>						
Clinical gait speed	0.70	0.59	0.79	-	-	-
Rhythm	0.69	0.58	0.77	-0.22	0.83	No difference in diagnostic capacity
Turning	0.62	0.50	0.72	-1.1	0.27	No difference in diagnostic capacity
Pace	0.72	0.61	0.81	0.68	0.49	No difference in diagnostic capacity
Variability	0.56	0.45	0.67	-2.4	0.02	Clinical gait speed was significantly better
<i>Dual-task gait</i>						
Clinical gait speed	0.71	0.61	0.80	-	-	-
Rhythm	0.71	0.61	0.80	-0.01	1.00	No difference in diagnostic capacity
Turning	0.57	0.46	0.68	-2.10	0.04	Clinical gait speed was significantly better
Pace	0.70	0.60	0.80	-0.13	0.90	No difference in diagnostic capacity
Variability	0.56	0.45	0.66	-2.60	0.01	Clinical gait speed was significantly better

The best measures to classify mTBI vs control were SOT composite (for sensory weighting), instrumented sway (static balance) and dual task gait speed (dynamic balance). The SOT composite score was significantly better at distinguishing between the two groups compared with 2/3 of the sensory weight scores (the eyes-closed, moving surface condition and the eyes-open, moving surface and visual surround condition), while the sensory weight score derived from the eyes-open, moving surface condition was not significantly different in its diagnostic capacity. The CSMI involves more complex modeling of balance control than the SOT, and has the potential to provide more detailed information, including motor activation (see **Aim 1c** describing different CSMI factors) in this population. However, for the purpose of classification, the SOT composite score should be used rather than the CSMI sensory weight scores.

With regards to static balance assessment, the instrumented postural sway data outweighed the capacity of the clinical mBESS error score and the clinical mCTSIB time. The ML RMS sway has been previously recognized as having superior sensitivity and specificity in its diagnostic capacity in other mTBI cohorts (cite King 2014 and King 2017), and results herein are in agreement with previous findings. The ability to measure ML RMS sway in the clinic is simple, minimally invasive, and is time efficient for both the patient and clinician. Based on our findings, we suggest that clinicians should consider the translation of simple instrumented balance assessment into clinical practice.

The lack of difference between clinical single and dual task gait speed (measured with a stop watch and known distance) and turning, pace or rhythm domain scores (measured using instrumented sensors) indicated that for the purpose of classification, there would be no benefit of using a more complex method of assessment. That the clinical single and dual task gait speed was a better classifier than single and dual task variability, and turning domain scores, provide further evidence that are in support of simply using a stop watch to determine gait speed for this purpose. We note that there are benefits in the ability to evaluate multiple different parts of gait using inertial sensors, however, for the purpose of classification of persons with chronic mTBI, use of inertial sensors may not be warranted.

Aim 1b: To determine if a subset of people with mTBI will have abnormal central sensorimotor integration test measures, even without peripheral vestibular or ocular motor deficits

For this aim, we proposed classifying chronic mTBI subjects into four categories (peripheral-central systems): 1) abnormal – abnormal; 2) abnormal-normal, 3) normal-abnormal, 4) normal-normal. We completed this investigation on 119 participants, including 58 chronic mTBI (72% female, age = 39.16 (11.43), height = 170.87 (9.35), mass = 78.34 (19.06), days since injury as median [1st Quartile, 3rd Quartile] = 343[201, 796]), and 61 healthy controls (61% female, age = 37.13 (12.64), height = 171.17 (9.50), mass = 74.87 (19.06). Participants with a history of blast exposure (n=6) were not included in this analysis.

To determine peripheral vestibular and/ or oculomotor deficits, participants completed a testing battery that included the following tests, performed in order:

- 1) horizontal video head impulse test (vHIT)
Outcomes included the vestibulo-ocular reflex (VOR) gain averaged across rightward and leftward head rotations, and VOR average gain asymmetry between rightward and leftward head rotations.
- 2) cervical vestibular evoked myogenic potential (cVEMP) test
Replicated peak-to-peak amplitudes of the P13/N23 waveforms were averaged, and asymmetry ratios were calculated between ears.
- 3) ocular vestibular evoked myogenic potential (oVEMP) test
Replicated peak-to-peak amplitudes of the P13/N23 waveforms were averaged, and asymmetry ratios were calculated between ears.
- 4) horizontal random saccades
Outcomes included tracking accuracy, peak saccade velocity, and saccade onset latency.
- 5) horizontal smooth pursuits
Outcomes included the eye velocity gain asymmetry between rightward and leftward pursuit directions.

- 6) the Dix-Hallpike maneuver for benign paroxysmal positional vertigo (BPPV) screening
Patterns of eye movements indicative of BPPV were used as a screening tool.
- 7) bi-thermal caloric tests.
Outcomes included unilateral weakness percentage, and the average peak slow phase velocity from all irrigations.

To determine central sensorimotor integration deficits, participants were evaluated using the SOT (NeuroCom SMART Balance Master, Natus, California, USA). The central integration measures included the SOT composite score, and somatosensory, visual and vestibular ratios (an indication of how much participant's rely on these sensory systems for balance). A more detailed description of the testing procedures can be found in Appendix A.

Determining peripheral vestibular, oculomotor and central sensorimotor integration abnormality

To evaluate abnormalities in our chronic mTBI sample across the battery of vestibular, oculomotor and central integration tests, we calculated percentiles based on our healthy control sample. An abnormal response for our mTBI group was then determined if the measures fell outside a 10th-percentile cutoff determined from all healthy control data. There were a different number of participants included in the final analyses of each test, as a result of participants' inability to complete a test (i.e., participant aborting due to symptoms) and technical issues (impacted cerumen or participant mascara effecting data capture). Only 28 participants from the healthy control group and 12 from the chronic mTBI group were able to complete the entire testing battery with quality data sufficient for analysis. Thus, abnormalities were derived on a test-by-test basis, where the 10th percentile score from the healthy controls may not have included the exact same participants each time. In order to classify participants into the prescribed categories, participants were indicated as having peripheral vestibular, oculomotor or central abnormalities if they fell within the abnormal (below the 10th percentile of the controls) on one or more of the tests from a specific category. For example, someone who had an abnormal peak saccade velocity but no other abnormalities would be considered within the abnormal oculomotor classification.

Classification crosstabs for peripheral vestibular and central sensorimotor integration abnormality are provided in Table 4. There was no association of abnormal peripheral vestibular findings with abnormal central sensorimotor integration (Pearson $\chi^2 = 0.002$, $p = 0.97$ (1 Degree of Freedom; DoF)). Classification crosstabs for oculomotor and central sensorimotor integration abnormality are provided in Table 5. There was no association of abnormal peripheral vestibular findings with abnormal central sensorimotor integration findings (Pearson $\chi^2 = 0.106$, $p = 0.75$ (1 DoF)). Finally, classification crosstabs which grouped both peripheral vestibular and/or oculomotor, and central sensorimotor integration abnormality are provided in Table 6. There was no association of abnormal peripheral vestibular findings with abnormal central sensorimotor integration findings (Pearson $\chi^2 = 0.045$, $p = 0.83$ (1 DoF)). The statistical findings indicate that these categorical variables are independent of each other. Thus, peripheral vestibular and/ or oculomotor abnormality does not change the probability distribution of central sensorimotor integration abnormality.

Table 4. Breakdown of chronic mTBI with any vestibular and any central sensorimotor integration abnormality

		Central sensorimotor integration			
			Abnormal	Normal	Total
Peripheral Vestibular	Abnormal	Frequency	15	8	23
		Percent	25.86	13.79	39.66
		Row %	65.22	34.78	
		Col %	39.47	40.00	
	Normal	Frequency	23	12	35
		Percent	39.66	20.69	60.34
		Row %	65.71	34.29	
		Col %	60.53	60.00	
	Total		38	20	58
			65.52	34.48	100.00

Table 5. Breakdown of chronic mTBI with any oculomotor and any central sensory abnormality

			Central sensorimotor integration		
			Abnormal	Normal	Total
Oculomotor	Abnormal	Frequency	13	6	19
		Percent	22.41	10.34	32.76
		Row %	68.42	31.58	
		Col %	34.21	30.00	
	Normal	Frequency	25	14	39
		Percent	43.10	24.14	67.24
		Row %	64.10	35.90	
		Col %	65.79	70.00	
	Total		38	20	58
			65.52	34.48	100.00

Table 6. Breakdown of chronic mTBI with any peripheral vestibular and/or oculomotor abnormality and any central sensory abnormality

			Central sensorimotor integration		
			Abnormal	Normal	Total
Peripheral vestibular and/or oculomotor	Abnormal	Frequency	22	11	33
		Percent	37.93	18.97	56.90
		Row %	66.67	33.33	
		Col %	57.89	55.00	
	Normal	Frequency	16	9	25
		Percent	27.59	15.52	43.10
		Row %	64.00	36.00	
		Col %	42.11	45.00	
Total		38	20	58	
		65.52	34.48	100.00	

We further evaluated whether the proportion of normal/abnormal responses on each peripheral vestibular, oculomotor and central integration test results were different between the chronic mTBI group and healthy controls on a per test basis. This comparison was completed using a chi-squared test of association.

There were no significant differences in the proportions of normal and abnormal peripheral vestibular function between the healthy control and chronic mTBI groups (p 's > 0.113). For the peripheral vestibular assessments, the highest percentage of abnormal function in the chronic mTBI group was for caloric unilateral weakness (18%). Caloric average slow phase velocity was abnormal in 15% of the chronic mTBI group. Average VOR gain derived from the vHIT had the lowest percentage of abnormal function in the chronic mTBI group (4%), while VOR gain asymmetry was abnormal in 14% of the chronic mTBI group. cVEMP asymmetry and oVEMP asymmetry were abnormal in 8% and 17% of the chronic mTBI group, respectively. Similar to peripheral vestibular function, there were no significant differences in the proportion of participants with normal versus abnormal oculomotor function between the healthy control and chronic mTBI groups for any of the oculomotor tests ($p \geq 0.113$). Eight percent of chronic mTBI had abnormal saccade accuracy, and 12% had abnormal saccade latency, while average saccade velocity had the smallest percentage of chronic mTBI with abnormal function (2%). Smooth pursuit velocity gain had the largest percentage of chronic mTBI with abnormal function (14%). Ten percent of chronic mTBI had smooth pursuit velocity gain asymmetry abnormalities.

In contrast with the oculomotor and peripheral vestibular findings, there were significant differences in the proportions of the chronic mTBI group who had abnormal central sensorimotor function, according to SOT results. Fifty-two percent of chronic mTBI participants had an abnormal SOT composite score. The highest proportion of abnormal response in the mTBI group occurred for the SOT somatosensory ratio (61%), while the percentage of abnormal function for the SOT visual ratio and the SOT vestibular ratio scores were 43% and 41%, respectively. For each of these sensorimotor integration measures, the chronic mTBI group had significantly higher proportions of abnormal responses compared with the healthy control group (all $p < 0.001$).

Few people in our chronic mTBI sample had deficits in their peripheral vestibular and/or oculomotor function. However, over half had impaired central sensory integration for balance control when compared to healthy, age-matched controls. From a clinical perspective, these findings suggest that patients with chronic complaints (persistent > 3 months post mTBI) should be referred to rehabilitation for balance training and avoid unnecessary initial referrals to otolaryngology or vestibular testing.

Aim 1c: To determine if the observed relationship between poorer static/dynamic balance performance and mTBI is regulated/mediated by central sensorimotor integration.

Aim 1c involved determining if the observed relationship between poorer static/dynamic balance performance and mTBI was mediated by central sensorimotor integration. This process involved two stages, including 1) variable reduction into factors using exploratory factor analysis and 2) testing mediation models using path analysis. Step 1 (generating factors) was necessary to reduce the myriad objective measures available from the wearable inertial sensor data. Factor analysis allows one to use the common shared variance among many indicators to create a single variable that represents the construct (e.g., gait). Factors were created for dynamic balance (gait), static balance (sway), level of impairment severity, and central sensorimotor integration. Step 2 was conducted to analyze the relationship of severity of mTBI impairment on balance, and to determine any mediating effect from central sensorimotor integration on balance.

Step 1 - Generating factors:

In order to reduce the number of mediation models required, Step 1 involved generating a factor for the predictor, outcome and mediating variables. The wearable sensor system (APDM Wearable Technologies Inc.) generates approximately 30 different measures for static balance and another 50 for dynamic balance. These measures capture different aspects of sway and gait across several conditions. We took a theory driven approach to exploratory factor analysis to reduce the volume of variables and to build a single variable for each construct. The constructs included overall mTBI impairment severity, static balance, dynamic balance, sensorimotor integration

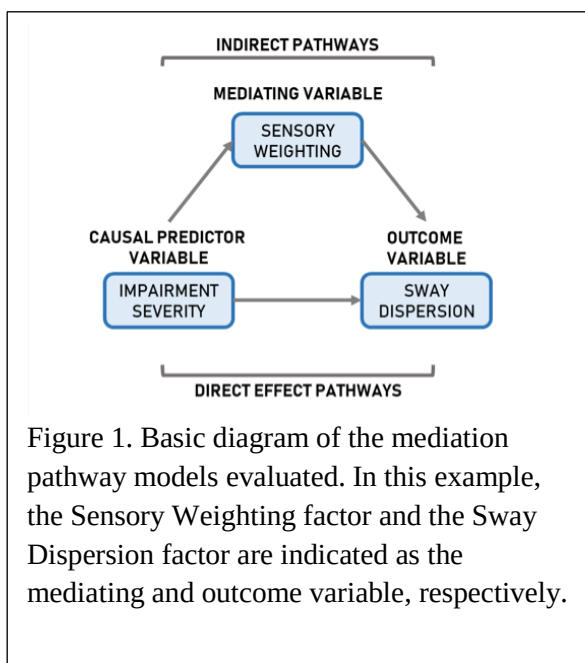
For each construct, we selected theoretically relevant variables and performed an exploratory factor analysis. Analyses were done using SAS 9.4 and the Principal Factor procedure. Squared multiple correlations (SMC) were used as the prior communality estimates. Promax rotation was used to provide both orthogonal and oblique rotations. We used eigenvalues and proportions of variance explained to determine the number of factors that would be retained. This process resulted in the following factor compositions:

- 1) mTBI impairment severity: Impairment was found to be one single factor with the following indicators: Dizziness Handicap Inventory (DHI) total score, Neurobehavioral Symptom Inventory (NSI) total score, and Sports Concussion Assessment Tool (SCAT) total symptom score and SCAT severity total.
- 2) Static balance: Static balance was characterized by Sway Dispersion, which was composed of the root mean square of sway acceleration across 6 balance conditions (double stance with eyes open on firm and foam surfaces, double stance with eyes closed on firm and foam surfaces, tandem and single leg stances).
- 3) Dynamic balance: Dynamic balance was characterized by a Gait factor composed of gait speed, double support time and turning speed.
- 4) Central sensorimotor integration: Central sensorimotor integration was not found to consist of a single factor. It appeared that the different components were indeed tapping into different aspects of central sensorimotor integration. As no single sensorimotor integration factor could be generated, four factors were generated, which included the SOT Ratio factor, a sensory weighting factor, a motor activation factor, and a motor latency factor.
 - a. SOT Ratio factor: was composed of the SOT somatosensory, vestibular and visual ratio scores.
 - b. Sensory Weighting factor: composed of W scores from three CSMI test conditions (1. EO, S, 2. EC, S, and 3. EO, S+V).
 - c. Motor Activation factor: composed of sensorimotor transformation parameters of normalized stiffness and normalized damping scores from three CSMI test conditions: (1) EO, S; (2) EC, S; and (3) EO, S+V.
 - d. Motor Latency factor: composed of the sensorimotor transformation parameter time delay from three CSMI test conditions: (1) EO, S; (2) EC, S; and (3) EO, S+V.

Step 2 - Testing mediation models (path analysis)

Step 2 was conducted to analyze the relationship of the impairment severity factor on the outcome variables (balance and gait factors), and determine any mediating effects from the central sensorimotor integration factors. Once factors were determined through Step 1, we created a factor score that was used as the variable for each construct. Creating factor scores allowed us to create measured variables for each factor, rather

than latent variables, and as a result, we were able to test the mediation models using path analyses. This was beneficial with our limited sample size, as measured variables require less power to model than latent variables in structural equation modeling.



Representation of the mediation models are presented in Figure 1. Each path model was evaluated using the Impairment Severity factor as the causal predictor variable. Outcome variables included the Sway Dispersion for static balance, and the Gait and Gait Variability factors for dynamic balance. Models evaluated each of the following mediating variables: SOT Ratio factor, Sensory Weighting factor, Motor Activation factor, and the Motor Latency factor. Since we had four mediating variables, four mediation models were tested for each outcome variable resulting in a total of 16 computed path models. Analyses were done using SAS 9.4 and the Proc CALIS procedure. Due to the exploratory nature of this analysis, the alpha level was set at 0.05.

Results of the mediation analysis indicated central sensorimotor integration factors (SOT Ratio, Motor Activation, and Motor Latency) mediated the relationship between Impairment Severity and Sway Dispersion. Yet, no central sensorimotor integration factors mediated between Impairment Severity and Gait. A summary of the mediation models tested and results are presented in Table 7.

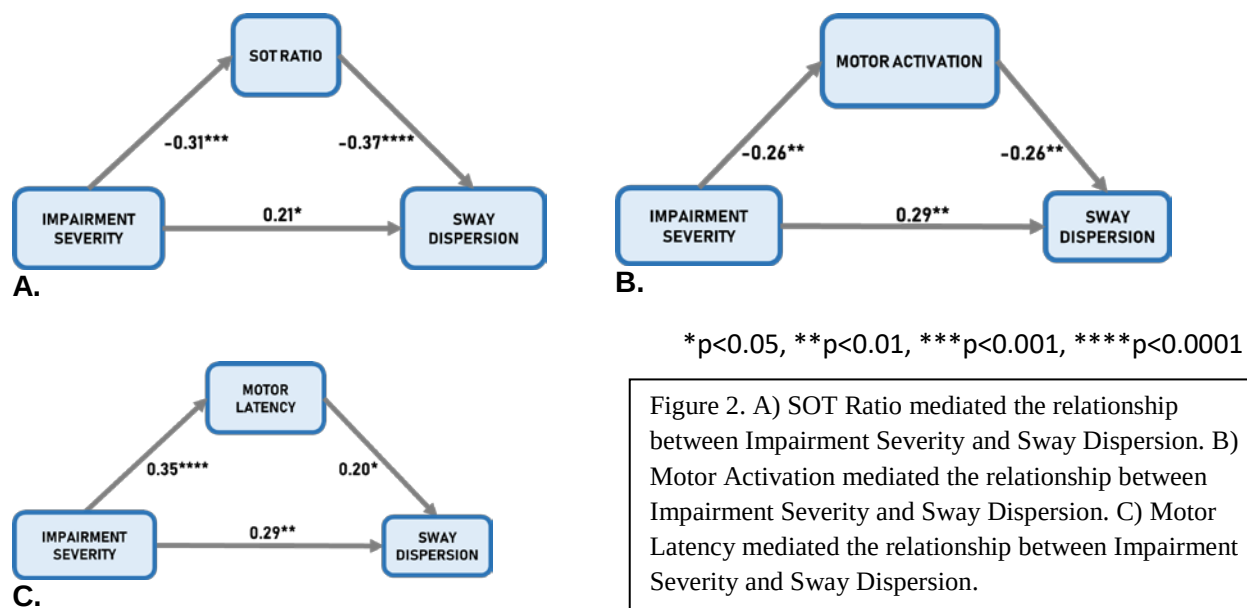
Table 7. A summary of presence of direct association and mediation for each of the mediation models.

Predictor variable	Outcome variable	Mediating variable	Direct effect	Indirect (mediating) effect
Impairment Severity	Sway Dispersion	SOT Ratio	Yes	Yes
		Sensory Weighting	Yes	No
		Motor Activation	Yes	Yes
		Motor Latency	Yes	Yes
Impairment Severity	Gait	SOT Ratio	Yes	No
		Sensory Weighting	Yes	No
		Motor Activation	Yes	No
		Motor Latency	Yes	No

Our results indicated that central sensorimotor integration factors (1. SOT Ratio, 2. Motor Activation, and 3. Motor Latency) mediated the relationship between Impairment Severity and Sway Dispersion. SOT Ratio mediated the relationship between Impairment Severity and Sway Dispersion. The SOT Ratio factor was composed of the SOT somatosensory, vestibular and visual ratio scores, which express how well a participant is able to use those specific cues for balance. As a mediator of the relationship between Impairment Severity and Sway Dispersion, this may be interpreted as greater impairment leads to a decreased ability to use vestibular, visual and somatosensory cues, which in turn, results in more sway. Clinically, focusing on improving a patient's ability to use these cues for balance during rehabilitation of persistent mTBI impairment, should plausibly help to decrease sway in these patients. This finding supports what is primarily already being practiced in the clinic during vestibular rehabilitation.

A more novel finding is that motor activation significantly mediated the relationship between Impairment Severity and Sway Dispersion. The Motor Activation factor was composed of stiffness and damping across conditions of the CSMI test. Thus, this mediation model suggests that higher impairment may lead to lower Motor Activation (i.e., lower stiffness and damping), and therefore a more “sloppy” motor response, which in turn results in more sway. From a rehabilitation perspective, targeting strategies to improve motor activation and control has the potential to improve a patient’s control of balance and thus decrease the amount of their sway. Unlike the focus on sensory cues for balance (as indicated above), this is an area that has not received attention in vestibular rehabilitation, but may have important implications for improving balance.

Motor Latency significantly mediated the relationship between Impairment Severity and Sway Dispersion. Motor Latency was composed of the parameter time delay from conditions of the CSMI test. This mediation model may be interpreted as greater impairment leads to longer time delay to respond to stimuli, which in turn results in more sway. This also has novel implication for expanding rehabilitation in this population. Including tasks that involve training response time to stimuli (e.g. such as perturbation training) may also benefit the rehabilitation of patients with persistent impairment after mTBI. These models are presented in Figure 2.



In contrast to the static balance findings, we found no mediating effects of central sensorimotor integration factors for dynamic balance (gait). As expected based on prior findings, there was a direct relationship between Impairment Severity and Gait (composed of gait speed, double support time and turning speed). These findings suggest impaired gait may not be affected by the same central sensorimotor integration mechanisms as balance, and therefore rehabilitation may need to focus on other systems. While this finding is an important step toward understanding rehabilitation of dynamic balance in this population, more research is required in this area to understand if and what central sensorimotor integration factors, or higher level cortical input mediate the quality of gait in these patients. Findings of this nature could better help guide rehabilitation.

Aim 2: To determine the efficacy of a novel, ABF balance rehabilitation program to improve central sensorimotor integration, static and dynamic balance, and functional activity in patients with chronic mTBI. For Aim 2, 40 participants involved in Aim 1 were randomized into an experimental (vestibular rehabilitation therapy augmented by ABF) and a control (standard care vestibular rehabilitation therapy without ABF) intervention. The intervention involved 6-weeks of vestibular focused physical therapy (therapy protocol described in Fino et al., 2017). Data from Aim 1 formed the pre-intervention baseline data for these participants. With the exclusion of peripheral vestibular and oculomotor tasks (See Aim 1b above), testing was completed using the same protocol from Aim 1 in the week following the intervention (follow up), and again a further 6-weeks out (retention).

Aim 2a: To determine if CSMI scores will improve with rehabilitation, and if audio biofeedback (ABF) increases the improvement of CSMI scores beyond the standard of care.

To evaluate whether CSMI scores improved with rehabilitation, and if rehabilitation with audio biofeedback (ABF) improved CSMI scores beyond the standard of care rehabilitation without ABF, we calculated the effect size of the change between pre- and post-rehabilitation scores (Hedge's G) using the Measures of Effect Size (MES) Toolbox in MATLAB 2021b. This method was chosen as the best approach for this exploratory aim. The outcome measures included the SOT composite score, and CSMI sensory weighting (W), and sensorimotor transformation parameters of normalized stiffness (Kp norm), normalized damping (Kd norm) and time delay (Td). The pre-post intervention change for all participants together is indicated in Table 8. Descriptive statistics for the vestibular rehabilitation therapy without, and with ABF are presented in Table 9, and effect sizes on the change between pre- and post-rehabilitation scores for both the vestibular rehabilitation therapy with and without ABF are presented in Table 10.

Table 8. Descriptive data for pre-post intervention for all mTBI participants, regardless of intervention type

Variable	Pre N	Pre Mean (SD)	Post N	Post Mean (SD)	Effect Size with Lower and Upper 95% CI
SOT composite score	30	56.47 (16.43)	28	72.32 (11.05)	1.11 (0.79, 1.65) ***
W (EC, S)	28	0.56 (0.08)	26	0.52 (0.08)	-0.44 (-0.81, -0.17) *
Kp norm (EC, S)	28	1.46 (0.15)	26	1.54 (0.15)	0.46 (0.15, 0.89) *
Kd norm (EC, S)	28	0.5 (0.06)	26	0.53 (0.05)	0.48 (0.09, 0.9) *
Td (EC, S)	28	157 (18)	26	149 (18)	-0.46 (-0.86, -0.14) *
W (EO, S)	29	0.33 (0.05)	26	0.31 (0.06)	-0.32 (-0.73, 0.05) *
Kp norm (EO, S)	29	1.47 (0.17)	26	1.51 (0.16)	0.22 (-0.23, 0.7) *
Kd norm (EO, S)	29	0.48 (0.07)	26	0.49 (0.07)	0.18 (-0.24, 0.6)
Td (EO, S)	29	138 (21)	26	129 (21)	-0.36 (-0.87, 0.13) *
W (EO, S+V)	28	0.6 (0.08)	26	0.58 (0.08)	-0.22 (-0.69, 0.17) *
Kp norm (EO, S+V)	28	1.42 (0.14)	26	1.47 (0.15)	0.33 (-0.02, 0.78) *
Kd norm (EO, S+V)	28	0.46 (0.06)	26	0.48 (0.06)	0.43 (0.04, 0.87) *
Td (EO, S+V)	28	154 (22)	26	146 (27)	0.35 (-0.84, 0.03) *

SOT = Sensory Organization Test; W = Sensory Weighting; EC, S = eyes-closed, moving surface; EO, S = eyes-open, moving surface; EO, S+V = eyes-open, moving surface and visual surround. ***Large effect; **Moderate effect; *Small effect

Results indicate that all participants improved overall balance performance, as indicated by the large increase in SOT composite score (see table 8,9,10). When separating sensory weighting from motor activation patterns, both groups demonstrated small effect sizes on improving sensory weighting, while we observed a general trend for the ABF group having larger improvements in motor activation measures

(increased stiffness and decreased time delay). Decreased sensory weighting across both groups for conditions from the CSMI test indicates that participants became less reliant on proprioception for balance and improved reliance on the vestibular system. The effectiveness of vestibular rehabilitation with and without ABF was similar on improving sensory weighting.

The increased stiffness and damping indicates that participants improved motor activation, and the decreased time delay suggests that participants were faster in their response when correcting balance. In the two conditions that more purely test vestibular function from the CSMI test (EC, S and EO, S+V), the ABF group had more improvements in motor activation measures compared to the standard vestibular rehabilitation group without ABF. We observed less differences between the rehabilitation groups when accurate vision was available (EO, S). The ABF provided immediate auditory feedback on postural sway changes during balance exercises performed in the rehabilitation program, and the moderate changes in stiffness and time delay after rehabilitation suggests that this may be an effective method for improving motor activation. This is an important finding because motor activation is not measured during clinical care and vestibular rehabilitation does emphasize motor activation but rather focuses more on sensory integration. Nonetheless, at this stage, further work and evidence is required to confirm this finding.

Table 9. Descriptive data for pre-post intervention for vestibular rehabilitation therapy without ABF and with ABF

Variable	Without ABF		With ABF		Without ABF		With ABF	
	Pre N	Pre Mean (SD)	Pre N	Pre Mean (SD)	Post N	Post Mean (SD)	Post N	Post Mean (SD)
SOT composite score	15	54.00 (16.82)	15	58.93 (16.22)	13	71.62 (12.96)	15	72.93 (9.51)
W (EC, S)	13	0.59 (0.07)	15	0.52 (0.07)	11	0.56 (0.09)	15	0.49 (0.07)
Kp norm (EC, S)	13	1.47 (0.18)	15	1.46 (0.13)	11	1.54 (0.2)	15	1.53 (0.12)
Kd norm (EC, S)	13	0.49 (0.08)	15	0.51 (0.05)	11	0.52 (0.05)	15	0.54 (0.05)
Td (EC, S)	13	156 (23)	15	158 (13)	11	149 (20)	15	149 (17)
W (EO, S)	14	0.34 (0.05)	15	0.32 (0.05)	11	0.34 (0.06)	15	0.30 (0.06)
Kp norm (EO, S)	14	1.46 (0.17)	15	1.49 (0.17)	11	1.5 (0.18)	15	1.52 (0.16)
Kd norm(EO, S)	14	0.48 (0.07)	15	0.48 (0.07)	11	0.5 (0.05)	15	0.48 (0.09)
Td (EO, S)	14	140 (22)	15	136 (21)	11	133 (25)	15	125 (18)
W (EO, S+V)	13	0.62 (0.08)	15	0.57 (0.07)	11	0.61 (0.09)	15	0.56 (0.07)
Kp norm(EO, S+V)	13	1.44 (0.18)	15	1.41 (0.1)	11	1.46 (0.17)	15	1.48 (0.15)
Kd norm (EO, S+V)	13	0.47 (0.06)	15	0.45 (0.05)	11	0.48 (0.07)	15	0.49 (0.06)
Td (EO, S+V)	13	151 (24)	15	156 (21)	11	145 (29)	15	146 (27)

SOT = Sensory Organization Test; W = Sensory Weighting; EC, S = eyes-closed, moving surface; EO, S = eyes-open, moving surface; EO, S+V = eyes-open, moving surface and visual surround. ***Large effect; **Moderate effect; *Small effect

Table 10. Effect sizes for pre-post intervention data for vestibular rehabilitation therapy without and with ABF

Variable	Without ABF	With ABF
	Effect Size with Lower and Upper 95% CI	Effect Size with Lower and Upper 95% CI
SOT composite	1.15 (0.73, 2.38) ***	1.01 (0.62, 1.59) ***
W (EC, S)	-0.47 (-0.98, -0.1) *	-0.48 (-1.02, -0.05) *
Kp norm (EC, S)	0.3 (0.05, 0.77) *	0.60 (0.01, 1.37) **
Kd norm (EC, S)	0.43 (-0.1, 1.14) *	0.49 (-0.07, 1.12) *
Td (EC, S)	-0.34 (-0.92, -0.03) *	-0.56 (-1.24, -0.01) **
W (EO, S)	-0.27 (-1.03, 0.09) *	-0.36 (-0.94, 0.22) *
Kp norm (EO, S)	0.22 (-0.24, 0.86) *	0.21 (-0.52, 0.87) *
Kd norm (EO, S)	0.41 (0.04, 1.06) *	0.03 (-0.61, 0.61)
Td (EO, S)	-0.17 (-0.89, 0.39)	-0.52 (-1.18, 0.28) **
W (EO, S+V)	-0.26 (-1.11, 0.28) *	-0.20 (-0.82, 0.42) *
Kp norm (EO, S+V)	0.07 (-0.34, 0.68)	0.56 (0.04, 1.18) **
Kd norm (EO, S+V)	0.21 (-0.34, 0.99) *	0.57 (0.07, 1.14) **
Td (EO, S+V)	-0.24 (-0.92, 0.14) *	-0.41 (-1.16, 0.18) *

SOT = Sensory Organization Test; W = Sensory Weighting; EC, S = eyes-closed, moving surface; EO, S = eyes-open, moving surface; EO, S+V = eyes-open, moving surface and visual surround.

***Large effect; **Moderate effect; *Small effect

Aim 2b: To determine if ABF intervention improves objective summary measures of balance.

To determine if rehabilitation with ABF improves objective summary measures of balance, we evaluated static balance using ML RMS sway during 30 seconds quiet stance, and dynamic balance using gait speed during single and dual-task gait. Data were collected using wearable inertial sensors worn on the lumbar area (for static balance), and the lumbar area, trunk, forehead and both feet for gait. Participants were tested before and after rehabilitation as indicated in Aim 2a, above.

For balance, single-task and dual-task gait, linear mixed effects (LME) models were used to evaluate the fixed effects of group (ABF vs. no ABF) and of time (pre intervention, post intervention, retention), and the group x time interaction. A random intercept and slope by participant was included in the models to adjust for within-subject correlations. The no ABF group was the reference group. Due to the exploratory nature, an alpha level of 0.05 was used.

Balance (evaluation of ML RMS sway)

Results revealed a significant difference group effect ($B_{group} = -0.05$, SE 0.03, $p=0.039$), indicating that groups differed in their baseline testing pre-rehabilitation, with the ABF group initially having less sway prior to initiating rehabilitation (Mean(SD); no ABF_{pre} = 0.132 (0.168) m/s²; ABF_{pre} = 0.078 (0.030) m/s²). Significant time effects were also found ($B_{time\ post} = -0.06$ SE 0.02, $p=0.007$, $B_{time\ retention} = -0.05$ SE 0.02, $p = 0.044$), indicating decreased sway in the reference group (no ABF) in post rehabilitation and retention testing (no ABF_{post} = 0.070 (0.036) m/s²; no ABF_{retention} = 0.084 (0.06) m/s²; ABF_{post} = 0.061 (0.015) m/s²; ABF_{retention} = 0.058 (0.019) m/s²). There were no significant group*time interactions, indicating that both groups improved (decreased sway), but the level of improvement through rehabilitation was not different

between the groups.

Single-task gait speed

No significant group effects were present, indicating gait speed was not different between groups during the pre-rehabilitation testing. (Mean(SD); no ABF_{pre} = 1.22 (0.17) m/s; ABF_{pre} = 1.18 (0.14) m/s). Significant time effects were found for retention ($B_{time\ retention} = 0.10$ SE 0.04, $p=0.005$), indicating increased gait speed in the reference group (no ABF) in retention testing (no ABF_{post} = 1.26 (0.12) m/s; no ABF_{retention} = 1.32 (0.08) m/s; ABF_{post} = 1.24 (0.16) m/s; ABF_{retention} = 1.26 (0.10) m/s). There were no significant group*time interactions, indicating that both groups improved (increased gait speed), but the level of improvement through rehabilitation was not different between the groups.

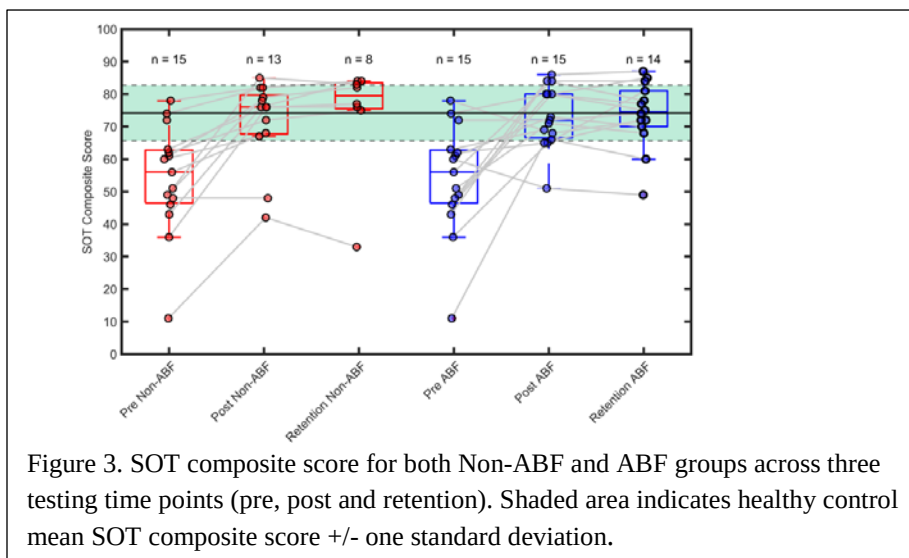
Dual-task gait speed

No significant group effects were present, indicating gait speed was not different between groups during the pre-rehabilitation testing (Mean(SD); no ABF_{pre} = 1.17 (0.16) m/s; ABF_{pre} = 1.14 (0.18) m/s). Significant time effects were found for post and retention ($B_{time\ post} = 0.07$ SE 0.03, $p=0.022$, $B_{time\ retention} = 0.12$, SE 0.03, $p<0.002$), indicating increased gait speed in the reference group (no ABF) in post rehabilitation and retention testing (no ABF_{post} = 1.24 (0.11) m/s; no ABF_{retention} = 1.28 (0.12) m/s; ABF_{post} = 1.20 (0.16) m/s; ABF_{retention} = 1.22 (0.13) m/s). Again there were no significant group*time interactions, indicating that both groups improved (increased gait speed), but the level of improvement through rehabilitation was not different between the groups.

Interpretation

Taken together, across measures of balance and gait, both groups (no ABF and ABF) improved with rehabilitation, as revealed by significant time effects. Interestingly, for ST gait, effects of time indicated significant increases in gait speed for the no ABF (reference group) for retention only. For balance and DT gait, improvements (less sway, faster gait) were still present at retention.

Aim 2c: To determine if people with central sensorimotor integration impairment will show sustained improvement in CSMI scores and balance after rehabilitation, even when ABF is discontinued

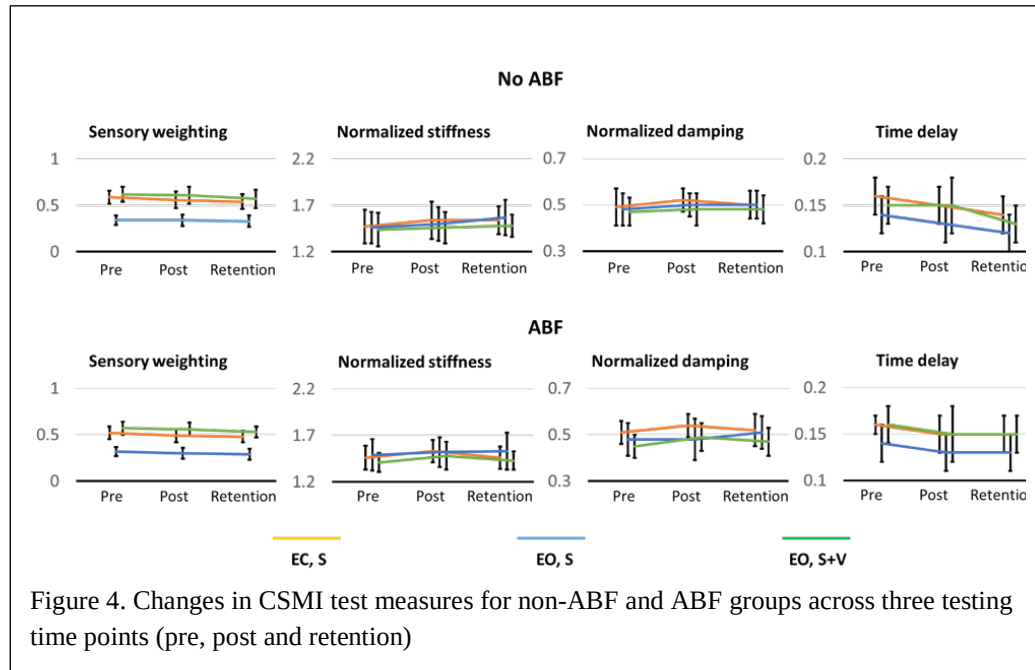


To evaluate whether improvement in central sensory integration and balance were sustained after rehabilitation, we re-evaluated participants during a retention testing session, which was conducted 6-weeks following the conclusion of rehabilitation. Given the small group numbers, we again used effect sizes to provide an estimate of whether there were any

changes between the post-rehabilitation testing session and retention testing. Again, the outcome

measures of interest included the SOT composite score, and CSMI sensory weighting (W), and sensorimotor transformation parameters of normalized stiffness (Kp norm), normalized damping (Kd norm) and time delay (Td). Performance on the SOT, as determined by the SOT composite score for pre, post, and retention testing sessions is provided in Figure 3, and changes in CSMI measures are provided in Figure 4.

Both the non-ABF group and the ABF group improved with rehabilitation (as indicated in Aim 2a), and both groups showed sustained improvement on the SOT. However, there was no indication that the changes across sessions were different between the non-ABF and ABF groups (Figure 3). Pre, post and retention CSMI data (effect sizes) are plotted for both groups, in all 3 conditions in Figure 4. The non-



ABF group showed continued improvement in sensory weighting across all conditions, with small decreases in sensory weighting continuing between post rehabilitation and retention (EC, S: $d = -0.30$, 95%CI -

1.03 to 0.04; EO, S: $d = -0.21$, 95%CI -0.85 to 0.34; EO, S+V: $d = -0.39$, 95%CI -0.99 to -0.11). Normalized damping increased in the non-ABF group only in the EC, S condition only ($d = -0.31$, 95%CI -1.1 to 0.05). In the ABF group, a lack of difference between post and retention data indicated that improvements to sensory weighting were retained 6 weeks after rehabilitation for both EC, S and EO, S conditions. Comparatively, in the EO, S+V condition, the ABF group showed a further small decrease, and thus improvement in sensory weighting ($d = -0.35$, 95%CI -0.8 to 0.07). In the EC, S there was a moderate decrease (improvement) in normalized stiffness ($d = -0.54$, 95%CI -1.11 to -0.23), and in the EO, S+V, the ABF group showed small declines in normalized stiffness ($d = -0.38$, 95%CI -0.87 to 0.03) and damping ($d = -0.32$, 95%CI -0.69 to -0.09). Finally, a small increase in time delay was seen in the EO, S condition ($d = 0.38$, 95%CI -0.07 to 0.89).

Limitations with analysis

Our sample sizes were effected due to the difficulty of the CSMI test and losing participants to follow up. Participant numbers for this analysis are provided in Table 11. Findings should be treated with caution, acknowledging the reduced sample sizes and the exploratory nature of this analysis.

Table 11. Participant numbers per group for each test condition and measure.

Variable	No-ABF N			ABF N		
	Pre	Post	Retention	Pre	Post	Retention
SOT composite	15	13	8	15	15	14
CSMI (EC, S)	13	11	8	15	15	14
CSMI (EO, S)	14	11	8	15	15	14
CSMI (EO, S+V)	13	11	8	15	15	14

Interpretation

Vestibular rehabilitation therapy, whether performed with or without ABF improved balance (as measured by the SOT composite score) and sensory weighting, and these improvements were retained 6 weeks after the conclusion of rehabilitation. This is an important finding since chronic imbalance after mTBI is traditionally thought to be difficult to treat. The moderate decrease in motor activation measures in the ABF group is a novel finding since this aspect of balance control is not directly measured or treated during rehabilitation after mTBI. The CSMI allows for a measurement of this component of balance control and the real-time audio feedback delivered during progressively difficult stance and walking tasks appears to be a good method to improve motor activation.

What opportunities for training and professional development has the project provided?

Our research team has had multiple opportunities to attend national (i.e. MHSRS) and international conferences (i.e. International Society of Posture and Gait Research, ISPGR). These conferences have provided the opportunity for our research team to discuss current and future work, and build domestic and international collaborations.

Military Health System Research Symposium in Kissimmee, Florida

Our team has had continuous attendance at the Military Health System Research Symposium in Kissimmee, Florida. Our representation at this symposium has grown since 2016, and presented a number of different members of the research team the opportunity to present research findings, meet and network with other scientists with overlapping interests and collaborations, resulting in further collaborations including a multi-site Department of Defense funded project (W81XWH-18-2-0049).

- 2016:** Dr. King (PI) attended the symposium and presented preliminary work that this project was founded on.
- 2017:** Dr. King, Dr. Parrington and Dr. Fino (postdoctoral fellows) attended symposium. Drs. Parrington and Fino presented preliminary findings from this study.
- 2018:** Dr. King, Drs. Parrington, Fino and Stuart (postdoctoral fellows), Jim Chesnutt M.D. (Co-I), Natalie Pettigrew (PT) each attended the symposium. Drs. Fino, Stuart and King presented their findings in a platform format, and Dr. Parrington presented a poster on the findings from this study.
- 2019:** Dr. King (PI) and Dr. Martini (postdoctoral fellow) attended the symposium and presented findings from this study.
- 2020:** Dr. Parrington was accepted for a platform presentation to provide data on the findings from Aim 2 of this study, however, the conference was cancelled due to COVID-19.

Annual TBI Symposium: From Research to Recovery

Members of our team have continuously participated in the planning of and presentations at the annual TBI Symposium: From Research to Recovery, and non-presenting members of our team have had the opportunity to attend the symposium and be involved in pre- and post-presentation discussions.

2016: Drs. King and Fino presented preliminary findings at the symposium.

2017: Drs. Parrington and Fino presented preliminary findings on CSMI and turning gait data. A number of experts involved in mTBI research from California, Oregon and Washington attended. Prior to presenting, Dr. King, Dr. Parrington and Dr. Fino attended a lunch to discuss collaborations with other researchers and to gain knowledge in both the current research as well as the clinical approaches to accurately diagnose and treat concussions.

2018: Dr. Parrington presented data from this study on peripheral vestibular, oculomotor and functional turning tasks. Dr. Stuart presented on home monitoring data.

2019: Dr. Martini presented on single and dual task gait data from this study. Prominent mTBI research Dr. Steve Broglio presented research at this symposium, and members of our research team (Drs. King, Martini, Campbell, and Chesnutt) met with Dr. Broglio following the symposium.

Our research team has also continually participated in yearly OHSU Research Week presentations. This has provided the opportunity for our postdoctoral and research based physical therapist team members the opportunity to fine tune their presentation skills. Additionally, it has provided opportunities for our junior team members to develop confidence in presenting research. Most prominently, it provided Research Assistant Mr. Nicholas Kreter and student intern Mr. Josh Koch the opportunity to present research posters in 2018 and 2019, respectively. In 2020, Exito program student Bryana Popa was accepted to give a poster presentation but unfortunately the presentation was not conducted due to COVID-19.

Other conferences:

2016: Dr. King attended two local conferences that addressed the issues of sensory motor integration and gait and balance assessment: 1) the International Symposium on Gait and Balance in Multiple Sclerosis, and 2) the World Parkinson Congress. These conferences involved discussions with internationally known speakers regarding the role of vestibular and proprioceptive information on gait and balance, which are central themes of this project.

Dr. Fino attended the Biomechanics and Neural Control of Movement Conference, allowing Dr. Fino to learn more about neural feedback control, motor coordination strategies, rehabilitation goals, and motor learning paradigms with goals of 1) identifying progress within the past 20 years and 2) outlining a research path for the next 20 years. Dr. Fino attended this meeting to meet with world leaders in sensory feedback control, a key domain to the current grant.

2017: Dr. Fino attended the *American Society of Biomechanics (ASB) annual conference in Boulder, CO* to present a poster on segmental turning velocity and coordination in adults with mTBI. Dr. Fino was also given the opportunity to discuss gait biomechanics with other prominent researchers in the field.

2018: Dr. King presented a summary of the study at the in-person review at *Ft. Detrick, MD*

Dr. King and Dr. Stuart attended the *Federal Interagency Conference on mTBI in Washington, D.C.* Dr. King presented a review of the project (platform) and Dr. Stuart presented a poster on home monitoring data collected in this study.

Drs. King, Parrington and Chesnutt presented a workshop at the *American College of Sports Medicine (ACSM) annual conference in Minneapolis, MN.* Attending and presenting at ACSM provided the opportunity to meet and network with a number of the top sports concussion researchers in the US.

Dr. Fino attended the *ASB annual conference in Rochester, MN* to present a poster on the reliability of the sensory organization test and the central sensorimotor integration (CSMI) test. Attending the ASB on a recurring basis provided Dr. Fino with the opportunity to maintain and grow further networks developed the prior year.

Drs. Parrington and Jehu attended the *North American Society for the Psychology of Sport and Physical Activity in Denver, CO.* Dr. Parrington gave a platform presentation on dual-task gait in our chronic mTBI group, and Dr. Jehu presented on vestibular and oculomotor results in chronic mTBI. Attending and presenting at this conference provided Drs. Parrington and Jehu to explore how areas and knowledge in motor learning and psychology may contribute to work on this project.

2019: Dr. Martini attended and presented a poster at the *ISPGR conference, Edinburgh, Scotland*, which provided him the opportunity to present findings on gait analysis in an international setting, and learn from other experts in the field of posture and gait research.

2021: Dr. Parrington has been accepted to present a virtual presentation at the *APTA Combined Sections Meeting*, which will be held virtually in 2021.

How were the results disseminated to communities of interest?

This study was registered on ClinicalTrials.gov, which is available to the public. This site provides information about the study as well as team contact information.

The results have been disseminated to broad communities of interest, such as:

- Other scientists (e.g. MHSRS, Federal Interagency, NASPSPA, APTA CSM, ASB, ISPGR, and OHSU Research Week)
- Clinician audience (OHSU Ground Rounds, OHSU Primary Care Physician Group, Brain Injury Rehab Center, Columbia Memorial Hospital, Keizer Oregon, Reed College, Oregon Physical Therapy Association PT Education, Oregon Athletic Training Symposium)
- Patient groups (Brain Injury Association of Oregon, International School, and Community Lab Tours)

What do you plan to do during the next reporting period to accomplish the goals?

Not applicable.

4. IMPACT:

What was the impact on the development of the principal discipline(s) of the project?

This project has furthered our understanding of balance deficits in people with chronic complaints of balance deficits after mTBI. Specifically, we focused on the role that sensorimotor integration plays in chronic balance deficits. One of the major findings from this project is that there are multiple and independent domains that should be considered when evaluating a person with chronic non-resolving balance complaints and that objective measures should be implemented alongside subjective complaints. The work we did in generating domains is an important finding since each could be impaired differently, in different people. This could help explain the heterogeneity we see in this population and also could explain poor outcomes in general for people with chronic mTBI. If an impaired domain is not detected, it will therefore not be treated. This project also has a direct impact on rehabilitation of this population. Through the work we have done in showing that some people with mTBI have low motor activation deficits, this opens up a new angle on rehabilitation. Traditionally, vestibular rehabilitation focuses mainly on the sensory aspects whereas the motor activation components are less of a focal point. One reason for this is that motor activation is not directly assessed in the clinic. CSMI measurements revealed lower stiffness and damping in people with mTBI. By using auditory feedback to help the patient reduce postural sway during increasingly difficult motor tasks, we have some evidence that this approach could improve motor activation parameters. This is a challenging population to treat in rehabilitation and our findings provide exciting new information on how different aspects of balance control may improve after rehabilitation, even in the chronically impaired population.

What was the impact on other disciplines?

Our research team meets monthly with an interdisciplinary mTBI group that includes doctors, researchers, neuropsychologists, physical therapists, athletic trainers, audiologists, and affiliated clinicians from other clinics locally. One important impact our work has had is that of Otolaryngology versus Rehabilitation referrals. We found that people with chronic mTBI had abnormal measures in central sensory integration and motor activation scores but did not have abnormal peripheral vestibular function. Referrals to Otolaryngology in this population are most often expensive, time consuming and do not typically improve patient care and outcomes. Conversely, the physical therapy intervention was helpful in the majority of our participants. Our findings have also spurred a collaboration with the Portland VA Audiology Center since they are interested in auditory processing, which has an overlap with our focus on sensory integration. Together, we published a paper “Concussion Management Guidelines Neglect Auditory Symptoms” outlining how auditory function has not traditionally been part of clinical guidelines but many of the people in our study report difficulty with hearing.

What was the impact on technology transfer?

The primary impact on technology transfer was the publication of a methods-based manuscript to Frontiers, special edition: “Current State of Postural Research – Beyond Automatic Behavior”. This paper provides details on how the NeuroCom Clinical Research System™ can be customized for the CSMI protocol. From this publication we have interacted with several outside groups, as well as two companies, interested in incorporating aspects of the CSMI to measure multiple components of sensorimotor integration for balance control. This is something we will continue to pursue. Another impact this study has had is in the area of home monitoring after mTBI. We published a paper showing that quality of movement, measured with inertial sensors in the home after mTBI was more sensitive to classifying people with mTBI compared to quantity of movement. We are working closely with APDM to continue with this approach to measure

daily life function after mTBI using instrumented socks. We recently received a grant from the Medical Research Foundation to look at how the quality of movement in the home changes over the recovery timeline. This project is titled “Can continuous monitoring of mobility with wearable sensors measure recovery after mTBI with and without rehabilitation?”

What was the impact on society beyond science and technology?

We improved public knowledge on mTBI using a variety of methods, including presenting at symposiums, meeting with physicians and physical therapists, distributing fliers, and engaging in direct discussion with patients and their families. Through these interactions, this project will likely influence the perception of chronic balance problems in mTBI and the likelihood of improving symptoms, even in the chronic phase of recovery, with rehabilitation. This will likely have a positive impact on patients, their families and health care professionals, to adequately seek and offer treatment for balance problems.

From 2017- 2020 our team attended the OHSU Brain Fair, an annual event held at the Oregon Museum of Science and Industry (OMSI). The fair is open to the public with approximately 1,000 attendees varying in age. Our research team was able to perform gait and balance demonstrations, educate how wearable sensors can provide objective measures of balance, and the importance of this type of testing in people with chronic balance problems following mTBI. We also had a published blog written about our research that was featured on the OHSU news website in 2018.

Our research team has provided internships and volunteer opportunities for high schools students and undergraduate students throughout the project. We provide them with the opportunity to learn about our study and complete independent projects to help build their knowledge in the area of mTBI, balance and gait. Two students received an award from NIH Build Exito to join our lab for two years to help with this project. Another student received a grant for three months to work in our lab on this project from the Promoting Opportunities for Diversity in Education and Research “Build Poder”. During the summer months we had several student volunteers working on study activities as well.

5. CHANGES/PROBLEMS:

Changes in approach and reasons for change

Nothing to report.

Actual or anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that had a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Nothing to report.

6. PRODUCTS:

Publications, conference papers, and presentations

Published manuscripts:

- Parrington, L., Popa, B., Martini, D. N., Chesnutt, J. C., & King, L. A. (2020). Instrumented balance assessment in mild traumatic brain injury: Normative values and descriptive data for acute, sub-acute and chronic populations. *Journal of Concussion*, 4, 2059700220975605. <https://doi.org/10.1177/2059700220975605>
- Fino, P. C., Raffegeau, T. E., Parrington, L., Peterka, R. J., & King, L. A. (2020). Head stabilization during standing in people with persisting symptoms after mild traumatic brain injury. *Journal of Biomechanics*, 112, 110045. <https://doi.org/10.1016/j.jbiomech.2020.110045>
- Stuart, S., Parrington, L., Morris, R., Martini, D. N., Fino, P. C., & King, L. A. (2020). Gait measurement in chronic mild traumatic brain injury: A model approach. *Human Movement Science*, 69, 102557. <https://doi.org/10.1016/j.humov.2019.102557>
- Martini, D. N., Parrington, L., Stuart, S., Fino, P. C., & King, L. A. (2020). Gait performance in people with symptomatic, chronic mild traumatic brain injury. *Journal of Neurotrauma*. <https://doi.org/10.1089/neu.2020.6986>
- Stuart, S., Parrington, L., Martini, D. N., Kreter, N., Chesnutt, J. C., Fino, P. C., & King, L. A. (2020). Analysis of free-living mobility in people with mild traumatic brain injury and healthy controls: quality over quantity. *Journal of Neurotrauma*, 37(1), 139-145. <https://doi.org/10.1089/neu.2019.6450>
- Peterka, R. J., Murchison, C. F., Parrington, L., Fino, P. C., & King, L. A. (2018). Implementation of a central sensorimotor integration test for characterization of human balance control during stance. *Frontiers in Neurology*, 9, 1045. <https://doi.org/10.3389/fneur.2018.01045>
- Fino, P. C., Wilhelm, J., Parrington, L., Stuart, S., Chesnutt, J. C., & King, L. A. (2019). Inertial sensors reveal subtle motor deficits when walking with horizontal head turns after concussion. *The Journal of Head Trauma Rehabilitation*, 34(2), E74. <https://doi.org/10.1097/HTR.0000000000000418>
- Fino, P. C., Parrington, L., Walls, M., Sippel, E., Hullar, T. E., Chesnutt, J. C., & King, L. A. (2018). Abnormal turning and its association with self-reported symptoms in chronic mild traumatic brain injury. *Journal of Neurotrauma*, 35(10), 1167-1177. <https://doi.org/10.1089/neu.2017.5231>
- Fino, P. C., Peterka, R. J., Hullar, T. E., Murchison, C., Horak, F. B., Chesnutt, J. C., & King, L. A. (2017). Assessment and rehabilitation of central sensory impairments for balance in mTBI using auditory biofeedback: a randomized clinical trial. *BMC Neurology*, 17(1), 41. <https://doi.org/10.1186/s12883-017-0812-7>

Manuscript in press:

- Theodoroff, S.M., Papesh, M., Gallun, F.J., King, L.A., Chesnutt, J.C., Novak, M., Duffield, T.C., Rockwood, R., Palandri, M., & Hullar, T. Concussion management guidelines neglect auditory symptoms. *Clinical Journal of Sport Medicine*.

Submitted manuscripts under peer review:

- Campbell, K.R., Parrington, L., Peterka, R.J., Martini, D.N., Hullar, T.E., Horak, F.B., Fino, P.C., & King, L.A. Balance in patients with chronic mTBI; the role of oculomotor, vestibular, and central sensory integration.

Manuscripts in preparation:

- Parrington, L., Stuart, S.S., Fino, P.F., & King, L.A. Does vestibular rehabilitation improve traditional laboratory measures of balance or home monitoring measures? A look at near and far transfer.
- Parrington, L., Brumbach, B., Campbell, K.R., Martini, D.N., Peterka, R.J., & King, L.A. Exploring sensory integration as a mediator for balance and gait in persons with chronic mTBI.
- Campbell KR, Parrington LP, Geetanjali G, Peterka RJ, & King LA. Rehabilitation of Central Sensory Integration for Balance in People with Chronic Mild Traumatic Brain Injury.

Accepted conference educational session:

- Wearable Sensors and the Instrumented Assessment of Balance and Gait after Concussion. King LA, Parrington L, Chesnutt JC. Presented at the American College of Sports Medicine Conference, Minneapolis, MN. May 2018.
- Scherer M, King LA, Lester M, McCulloch K, & Weightman M. Functional return-to-duty decision making post mTBI and musculoskeletal injury. Combined Sections Meeting, APTA, Washington, DC. January 2019.

Completed conference presentations:

2017:

- Fino PC, Parrington L, Walls M, Sippel E, & King LA. Slower turning velocity and increased coordination variability are associated with self-reported symptoms in adults with mTBI. OHSU Research Week, Oregon Health & Science University, Portland, OR. May 2017. Platform Presentation.
- Parrington L, Fino PC, Peterka R, Chesnutt JC, Walls M, Sippel E, Wilhelm J, Schlimgen J, & King, LA. The effects of rehabilitation on sensory reweighting in patients with chronic mTBI. OHSU Research Week, Oregon Health & Science University, Portland, OR. May 2017. Poster Presentation.
- Fino PC, Parrington L, Walls M, Sippel E, & King LA. Segmental turning velocity and coordination in adults with mTBI. American Society of Biomechanics Conference. Boulder, CO. August 2017. Poster Presentation.
- Fino PC, Parrington L, Walls M, Sippel E, & King LA. Slower turning velocity and increased coordination variability are associated with self-reported symptoms in adults with mTBI. Military Health System Research Symposium, Kissimmee, FL. August 2017. Platform Presentation.
- Parrington L, Fino PC, Peterka R, Chesnutt JC, Walls M, Sippel E, Wilhelm J, Schlimgen J, & King LA. The effects of rehabilitation on sensory reweighting in patients with chronic mTBI. Military Health System Research Symposium, Kissimmee, FL. August 2017. Platform Presentation.
- Parrington, L. The effects of rehabilitation on sensory reweighting in patients with chronic mTBI. TBI Symposium: From Research to Recovery. Oregon Health & Science University, Portland, OR. September 2017. Platform Presentation.
- Fino, PC. Abnormal turning and its association with symptoms in chronic mTBI. TBI Symposium: From Research to Recovery. Oregon Health & Science University, Portland, OR. September 2017. Platform Presentation.

2018

- Parrington L, Fino PC, Peterka R, Chesnutt JC, Walls M, Sippel E, Wilhelm J, Schlimgen J, & King LA. Rehabilitation and sensory reweighting in patients with chronic mTBI. Combined Sections Meeting, New Orleans, LO. February 2018. Platform Presentation (presented by King).
- Jehu DA, Kampel S, Stuart S, Parrington L, Fino P, Hullar T, & King LA. Vestibular function following chronic mild traumatic brain injury: examining the association between otolith function, sensorimotor integration, and posture. OHSU Research Week, Oregon Health & Science University, Portland, OR. April 2018. Platform Presentation.
- Parrington L, Duffield T, Fino PC, & King LA. Dual-task cost and cognition in patients with chronic mTBI. North American Society for the Psychology of Sport and Physical Activity Conference, Denver, CO. June 2018. Platform Presentation.
- Jehu DA, Kampel S, Parrington L, Fino P, Hullar T, & King LA. Vestibular function following chronic mild traumatic brain injury (mTBI): Cervical vestibular-evoked myogenic potential parameters, convergence, and symptoms discriminated between mTBI patients and healthy controls. North American Society for the Psychology of Sport and Physical Activity Conference, Denver, CO. June 2018. Platform Presentation.
- Stuart S, Fino P, Parrington L, Chesnutt JC, & King LA. Turning the tide: Real-world turns are more sensitive to mild traumatic brain injury deficits than daily activity measures. 4th Federal Interagency Conference of Traumatic Brain Injury, Washington, DC. June 2018. Poster Presentation.
- Parrington L, Fino PC, Reterka RJ, Kreter N, & King LA. (August 2018). Test-retest reliability of the sensory organization test and central sensorimotor integration (CSMI) test. American Society of Biomechanics Conference, Rochester, MN. Poster Presentation (presented by Fino).
- Stuart S, Fino P, Parrington L, Jehu D, Chesnutt JC, & King LA. Free-living mobility improves with vestibular rehabilitation following mild traumatic brain injury. Military Health System Research Symposium, Kissimmee, FL. August 2018. Platform Presentation.
- Fino P, Parrington L, Stuart S, Jehu D, Chesnutt JC, & King LA. Improvements in turning speed but not gait speed in people with mild traumatic brain injury following vestibular rehabilitation. Military Health System Research Symposium, Kissimmee, FL. August 2018. Platform Presentation.
- Jehu DA, Fino PC, Parrington L, Kampel S, Peterka RJ, Hullar T, & King LA. Assessment of balance after mild traumatic brain injury: Are vestibular and ocular-motor testing capturing all balance deficits? Military Health System Research Symposium, Kissimmee, FL. August 2018. Platform Presentation (presented by King).
- Parrington L, Kreter N, Fino PC, Peterka RJ, & King LA. Central sensorimotor integration test: Test-retest reliability and learning effects. Military Health System Research Symposium, Kissimmee, FL. August 2018. Poster Presentation.
- Wilhelm JL, Parrington L, Pettigrew NC, Chesnutt JC, & King LA. Exploring outcome measures after vestibular rehabilitation in chronic concussion patients. International Conference for Vestibular Rehabilitation, Chicago, IL. August 2018. Poster Presentation.
- Kreter N, Parrington L, Pettigrew N, Peterka R, & King LA. Test-retest reliability of systems assessing sensory contributions to balance. International Conference for Vestibular Rehabilitation, Chicago, IL. August 2018. Poster Presentation.

- Parrington L, Stuart S, Jehu D, Huller T, Kampel S, & King LA. Sensory weighting in chronic mTBI with vestibular dysfunction. Society for Neuroscience, San Diego, CA. November 2018. Poster Presentation (presented by King).

2019:

- Koch, J, Parrington, L, & King, L. Gait velocity variances in chronic mild traumatic brain injury (mTBI) subjects through single and dual-task activity. OHSU Research Week, Oregon Health & Science University, Portland, OR. May 2019. Poster Presentation.
- Martini, D, Parrington, L, Kreter, N, Chesnutt, J, & King, L. Assessing the relationship between symptom severity and gait performance in a symptomatic, chronic mTBI population before and after vestibular rehabilitation. Military Health System Research Symposium, Kissimmee, FL. August 2019. Platform Presentation.
- Martini D, Parrington L, Fino, PC, Peterka R, & King LA. Central sensorimotor integration delays: does response latency to pseudorandom balance perturbations relate to reaction time? International Society of Posture and Gait Research, Edinburgh Scotland. July 2019. Poster Presentation.
- Raffegeau T, Clark M, Parrington L, Peterka R, Chesnutt J, King LA, & Fino PC. Sensory contributions to head and lumbar sway in healthy individuals and those with mild traumatic brain injury. International Society of Posture and Gait Research, Edinburgh Scotland. July 2019. Poster Presentation.

Accepted conference abstract:

- Peterka RJ, Campbell KR, Parrington L, & King LA. Deficits in standing balance control in mTBI subjects with chronic balance complaints. Vestibular Oriented Research Meeting. 2021. Accepted as Podium Presentation.
- Parrington L, Fino PC, Campbell K, & King LA. Effects of vestibular rehabilitation on sensory integration and turning in people with chronic mTBI. Combined Sections Meeting. 2021. Accepted as Podium Presentation.

Submitted conference abstracts cancelled due to COVID-19:

- Parrington L, Pettigrew N, Stuart S, Fino PC, & King LA. Effects of vestibular rehabilitation on measures of daily function in people with persistent balance complaints following mTBI. Military Health System Research Symposium (2020). (Platform: canceled due to COVID-19).
- Martini DN, Parrington L, Campbell K, Chesnutt J, & King LA. Gait variability and cognition in people with a mild traumatic brain injury. Military Health System Research Symposium (2020). (Poster: canceled due to COVID-19).
- Campbell KR, Parrington L, Hullar TE, Peterka RJ, Horak FB, & King LA. Quantifying peripheral vestibular and balance abnormalities in people with chronic dizziness and imbalance following mild traumatic brain injury. Vestibular Oriented Research Meeting. Toronto, ON. CAN (2020). (Poster: canceled due to COVID-19).

Community presentations:

- Chesnutt, JC, "The Medical Perspective of TBI. Brain Injury: Clinical Implications across the Spectrum of Care", October 30 2018, Keizer Oregon.
- Wilhelm JL, Chesnutt JC: "Updates on Concussion Rehabilitation", March 15 2019, Reed College.

- Wilhelm JC, Chesnutt JC: “Active Concussion Rehabilitation”, April 12 2019, Columbia Memorial Hospital.
- Wilhelm JC, Pettigrew N, Stuart S: “Updates on Concussion Rehabilitation”, April 25 2019, Oregon Physical Therapy Association PT Education.
- Wilhelm JL, Rockwood R: “Updates in Concussion Assessment and Rehabilitation”, June 8 2019, Oregon Athletic Training Symposium.

Community outreach event (1000 attendees):

- OMSI Brain Fair, March 11th 2017, Portland Oregon.
- OMSI Brain Fair, March 10th 2018, Portland Oregon.
- OMSI Brain Fair, March 16th 2019, Portland Oregon.
- OMSI Brain Fair, March 7th 2020, Portland Oregon.

Website(s) or other Internet site(s)

In 2017

- Blog post on the OHSU Brain Institute site providing a lay explanation of preliminary findings from the study:
Lucy Parrington; OHSU research targets chronic balance dysfunction in mTBI patients. OHSU Brain Institute blog post <http://www.ohsu.edu/blogs/brain/2017/09/21/ohsu-research-targets-chronic-balance-dysfunction-in-mtbi-patients/>
- OHSU Brain Institute (@OHSUBrain) Twitter feed and link to OHSU Brain Institute blog post indicated above.
OHSU Brain Institute Twitter feed
<<https://twitter.com/OHSUBrain/status/911252002100977664>>

In 2018

- Our research was featured on the OHSU news website:
Erik Robinson: Traumatic brain injury is ‘incredibly isolating’ blog post:
<https://news.ohsu.edu/2018/06/20/traumatic-brain-injury-is-incredibly-isolating>

Technologies or techniques

- Peterka, R. J., Murchison, C. F., Parrington, L., Fino, P. C., & King, L. A. (2018). Implementation of a central sensorimotor integration test for characterization of human balance control during stance. *Frontiers in Neurology*, 9, 1045. <https://doi.org/10.3389/fneur.2018.01045>
- Mancini M, Stuart S, King LA, El-Gohary M, & Horak F. (2018). Wearable technologies: from theory to clinical practice. *IEEE Conference on Biomedical and Health Informatics and Body Sensor Networks*.
- Mancini M, Stuart S, King LA, El-Gohary M, & Horak FB. Wearable technology: from theory to clinical practice. *Institute of Electrical and Electronics Engineers (IEEE) International Conference on Biomedical and Health Informatics Symposium*, Las Vegas, NV. March 2018. Platform Presentation.

Inventions, patent applications, and/or licenses

Nothing to report.

Other products

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS:

What individuals have worked on the project?

Heather Belding	Robert Peterka
Emily Sippel	Timothy Hullar
Merissa Walls	Jim Chesnutt
Peter Fino	Fay Horak
Sam Gordon	Laurie King
Shelia Markwardt	Alexa Beeson
Marco Juado	Lucy Parrington
Sean Kampel	Nick Kreter
Edward King	Natalie Pettigrew
Jennifer Wilhelm	Samuel Stuart
Daniel Putterman	Shelby Martin
Sharna Donovan	Josh Koch

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

Nothing to report

What other organizations were involved as partners?

Nothing to report

8. SPECIAL REPORTING REQUIREMENTS

None

9. APPENDICES

APPENDIX A. Manuscript under review: Exploring persistent complaints of imbalance after mTBI: oculomotor, peripheral vestibular and central sensory integration function

APPENDIX B. Conference abstracts

APPENDIX A. Manuscript under review: Exploring persistent complaints of imbalance after mTBI: oculomotor, peripheral vestibular and central sensory integration function

Title: Exploring persistent complaints of imbalance after mTBI: oculomotor, peripheral vestibular and central sensory integration function

Kody R. Campbell^{a*}, Lucy Parrington^a, Robert J. Peterka^b, Douglas N. Martini^c, Timothy E. Hullar^{b,d}, Fay B. Horak^a, James C. Chesnutt^e, Peter C. Finof^f, and Laurie A. King^a

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^eDepartments of Family Medicine, Neurology, and Orthopedics & Rehabilitation, Oregon Health and Science University, Portland, OR, USA

^fDepartment of Health and Kinesiology, University of Utah, Salt Lake City, UT, USA

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Abstract

BACKGROUND: Little is known on the peripheral and central sensory contributions to persistent dizziness and imbalance following mild traumatic brain injury (mTBI).

OBJECTIVE: To identify peripheral vestibular, central integrative, and oculomotor causes for chronic symptoms following mTBI.

METHODS: Individuals with chronic mTBI symptoms and healthy controls (HC) completed a battery of oculomotor, peripheral vestibular and instrumented posturography evaluations and rated subjective symptoms on validated questionnaires. We defined abnormal oculomotor, peripheral vestibular, and central sensory integration for balance measures among mTBI participants as falling outside a 10-percentile cutoff determined from HC data. A X-squared test associated the proportion of normal and abnormal responses in each group. Partial Spearman's rank correlations evaluated the relationships between chronic symptoms and measures of oculomotor, peripheral vestibular, and central function for balance control.

RESULTS: The mTBI group (n=58) had more abnormal measures of central sensory integration for balance than the HC (n=61) group (mTBI: 41% – 61%; HC: 10%, p 's < 0.001), but no differences on oculomotor and peripheral vestibular function (p > 0.113). Symptom severities were negatively correlated with central sensory integration for balance scores (p 's < 0.048).

CONCLUSIONS: Ongoing balance complaints in people with chronic mTBI are explained more by central sensory integration dysfunction rather than peripheral vestibular or oculomotor dysfunction.

1. Introduction

Although symptoms often resolve for people that sustain a mild traumatic brain injury (mTBI) within a month, between 11% to 64% of people can experience a wide range of persistent symptoms including headaches, slowed thinking, and forgetfulness [35, 41, 46]. These persistent symptoms can directly impact daily function and quality of life [7, 44]. A common, persistent symptom is imbalance, with approximately 28% of people reporting imbalance more than a year following their injury [48]. The cause of imbalance after mTBI is poorly understood, making clinical management challenging [6, 40]. In the months following an injury, this patient population may seek care from primary care physicians, sports medicine physicians, athletic trainers, physical therapists, neurologists, and otolaryngologists for vestibular evaluations [6, 29, 40]. These practitioners may employ a variety of assessment approaches, ranging from self-reported symptom questionnaires to sophisticated vestibular laboratory tests [6]. Determining objective findings for ongoing balance complaints would be helpful in directing care for chronic, non-resolving balance complaints.

In order to maintain balance, sensory information from visual, vestibular, and somatosensory systems must be integrated in the brain [23, 38]; disruptions to any of these systems can impair balance. There is evidence that several of these systems may be compromised after acute mTBI [21]. For example, after mTBI, there are several reports of impaired oculomotor function including saccadic eye movements, and impaired smooth pursuit [10, 19, 20, 33, 43]. However, the majority of these deficits have only been reported in the acute recovery phase following sport-related concussion and in younger ages [10, 33]. Because chronic mTBI symptoms can affect a wide range of ages, and because the oculomotor quality can decrease with aging, it is important to determine the contribution of impaired oculomotor function to balance impairments in older people with mTBI [12].

The contribution of peripheral vestibular disruption system to chronic balance impairments after mTBI in older people is also unclear [2]. A recent review reported inconsistent

findings regarding whether individuals with mTBI have abnormal semicircular canal function (3 to 51%) as identified with caloric testing [2]. However, this review predominantly presented results of military personnel, where the prevalence of mTBI due to blast is high [37]. The brain injury mechanics due to primary blast are different than injuries to the civilian population such as blunt head trauma from motor vehicle accidents, falls, or sport, which may affect peripheral vestibular structures differently [30]. Like damage to the semicircular canals, studies of the effects of mTBI on the otoliths have been limited primarily to people in the military who often sustain blast injuries [2, 31, 32]. Furthermore, there are conflicting results on whether people with mTBI have impaired semicircular canal function when tested with video head impulse test (vHIT) [3, 5, 27]. These previous studies using the vHIT to identify impaired semicircular canal function post injury were with younger populations that were tested in the acute phase of mTBI recovery, so abnormalities of semicircular canal function in the chronic phase of mTBI in relatively older adults is unknown.

Like visual and peripheral vestibular function, central sensory integration deficits affecting balance control following mTBI have been primarily reported in current and former service members and not the general population [18, 32, 47]. Not only does balance control require correct sensory information from peripheral sources, but also central sensorimotor integration [23, 39]. Proper sensory integration relies on the central nervous system to select the optimal combination of sensory sources for balance and to reweight the sensory contributions as sensory conditions change [39]. Most often measured using the sensory organization test (SOT), an instrumented balance test representative of central sensory integration, people in the acute and subacute phases of recovery have lower composite scores compared with normative data [15, 34, 42]. There is also evidence that sensory integration deficits affecting standing balance can persist beyond 6 months from the initial injury in military populations [18, 31, 32, 47], but this has not been observed in the general, non-blast population. For central sensory integration processes required for balance, cognitive factors may affect results. For example,

post-traumatic stress disorder (PTSD) can complicate the relationship between central sensory integration and balance function. In fact, service members with PTSD had more abnormal SOT balance scores than service members without a PTSD diagnosis, even when they did not suffer a mTBI [31, 47]. PTSD has a distinct affect on sensory integration for balance that has not been examined in the civilian population [47]. Thus, PTSD symptoms should be considered with respect to balance measurements in people suffering from chronic mTBI symptoms.

Understanding persistent imbalance following mTBI in the general population would ideally include a simultaneous analysis of peripheral and central factors, but this has not been done in the civilian population [31, 32]. Therefore, the purpose of this study was to explore the peripheral and central basis for persistent complaints of imbalance in the civilian, non-blast injured population. To do this, we: 1) compared oculomotor, peripheral vestibular and central sensory integration in people with chronic mTBI with healthy controls; 2) determined the relationship between measures of peripheral and central function for balance control in chronic mTBI, and 3) determined the relationship between chronic mTBI symptoms and measures of peripheral and central function for balance control.

2. Methods

2.1. Participants

People with chronic mTBI ($n = 58$) and healthy age- and sex-matched controls ($n = 61$) participated in the study. Demographic details are given in Table 1. All study participants gave written informed consent and the Oregon Health & Science University and Veterans Affairs Portland Health Care System joint institutional review board approved recruitment procedures and experimental protocols. These participants were recruited for a larger study aimed at assessing and providing rehabilitation of central sensory impairments for balance after mTBI (NCT02748109).

Participants were included if they: 1) were between 18 and 60 years old, 2) had minimal-to-no cognitive deficits indicated by a Short Blessed Test score ≤ 8 , and 3) were >3 months post

mTBI with non-resolving balance complaints (for mTBI group); or 4) had no history of brain injury in the prior year (for control group). Participants were excluded if they had: 1) a previous or current musculoskeletal injury, surgery, medication, or neurological illness that would influence balance, 2) a pre-existing or current peripheral vestibular/ oculomotor pathology for control participants or a pre-existing peripheral vestibular/oculomotor pathology for the mTBI participants, or 3) moderate to severe substance abuse. We excluded participants with a history of blast exposure in the current study. Broader study protocol, including definitions for mTBI, mTBI diagnosis confirmation, and additional inclusion and exclusion criteria were detailed in a previous publication [14].

2.2. Symptom Assessment

All participants completed the Neurobehavioral Symptom Inventory (NSI) and the Dizziness Handicap Inventory (DHI) prior to peripheral vestibular, oculomotor, and balance evaluations. The NSI assesses how much a participant was disturbed in the last two weeks due to their post-concussion symptoms on a scale ranging from 0 (none) to 4 (very severe). The NSI is comprised of a total score and sub scores (vestibular, somatic, cognitive, and affective) and has good internal consistency and stability [8, 26]. The DHI assesses the functional, emotional, and physical effects of dizziness using a 25 item questionnaire [25, 45]. Participants rated each item according to the perceived handicap caused by their dizziness using 0 (no handicap), 2 (sometimes), or 4 (yes). We used the total and sub scores from the NSI and DHI as our outcome variables. Participants rated PTSD symptoms using the PTSD Checklist [49]. The scale has 17 items with a self-rating response to stressful situations using a scale ranging from not at all (1) to extremely (5).

2.3. Peripheral Vestibular and Oculomotor Evaluations

Participants completed a vestibular and oculomotor test battery in the following order: 1) horizontal video head impulse test (vHIT), 2) cervical vestibular evoked myogenic potential (cVEMP) test, 3) ocular vestibular evoked myogenic potential (oVEMP) test, 4) horizontal

random saccades, 5) horizontal smooth pursuits, 6) the Dix-Hallpike maneuver for benign paroxysmal positional vertigo (BPPV) screening, and 7) bithermal caloric tests. Testing equipment and procedures are outlined in **Supplementary Table 1** and a brief explanation of the tests are in the following paragraphs. Prior to this testing battery, a certified audiologist performed otoscopy to inspect the participant's ear canals and tympanic membrane for obstacles and abnormalities, such as impacted cerumen. If excessive cerumen was found it was not removed prior to peripheral vestibular assessment but was noted and incorporated into subsequent evaluation of data quality.

All participants completed 20 trials of the vHIT test with both rightward and leftward head rotations. Individual trials with artifacts were discarded [28]. Our vHIT outcomes were the vestibulo-ocular reflex (VOR) gain averaged across rightward and leftward head rotations, and the VOR average gain asymmetry between rightward and leftward head rotations.

VEMP tests measured short latency electromyographic (EMG) potentials in response to acoustic tone-bursts presented at 95 dB above a normal adult hearing level to individually test ears. Additional testing parameters for VEMP tests are in supplementary table 2. For the cVEMP test, EMG potentials were measured on the ipsilateral sternocleidomastoid muscle to the tested ear. For the oVEMP test, EMG potentials were measured on the contralateral infraorbital muscle to the tested ear. EMG electrodes were placed according to previous studies [32]. Each ear was tested separately and at least 2 trials in each ear were needed to verify a replicable response. Replicated peak-to-peak amplitudes of the P13/N23 waveforms were averaged, and asymmetry ratios were calculated between ears. Only participants with measured responses in both ears were considered for statistical analysis.

The Dix-Hallpike maneuver was used to test for right and left side posterior semicircular canal BPPV [11]. Audiologists evaluated the recorded horizontal and vertical eye movements and video recordings to identify patterns of eye movements indicative of BPPV.

Horizontal random saccade testing had the participant track a visual red-dot target that randomly jumped to different horizontal locations along a light-bar during a 45 s test. Eye movement analysis measured the accuracy, peak saccade velocity, and saccade onset latency. Smooth pursuit testing had the participant follow a horizontal sinusoidal target increasing in frequency from 0.2 Hz to 0.7 Hz over the course of approximately 48 s. The analysis software measured the average eye velocity gain of the eye movements and we calculated eye velocity gain asymmetry between rightward and leftward pursuit directions. Left and right eye tracings were averaged for this battery of tests.

Bithermal caloric tests consisted of warm and cold air irrigations to each ear at 7°C above and below body temperature. Recorded eye movements were analyzed to measure the slow-phase eye velocity at the peak of the response. A 5-minute break was provided between each caloric irrigation. We calculated the unilateral weakness percentage (an asymmetry ratio of the peak slow phase velocities between the right and left ear irrigations), and the average peak slow phase velocity from all irrigations. We used data for analysis from participants without excessive cerumen noted and participants that completed all 4 irrigations or only cold irrigations.

2.4. Balance Evaluation

Balance evaluation was performed on a separate day from the peripheral vestibular and oculomotor tests. Participants completed the sensory organization test (SOT) on a NeuroCom SMART Balance Master (Natus, California, USA). Participants performed SOT testing barefoot in a standardized foot position according to their height and completed six SOT conditions (**Supplementary Table 1**), with each condition presented in ascending order, repeated 3 times, and each trial lasting 20 s. The SOT provides an equilibrium score ranging from 0 to 100 for each trial, with 100 indicating perfect stability and 0 indicating that the participant fell, and testing had to halt during that trial. A composite score was calculated as a weighted average of the 6 conditions. Additionally, the SOT provided somatosensory, visual, and vestibular sensory

analysis ratio scores that indicated how participants used these sensory cues to maintain balance [36].

2.5. Statistical Analyses

To compare oculomotor, peripheral vestibular and central sensory integration in people with mTBI compared to healthy controls, we classified responses as abnormal or normal. We quantified an abnormal response for our mTBI group on all our tests according to whether the measures fell outside a 10th-percentile cutoff determined from all healthy control data. A Chi-Squared test associated the proportion of normal and abnormal responses on the oculomotor, peripheral vestibular, and balance test outcomes with health status (healthy control or mTBI).

We used partial Spearman's rank correlations to relate oculomotor and peripheral vestibular function with balance performance for mTBI participants. We used partial Spearman's rank correlations to relate self-reported function on total and subscores for the DHI and NSI with the oculomotor, peripheral vestibular and balance tests, controlling for PTSD and age. Due to the exploratory nature of this study, we used an uncorrected *a priori* alpha of 0.05. The strengths of the relationships (correlation coefficients – r) were quantified as negligible: $r < 0.10$, low: $0.10 < r < 0.30$, moderate: $0.30 < r < 0.50$, and high: $r > 0.50$ [9]. Statistical analyses were conducted in SAS version 9.4.

3. Results

Each test had a different number of participants included in the final analyses due to inability to complete a test or to extraneous variables impacting test results, such as participants wearing mascara during vHIT testing (Total N, **Table 2**). Only 28 participants from the healthy control group and 12 from the chronic mTBI group were able to complete the entire testing battery with quality data sufficient for analysis (See Supplementary **Table 3**). The percentage of control and mTBI participants for which data was available was similar for the two groups on most tests with the exception of caloric and oVEMP tests where fewer mTBI participants had complete results. The primary reason for the reduced number of caloric results was participants

declining the test due to symptom provocation. The primary reason for the reduced number of oVEMP results was the number of participants with excessive cerumen (See Supplementary **Table 3**).

The proportions of participants with normal versus abnormal oculomotor function did not differ between the healthy control and chronic mTBI groups (p 's > 0.113). Of the oculomotor assessments within the mTBI group, smooth pursuit velocity gain had the largest percentage of people with abnormal function, and average saccade velocity had the smallest percentage of people with abnormal function (**Table 2**). Similarly, there were no differences in the proportions of normal and abnormal peripheral vestibular function between the healthy control and chronic mTBI groups (p 's > 0.113). Of the peripheral vestibular assessments within the mTBI group, caloric unilateral weakness had the largest percentage of people with abnormal function, and average VOR gain had the smallest percentage of people with abnormal function (**Table 2**).

The mTBI group had significantly higher proportions of abnormal responses on the SOT composite score and sensory ratio scores than the healthy control group (p 's < 0.001; **Table 2**). The somatosensory ratio score had the largest percentage of abnormalities from the mTBI group, and the vestibular ratio score had the smallest percentage of abnormalities from the mTBI (**Table 2**).

There was one significant relationship between peripheral vestibular function with central sensory integration for standing balance. Specifically, chronic mTBI participants with larger cVEMP asymmetries had significantly lower visual sensory ratio scores ($p = 0.032$; **Table 3**) and the strength of this relationship was moderate. The remaining peripheral vestibular outcomes and oculomotor outcomes did not significantly relate to SOT composite or sensory ratio scores (p 's > 0.069 and p 's > 0.102, respectively). The strengths for the remaining correlations between the peripheral vestibular and oculomotor testing outcomes with the SOT composite and sensory ratio scores ranged from negligible to moderate (**Table 3**).

Among the oculomotor measures, worse symptom severities reported on the NSI somatosensory subscore had a moderate strength and significant relationship with lower smooth pursuit velocity gains ($p = 0.041$, **Table 4**). Among the peripheral vestibular measures, worse symptom severities reported on the NSI affective subscore had a moderate strength and significant relationship with lower vHIT VOR gains ($p = 0.030$, **Table 4**). Worse symptom severities reported on the DHI physical subscore and the NSI vestibular subscore were significantly correlated with worse performance on the SOT (p 's < 0.048). The strengths for the significant central sensory integration measures with self-reported symptoms ranged from low to moderate (**Table 4**). All correlations of symptom severities with oculomotor, peripheral vestibular and central sensory integration for balance measures are presented in Table 4.

DISCUSSION

The contributions to persistent balance impairments in chronic mTBI are poorly understood. We characterized oculomotor, peripheral vestibular and central sensory integration in people with chronic symptoms of imbalance after mTBI. Our main findings were: 1) People with chronic mTBI typically had normal oculomotor and peripheral vestibular function, but abnormal central sensory integration compared to healthy control participants, 2) Few measures of oculomotor and peripheral vestibular function related to central sensory integration for standing balance, and 3) Self-reported mTBI symptoms were related to most central sensory integration measures for standing balance, but with only a few oculomotor and peripheral vestibular measures. To the authors' knowledge, this is the first publication to characterize extensive oculomotor, peripheral vestibular and central sensory integration for standing balance function in an adult, civilian, non-blast-induced mTBI population with chronic, unresolved balance complaints.

Our finding that there were almost no significant differences in the proportion of normal/abnormal performance on any of the oculomotor or peripheral vestibular tests between control and mTBI groups is not easily compared with existing literature because of the

differences in cohort demographics [2, 31-33]. Differences in inclusion/ exclusion criteria, such as including blast-induced mTBI, and differences in age of the cohorts, complicate effective comparison. For example, it is plausible that military service members subject to blast- and noise-induced trauma (but not other causes of mTBI) may be at increased risk of peripheral vestibular dysfunction, based on histological data in animals [24]. In this study, however, oculomotor and/or peripheral vestibular abnormality did not seem to largely characterize our chronically symptomatic mTBI cohort.

In contrast, there were a higher proportion of abnormal SOT results in people with chronic mTBI compared with healthy control participants, suggesting that differences in central sensory integration may exist in the civilian, non-blast population. This high proportion of abnormal SOT results were also observed in military personnel with TBI from blast exposure [1, 32]. It is also possible that during the time after injury, patients may have developed maladaptive strategies to counter any chronic negative symptoms, and that any maladaptive change over time resulted in a shift in the reliance on certain sensory systems [13, 22]. Longitudinal assessments over months would be required to confirm this notion, but also present the opportunity to test the effectiveness of initiating physical therapy early during the recovery process to help prevent development of potential maladaptive movement strategies.

Although we found almost no relationships between participant self-reported symptoms and oculomotor and peripheral vestibular measures, significant relationships existed between symptoms and central sensory integration measures of balance control. Worse self-reported symptom severity in the DHI physical subscore and NSI vestibular subscore was related to poorer general balance performance (SOT composite scores) and poorer balance when using specific sensory cues to maintain balance (SOT somatosensory, visual and vestibular ratio scores). It should be recognized, however, that our cohort inclusion criteria specifically selected participants with chronic, unresolved balance complaints. Therefore, it is not surprising that existing symptoms would be associated with poorer balance performance. It is important to note

that our subjects had a high symptom load overall on the NSI and DHI total scores, but the strongest relationships were found in the subscales specifically the NSI vestibular and DHI physical subscales.

These findings support our overall finding that oculomotor and peripheral vestibular tests may not provide valuable information for a civilian, non-blast exposed population suffering chronic complaints of imbalance after mTBI and draw into question the utility of these tests in this population. In particular, referral for peripheral vestibular and oculomotor evaluation in this particular population has a low likelihood of informing treatment options while placing increased burden on the patient both financially and by possible exacerbation of symptoms due to the assessments. The vestibular battery can be uncomfortable and difficult to administer. This is exemplified by only 12 participants with mTBI completing the entire vestibular and oculomotor testing battery with sufficient data quality. It was particularly difficult to obtain data from the caloric test with 14 mTBI participants declining to perform the caloric testing, and an additional 4 participants requesting to discontinue with the test after receiving the cold air stimulations. Although our results show that an exhaustive search for peripheral vestibular dysfunction is not typically necessary in patients with chronic imbalance following mTBI, examination for BPPV may nonetheless be worthwhile. Only one participant in our cohort had a positive Dix-Hallpike test. BPPV did not seem to be contributing to the chronic, un-resolving complaints of dizziness and imbalance in this cohort. However BPPV is a common and treatable condition, even in people without head trauma, and can cause generalized imbalance even without pronounced positional symptoms. Particularly because treatment is so easy and usually successful, screening with a Dix-Hallpike test in these patients may be appropriate.

People with ongoing balance concerns following mTBI have measurable balance related problems due to central nervous system disruption without peripheral vestibular or oculomotor disorders that explain the dysfunction. Deficits across each SOT ratio score (visual, somatosensory, and vestibular), indicated balance limitations under varying limited sensory

conditions. Therefore, participants with chronic, disabling balance disorders may benefit from rehabilitation programs that focus on improving central sensory integration and reweighting for balance rather than strategies directed at peripheral sensory problems. With the goal of improving central sensory re-weighting and integration for balance, rehabilitation programs would use a variety of challenging sensory conditions such as removing vision or providing moving visual surrounds, changing surface conditions with compliant foam or unstable or narrow surfaces, or vestibular challenges with head movements and changes of position. Vestibular rehabilitation with balance exercises have been shown to be useful in patients with subacute and chronic symptoms after mTBI with larger improvements in balance and dizziness severity observed in children than in adults [4].

4.1. Limitations

This study had several limitations. First, we had different participant numbers in each test due to the symptom-provoking nature of many of the vestibular assessments in the testing battery, for both the healthy control group but more so in the mTBI group. As a result, there were different participant numbers in each of the tests and consequently in groups statistically analyzed. Additionally, there may be a bias for the vestibular outcomes from the chronic mTBI participants with less severe symptomatology. This could limit the generalizability of the vestibular results to more severe chronic mTBI populations. Second, the fixed order of testing may have resulted in heightened symptoms, fatigue, and/ or disengagement in tests conducted later in the protocol, such as oculomotor and caloric testing, especially in the mTBI group. Third, because not all assessments have established clinical cutoff values for determining abnormal responses, we used our healthy control data to classify normal and abnormal responses on the assessments. Therefore, these cutoff values are somewhat arbitrary and could potentially change if we resampled another healthy control group. It is worth noting that our healthy control derived cutoff values were similar to established clinical cutoff values for peripheral vestibular assessments or were more conservative than established normative data on the SOT [2, 36].

Fourth, technical expertise is required for administering the peripheral vestibular assessments that may have introduced technique-based measurement variability across audiologists. We had four certified audiologists administer the oculomotor and peripheral vestibular testing battery with one audiologist administering 75% of the assessments. This helped to reduce the measurement variability associated with multiple audiologists administering the peripheral vestibular assessments. Lastly, we did not control for multiple comparisons when determining relationships between peripheral vestibular, oculomotor, and central sensory integration for balance function and with participant symptom reporting due to the exploratory nature of this study. Few relationships may remain significant after applying a correction. However our results can provide the groundwork for future investigation into peripheral vestibular and oculomotor contributions to central sensory integration for balance and the relationship among these variables contributing to subjective symptom reporting in chronic mTBI.

5. Conclusions

In summary, few people with chronic mTBI with complaints of imbalance had deficits in their peripheral vestibular or oculomotor function, but over half had impaired central sensory integration for balance control when compared to healthy, age-matched controls. Moreover, worse balance control was related to subjective complaints. These results suggest that patients with persistent imbalance post mTBI should be referred to rehabilitation for balance training and avoid unnecessary initial referrals to otolaryngology or vestibular testing.

Acknowledgements

This study was supported by the Assistant Secretary of Defense for Health Affairs under the Award Number W81XWH-15-0620 and by the National Center for Advancing Translational Sciences, National Institutes of Health, through Grant Award Number UL1TR002369. All interpretations and opinions are those of the author and are not necessarily endorsed by the Department of Defense. The authors would like to thank the research team that contributed to

376 data collection and specifically audiologists Sean Kempel, AuD, Daniel Putterman, AuD, and
377 Marco Jurado, AuD. Study data were collected and managed using REDCap electronic data
378 capture tools hosted at Oregon Health and Science University [16, 17]. REDCap (Research
379 Electronic Data Capture) is a secure, web-based software platform designed to support data
380 capture for research studies, providing 1) an intuitive interface for validated data capture; 2)
381 audit trails for tracking data manipulation and export procedures; 3) automated export
382 procedures for seamless data downloads to common statistical packages; and 4) procedures for
383 data integration and interoperability with external sources.

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TABLES

Table 1: Participant demographics according to the healthy control group and the chronic mild traumatic brain injury (mTBI) group

	Healthy Controls (n = 61)	Chronic mTBI (n= 58)
Age (years)	37.13 (12.64)	39.16 (11.43)
Height (cm)	171.17 (9.50)	170.87 (9.35)
Mass (kg)	74.87 (19.06)	78.34 (19.06)
Sex (M/F)	24 M / 37 F	16 M / 42 F
DHI Total Score (out of 100)	0.66 (2.20)	40.67 (21.27)
NSI Total Score (out of 88)	3.84 (3.97)	36.50 (15.39)
PTSD Checklist Total Score (out of 85)	20.97 (7.11)	39.89 (14.83)
Days Since Injury (median and 1st Quartile, 3rd Quartile)		343 (201, 796)
Injury Mechanism (N and Percent)		
Fall		8 (14%)
Motor Vehicle Accident		31 (53%)
Sport		7 (12%)
Other		12 (21%)

Means and standard deviations are presented unless noted otherwise for days since injury and injury mechanism. DHI – Dizziness Handicap Inventory; NSI – Neurobehavioral Symptom Inventory; PTSD – Post Traumatic Stress Disorder

Table 2: Overview of abnormal and normal oculomotor, peripheral vestibular, and central sensory integration for static balance function for healthy control and chronic mild traumatic brain injury (mTBI) groups.

Parameter	Abnormal Cutoff Value	Healthy Control N Abnormal / Total N (%)	Chronic mTBI N Abnormal / Total N (%)	Chi Square <i>p</i> Value
Oculomotor				
Saccades - Accuracy	< 85 %	5 / 52 (10%)	4 / 50 (8%)	1.000
Saccades - Latency	> 218 ms	6 / 52 (12%)	6 / 50 (12%)	0.942
Saccades - Velocity	< 339 deg/s	6 / 52 (12%)	1 / 50 (2%)	0.113
Smooth Pursuit – Average Velocity Gain	< 0.72	6 / 52 (12%)	7 / 49 (14%)	0.680
Smooth Pursuit - Velocity Gain Asymmetry	> 6 %	6 / 52 (12%)	5 / 49 (10%)	0.830
Peripheral Vestibular				
Caloric - Unilateral Weakness	> 30 %	4 / 49 (8%)	6 / 33 (18%)	0.302
Caloric - Average Slow Phase Velocity	< 9.35 deg/s	5 / 49 (10%)	5 / 33 (15%)	0.733
vHIT - Average VOR Gain	< 0.87	6 / 52 (12%)	1 / 49 (4%)	0.113
vHIT - VOR Gain Asymmetry	> 8% %	6 / 52 (12%)	7 / 49 (14%)	0.680
cVEMP - Asymmetry	> 31 %	5 / 49 (10%)	3 / 40 (8%)	0.726
oVEMP - Asymmetry	> 39 %	4 / 41 (10%)	5 / 29 (17%)	0.473
Central Sensory Integration				
<i>SOT - Composite Score</i>	< 61.8	6 / 60 (10%)	<i>28 / 54 (52%)</i>	<i>< 0.001</i>
<i>SOT - Somatosensory Ratio</i>	< 93.1	6 / 60 (10%)	<i>33 / 54 (61%)</i>	<i>< 0.001</i>
<i>SOT - Visual Ratio</i>	< 55.5	6 / 60 (10%)	<i>23 / 54 (43%)</i>	<i>< 0.001</i>
<i>SOT - Vestibular Ratio</i>	< 35.5	6 / 60 (10%)	<i>22 / 54 (41%)</i>	<i>< 0.001</i>

Abnormal cutoff values were derived from 10 percentile cutoffs calculated from healthy control data. Parameters bolded and italicized indicates a significant difference in the proportion of abnormal function for the mTBI group compared to the healthy control group ($p < 0.05$). N – number of participants; vHIT – video Head Impulse Test; VOR – Vestibular Ocular Reflex; cVEMP – cervical vestibular evoked myogenic potential; oVEMP – ocular vestibular evoked myogenic potential; SOT – Sensory Organization Test.

Table 3: Partial Spearman's rank correlations (*r* values) relating oculomotor and peripheral vestibular function with central sensory integration function.

		Sensory Organization Test		
Parameter	Composite Score	Somatosensory Ratio Score	Visual Ratio Score	Vestibular Ratio Score
Oculomotor				
Saccades – Accuracy (N = 46)	0.08	0.14	0.12	0.07
Saccades – Latency (N = 46)	-0.21	-0.05	-0.12	-0.06
Saccades – Velocity (N = 46)	-0.10	0.02	-0.03	-0.11
Smooth Pursuit – Average Velocity Gain (N = 45)	0.09	0.25	0.04	0.08
Smooth Pursuit - Velocity Gain Asymmetry (N = 45)	-0.12	-0.02	-0.01	-0.12
Peripheral Vestibular				
Caloric - Unilateral Weakness (N = 33)	0.02	0.07	-0.01	-0.12
Caloric - Total Slow Phase Velocity (N = 33)	0.06	0.30	0.12	-0.11
vHIT - Average VOR Gain (N = 49)	0.10	0.15	0.08	0.05
vHIT - VOR Gain Asymmetry (N = 49)	0.01	-0.02	0.09	0.01
cVEMP - Asymmetry (N = 37)	-0.31	-0.21	-0.36*	-0.27
oVEMP - Asymmetry (N = 26)	0.17	-0.08	0.16	0.19

* - Parameters bolded and italicized indicates a significant partial Spearman's rank correlation coefficient (*r*) within the mTBI group ($p < 0.05$). N – number of participants; vHIT – video Head Impulse Test; VOR – Vestibular Ocular Reflex; cVEMP – cervical vestibular evoked myogenic potential; oVEMP – ocular vestibular evoked myogenic potential.

Table 4: Partial Spearman's rank correlations (*r* values) relating subjective symptom scores for the DHI and NSI with oculomotor, peripheral vestibular, and central sensory integration assessments.

Parameter	Func	DHI			Total	Somat	Affect	NSI		Total
		Emot	Phys					Cog	Vest	
Oculomotor										
Saccades – Accuracy (N = 46)	-0.19	-0.22	-0.20	-0.26	-0.21	-0.11	-0.14	0.09	-0.20	
Saccades – Latency (N = 46)	-0.04	0.01	0.03	0.00	0.13	-0.17	-0.10	0.14	0.01	
Saccades – Velocity (N = 46)	-0.18	-0.15	-0.08	-0.17	-0.11	0.13	0.05	0.01	0.01	
Smooth Pursuit – Average Velocity Gain (N = 45)	-0.23	-0.29	-0.07	-0.23	-0.31*	0.15	-0.07	0.01	-0.13	
Smooth Pursuit - Velocity Gain Asymmetry (N = 45)	0.08	0.22	0.01	0.12	0.11	-0.13	-0.30	-0.17	-0.14	
Peripheral Vestibular										
Caloric - Unilateral Weakness (N = 33)	0.03	0.09	0.07	0.12	0.31	0.17	0.13	0.13	0.23	
Caloric - Total Slow Phase Velocity (N = 33)	0.22	0.30	-0.01	0.16	-0.13	-0.22	-0.07	-0.11	-0.19	
vHIT - Average VOR Gain (N = 49)	0.05	0.00	0.19	0.12	-0.22	-0.31*	-0.10	-0.01	-0.26	
vHIT - VOR Gain Asymmetry (N = 49)	-0.08	-0.14	-0.03	-0.08	-0.07	-0.18	-0.18	-0.09	-0.26	
cVEMP - Asymmetry (N = 37)	0.05	-0.09	0.14	0.02	0.14	-0.21	-0.01	0.03	-0.02	
oVEMP - Asymmetry (N = 26)	0.19	0.13	0.24	0.21	0.13	-0.24	0.12	0.20	0.04	
Central Sensory Integration										
SOT - Composite Score (N = 55)	-0.05	-0.17	-0.33*	-0.20	-0.13	0.06	-0.04	-0.29*	-0.14	
SOT - Somatosensory Ratio (N = 55)	0.01	-0.18	-0.25	-0.16	-0.14	0.01	-0.17	-0.33*	-0.23	
SOT - Visual Ratio (N = 55)	-0.08	-0.24	-0.34*	-0.24	-0.14	0.01	-0.17	-0.31*	-0.22	
SOT - Vestibular Ratio (N = 55)	-0.07	-0.22	-0.32*	-0.22	-0.05	0.08	-0.01	-0.28*	-0.07	

* - Parameters bolded and italicized indicates a significant partial Spearman's rank correlation coefficient (*r*) within the mTBI group ($p < 0.05$). N – number of participants; vHIT – video Head Impulse Test; VOR – Vestibular Ocular Reflex; cVEMP – cervical vestibular evoked myogenic potential; oVEMP – ocular vestibular evoked myogenic potential; SOT – Sensory Organization Test; DHI – Dizziness Handicap Inventory; NSI – Neurobehavioral Symptom Inventory; Func – Functional; Emot – Emotional; Phys – Physical; Somat – Somatosensory; Affect – Affective; Cog – Cognitive; Vest – Vestibular.

Slower turning velocity and increased coordination variability are associated with self-reported symptoms in adults with mTBI

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In daily activity, turning is common and requires rapid, coordinated reorientation of the head and trunk towards the new direction of travel. Yet, turning gait has not been well explored in populations with mTBI. We hypothesized that individuals with mTBI would reduce their reorientation velocity and increase the variability of head-to-trunk coordination compared to controls, and that reduced velocity and increased variability would be associated with their self-reported symptom score. Ten adults with mTBI and 25 controls provided informed consent. All mTBI participants had complaints of imbalance and a diagnosed mTBI for >3 months. Participants completed the Neurobehavioral Symptom Inventory (NSI) before walking 12 self-paced laps around a course containing various turns. Inertial sensors over the forehead and lumbar region collected angular velocities of the head and trunk, respectively. Linear mixed models compared the peak angular velocities of each turn between groups after adjusting for covariates of turning angle and walking speed. Independent sample t-tests compared coordination variability between groups. Pearson correlation coefficients compared the relationship between each outcome and NSI symptom scores in the mTBI group. After adjusting for walking speed and turning angle, participants with mTBI had slower peak angular velocities of the head ($p=0.01$) and trunk ($p<0.01$) compared to the control group. Head-trunk coordination variability was higher in mTBI participants ($p<0.01$). Slower head velocity and increased coordination variability were strongly associated with NSI symptom scores ($p<0.01$, $p<0.01$). The association of turning outcomes to symptoms suggests individuals with mTBI change reorientation patterns to minimize the exacerbation of symptoms.

The effects of rehabilitation on sensory reweighting in patients with chronic mTBI

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Keywords: mTBI, balance, sensorimotor integration, rehabilitation

This abstract presents preliminary findings assessing the effects of targeted rehabilitation on sensory weighting in patients with chronic balance impairment following mTBI. Patients with chronic imbalance complaints after mTBI ($n=4$) and controls with no recent history of mTBI ($n=7$) were recruited through Oregon Health & Science University and VA Portland Health Care System. Sensory weight scores were measured using a novel test of central sensorimotor integration. This procedure provides an indication through weight scores, which allow the evaluation of reliance on proprioceptive, vestibular or visual systems. Following baseline testing, patients were enrolled into a rehabilitation program (2x/week for 6 weeks) focused on maintaining balance under changing sensory conditions with increasing levels of difficulty. Follow-up testing was conducted at the conclusion of the intervention for people with mTBI and six weeks after baseline testing in controls, to establish stability of the measure. Changes in sensory weight scores were assessed using Cohen's d effect sizes. Large effects in the first two conditions tested suggest changes in vestibular and combined vestibular/visual weight in the rehabilitation group ($d=0.86$, $d=1.87$, respectively) but not in controls ($d=0.08$, $d=0.09$, respectively). Small and medium effects were found following rehabilitation for combined proprioception/vestibular systems ($d=0.43$) and vestibular system with conflicting visual/proprioceptive information ($d=0.69$), while only small effects were noted in the controls ($d=0.30$, $d=0.42$, respectively). Results suggest that people with chronic mTBI may be able to change the level of reliance on proprioceptive, vestibular or visual systems, which has practical applications for rehabilitation in patients suffering ongoing balance impairment.

SEGMENTAL TURNING VELOCITY AND COORDINATION IN ADULTS WITH MTBI

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INTRODUCTION

Abnormal standing balance and straight gait have been widely documented in individuals following mild traumatic brain injury (mTBI) [1]. Yet, daily activities require complex movements that involve change of direction and coordinated head and trunk reorientation [2]. Sport-related concussion has been associated with increased coordination variability during unplanned turns [2] and decreased center-of-mass speed and curvature when walking around an obstacle [3], but planned turning tasks have not been well explored in populations with mTBI. In particular, it is unclear whether turning performance is associated with self-reported symptoms in individuals with mTBI. As rapid head movements can exacerbate symptoms, individuals reporting mTBI symptoms may limit the velocity of reorientation based on their symptoms. We hypothesized that individuals with mTBI would reduce their reorientation velocity and increase the variability of head-to-trunk coordination during planned turns compared to controls. Further, we hypothesized that the reduction in the velocity and increase in variability would be associated with their self-reported symptom score.

METHODS

Ten individuals with mTBI {mean (SD) age = 34 (6.7) years, height = 171.8 (8.4) cm, mass = 90.7 (19.9) kg} and 25 healthy controls {age = 28 (8.4) years., height = 169.3 (8.46) cm, mass = 70.3 (13.9) kg} provided informed written consent to participate. All mTBI participants had self-reported complaints of imbalance and a diagnosed mTBI >3 months before the testing session. At the beginning of each session, participants completed the Neurobehavioral Symptom Inventory (NSI). Participants then walked at their comfortable pace around a marked course containing four 45° turns, four 90° turns, and two

135° turns (Figure 1). Each participant completed 12 continuous laps of the course. The first and last laps were excluded from the analysis. Walking speed was determined from the average time to complete each lap. Inertial sensors affixed over the forehead and lumbar region of the spine collected angular velocities of the head and trunk, respectively.

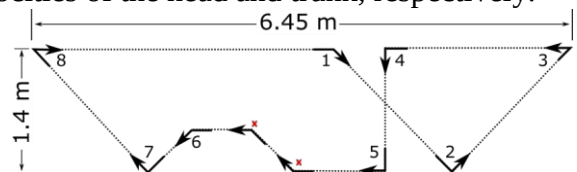


Figure 1: Turning course marked with arrows. Eight turns were analyzed, 2 turns (red x) were excluded.

Angular velocities were low-pass filtered at 1.5 Hz. For each turn, the magnitude and time of each peak axial angular velocity was extracted for the head and trunk. Two 45° turns were excluded from the analysis because a clearly defined peak velocity was lacking across all participants. Head-to-trunk coordination was defined as the lag time, calculated as the difference in time between peak velocities of head and trunk for each turn (Figure 2).

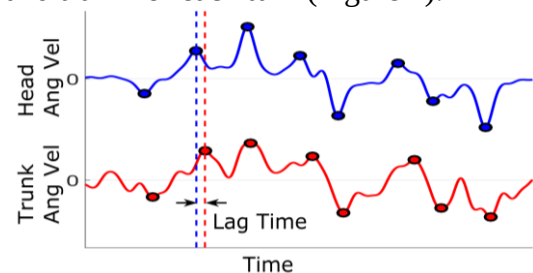


Figure 2: Example angular velocity traces showing the peak for each turn (markers) and lag time.

For each participant, the peak angular velocities were averaged across turns of the same angle. Lag time and lag time variability were determined from the mean and standard deviation, respectively, across all turns. Linear mixed models compared the average peak angular velocities between groups after adjusting for covariates of age, height, mass, walking

speed, and turning angle. Independent sample t-tests compared lag time and lag time variability between groups. Pearson correlation coefficients compared the relationship between each outcome and NSI symptom scores within the mTBI group.

RESULTS AND DISCUSSION

After adjusting for covariates of age, height, weight, walking speed, and turning angle, participants with mTBI had significantly slower peak angular velocities of the head (Figure 3, $p < 0.01$, $\beta = -0.30$, $SE = 0.11$) and trunk ($p < 0.01$, $\beta = -0.31$, $SE = 0.11$) compared to the control group. Lag time did not differ between groups, but lag time variability was significantly higher in the mTBI group compared to the control group ($p < 0.01$, $g = 0.58$).

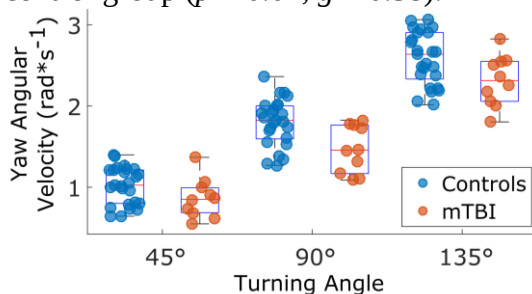


Figure 3: Average peak yaw angular velocity of the head for each participant for each turn angle.

Within the mTBI group, NSI total symptom scores were associated with slower average peak angular velocities of the head and trunk during 90° turns ($r = -0.77$, $p < 0.01$; $r = -0.71$, $p = 0.02$). Lag time variability was strongly associated with NSI symptom scores (Figure 4, $r = 0.87$, $p < 0.01$).

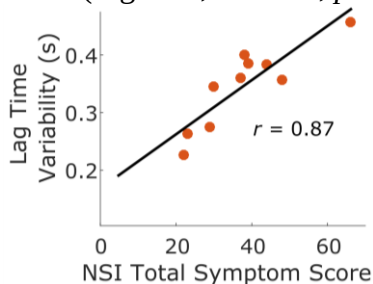


Figure 4: Lag time variability was significantly correlated with NSI total symptom score.

The slower peak velocities found in the mTBI group are consistent with previous reports of slower center-of-mass velocities in asymptomatic concussed athletes during a 90° turn [3]. Notably, the slower

angular velocities were significant after adjusting for walking speed, suggesting that the mTBI group may have cut corners to reduce the curvature [3] and angular velocity of each turn. Additionally, our results extend the evidence of increased segmental reorientation variability, previously reported during a light-induced turning task [2], to preplanned turns.

Importantly, measures of turning were associated with symptom scores. Standing balance and straight gait deficits are common after mTBI, but they have not been associated with symptom scores [4]. The association between higher symptom scores and measures of turning may be indicative of active avoidance of rapid rotations to prevent exacerbating symptoms. Alternatively, it could suggest symptoms are more apparent during specific dynamic activities such as turning, and such activities may heavily influence the self-reported symptom score given the high prevalence of turning in everyday locomotion. Further study of turning in symptomatic and asymptomatic individuals with mTBI is warranted.

CONCLUSIONS

Individuals with mTBI adopted slower turning velocities across all turning angles, and exhibited more variable head-to-trunk coordination timings compared to controls. These results provide knowledge of how self-reported symptoms influence daily locomotor function in adults with mTBI. The association of turning velocity and head-to-trunk coordination variability to self-reported symptoms suggests individuals with mTBI change reorientation patterns to minimize the exacerbation of symptoms.

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ACKNOWLEDGMENTS

Funding was provided by the US Department of Defense (W81XWH-15-1-0620).

Slower turning velocity and increased coordination variability are associated with self-reported symptoms in adults with mTBI

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Background: Abnormal balance and gait is common among individuals following mild traumatic brain injury (mTBI), yet measures of standing balance and straight gait have not been associated with self-reported symptoms. In daily activity and operational environments, complex movements involving change of direction are common and require rapid, coordinated reorientation of the head and trunk towards the new direction of travel. However, turning gait has not been well explored in populations with mTBI. Individuals with mTBI may limit their reorientation velocities based on their symptoms as rapid head movements can exacerbate symptoms. We hypothesized that individuals with mTBI would reduce their reorientation velocity and increase the variability of head-to-trunk coordination compared to controls, and that the reduction in velocity and increased variability would be associated with their self-reported symptom score.

Methods: Thirty-five young adults (10 mTBI, 25 controls) provided informed consent. All mTBI participants had self-reported complaints of imbalance and a diagnosed mTBI for >3 months. Each participant completed the Neurobehavioral Symptom Inventory (NSI) before walking 12 self-paced continuous laps around a marked course containing two 45° turns, four 90° turns, and two 135° turns. The first and last laps were excluded from analysis. Walking speed was determined from the average lap completion time. Inertial sensors affixed over the forehead and lumbar region collected angular velocities of the head and trunk, respectively. Angular velocities were low-pass filtered at 1.5 Hz. For each turn, the magnitude and time of peak axial angular velocity was extracted. Head-to-trunk coordination was defined using lag time, calculated as the difference in time between peak velocities of the head and trunk for each turn. For each participant, peak angular velocities were averaged across turns of the same angle. Lag times were averaged across all turns. Lag time variability was determined from the standard deviation of lag times. Linear mixed models compared the average peak angular velocities between groups after adjusting for covariates of turning angle and speed. Independent sample t-tests compared lag time and lag time variability between groups. Pearson correlation coefficients compared the relationship between each outcome and NSI symptom scores in the mTBI group.

Results: After adjusting for walking speed and turning angle, participants with mTBI had significantly slower peak angular velocities of the head ($p=0.01$, $\beta=-0.24$, $SE=0.10$) and trunk ($p<0.01$, $\beta=-0.29$, $SE=0.09$) compared to the control group. Average lag time did not differ between groups, but lag time variability was significantly higher in mTBI participants ($p<0.01$, $g=0.58$). Within the mTBI group, NSI total symptom scores were associated with slower average peak angular velocities of the head and trunk during 90° turns. Lag time variability was strongly associated with NSI symptom scores ($r=0.87$, $p<0.01$).

Conclusions: Individuals with mTBI adopted slower turning velocities and exhibited more variable head-to-trunk coordination timings compared to controls. The association of turning velocity and head-to-trunk coordination variability to self-reported symptoms suggests individuals with mTBI may change reorientation patterns to minimize the exacerbation of symptoms. These results provide knowledge of how self-reported symptoms influence daily locomotor function in adults with mTBI.

The effects of rehabilitation on sensory reweighting in patients with chronic mTBI

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Background: Balance impairments are a common complaint in patients suffering chronic effects of mild traumatic brain injury (mTBI) (Vanderploeg et al., 2007). Further, recent research has indicated vestibular and visual integration dysfunction is linked to postural instability in military service members with mTBI (Haran, et al., 2016). We propose that central sensorimotor integration disorders underlie chronic balance impairments and thus quantitative assessment of sensorimotor integration would have practical clinical applications for characterizing balance deficits and tracking recovery in Warfighters. This abstract presents preliminary findings from a larger study assessing the effects of targeted rehabilitation on sensory contributions to balance (sensory weights) under various test conditions using a novel test of central sensorimotor integration (CSMI) (Peterka, 2002).

Methods: Patients ($n=4$, age= 33.3 ± 8.65) and controls ($n=7$, age= 25.9 ± 6.08) were recruited through Oregon Health & Science University and VA Portland Health Care System. Participants were between 21-50, had either chronic complaints of imbalance after mTBI or no recent history of mTBI (control), had no significant cognitive impairment and had no illness that could explain balance deficits. Sensory weight scores were measured using CSMI tests (Peterka 2002). Briefly, a CSMI test elicits anterior-posterior sway through pseudorandom surface and/or visual display

rotations allowing measurements of sensory weights that indicate the relative contributions of proprioceptive, vestibular or visual systems to balance (Peterka, 2002). Four sensory conditions were evaluated: Condition 1 (C1) – reliance on the vestibular system; Condition 2 (C2) – reliance on combined vestibular and visual systems; Condition 3 (C3) – reliance on combined proprioceptive and vestibular systems; and Condition (C4) – reliance on vestibular system with conflicting visual and proprioceptive information. Whilst this abstract only reports the sensory weighting scores, the CSMI provides additional functionally meaningful parameters (e.g., system time delay, sensory-to-motor transformation properties), which are evaluated in the larger study. Following baseline testing, patients were enrolled into a rehabilitation program (2x/week for 6 weeks) focused on maintaining balance under changing sensory conditions with increasing levels of difficulty (Fino, et al., 2017). Follow-up testing was conducted at the conclusion of the intervention for people with mTBI and six weeks after baseline testing in controls, to establish stability of CSMI measures.

Results: Changes in sensory weights were assessed using Cohen's d effect sizes and the values reported are sensory weight measures ranging between 0 and 1. Increased weight scores were exhibited by the rehabilitation group (Rehab) in each of the four conditions: C1 (Rehab_{pre}=0.43±0.03, Rehab_{post}=0.49±0.09, d =0.86); C2 (Rehab_{pre}=0.61±0.05, Rehab_{post}=0.69±0.02, d =1.87); C3 (Rehab_{pre}=0.87±0.08, Rehab_{post}=0.89±0.03, d =0.43); and C4 (Rehab_{pre}=0.36±0.07, Rehab_{post}=0.42±0.11, d =0.69). No differences were indicated for the controls in follow up testing for conditions C1 (Con_{pre}=0.49±0.08, Con_{post}=0.50±0.11, d =0.08) or C2 (Con_{pre}=0.71±0.06, Con_{post}=0.72±0.07, d =0.09), however, small effects were noted in the control group for C3 (Con_{pre}=0.91±0.05, Con_{post}=0.92±0.01, d =-0.30) and C4 (Con_{pre}=0.47±0.04, Con_{post}=0.49±0.07, d =0.42).

Conclusion: Increased weight scores across each of the conditions in the rehabilitation group suggest the ability to change sensory weights in mTBI subjects, with the vestibular and combined weights (vestibular + vision/ proprioception) moving toward values consistent with those of controls following the intervention.

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Sensory weighting and rehabilitation in adults suffering chronic mTBI

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This abstract presents preliminary findings assessing the effects of rehabilitation on sensory weighting in patients with chronic balance impairment following mTBI. Nine patients (age=39.4±9.9) with chronic mTBI and seven controls (age=25.9±6.1) with no recent history of mTBI were recruited. Patients with mTBI were tested at baseline and then again after a 6 week (2x/week) balance rehabilitation program. The dizziness handicap inventory (DHI) was used to assess changes in symptoms. A novel test of central sensorimotor integration (CSMI) was used to collect measures of sensory weight (W, the relative contribution of vestibular and visual information to balance, range 0-100%), sensorimotor stiffness (Kp) and damping (Kd) parameters. Kp and Kd indicate the corrective ankle torque generated in proportion to the body sway angle and sway angular velocity, respectively. Here, we report on one condition that targets the visual and vestibular system. Between-group differences at baseline and within-group changes in the mTBI group following rehabilitation were assessed using Cohen's d effect sizes. Baseline results indicated lower W (control=71±6%, mTBI=63±6%, $d=-1.43$), Kp (control=1.73±0.36, mTBI=1.57±0.22, $d=-0.57$), and Kd (con=0.57±0.10, mTBI=0.47±0.06, $d=-1.17$) in the mTBI group compared with controls. Following rehabilitation, all measures increased toward control values (W: pre=63±6%, post=69±4%, $d=1.20$; Kp: pre=1.57±0.22, post=1.61±0.10, $d=0.26$; Kd: pre=0.47±0.06, post=0.53±0.03, $d=1.22$). DHI improved in 6/9 patients, with an overall decrease in symptoms (pre=45±15, post=39±21, $d=-0.34$). Results suggest people with chronic mTBI weight sensory information differently and exhibit a different motor response to stimuli. Increased W, Kp and Kd following rehabilitation suggests the potential for rehabilitation to change how people rely on sensory information and their motor response. Paired with the decrease in DHI, initial evidence suggests rehabilitation may improve physical function and symptoms.

Funding: This research was funded by the United States Department of Defense and US Army (W81XWH-15-1-0620)

Research Report

TITLE: Rehabilitation and sensory reweighting in patients with chronic mTBI

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Purpose/Hypothesis: Abnormal use of vestibular and visual systems may be linked to postural instability in patients with mild traumatic brain injury (mTBI)¹⁻³. The aim of this study is to assess the effects of rehabilitation on sensory contributions to balance in chronic mTBI patients. Here we present preliminary data from a novel test of central sensorimotor integration (CSMI)⁴.

Number of Subjects: 13

Materials/Methods: 6 patients (age=36±8) with chronic mTBI and 7 controls (age=25±6) with no recent history of mTBI were recruited. Patients with mTBI were tested at baseline and then again after a 6 week (2x/week)⁵ balance rehabilitation program. The dizziness handicap inventory (DHI) was used to assess changes in symptoms. Controls were tested 6 weeks apart to assess CSMI test-retest reliability.

The CSMI test uses pseudorandom rotations of the surface and/or visual display to elicit anterior-posterior sway. Here, we report on 2 of the relevant visual and vestibular conditions: C1) 2° surface rotations - eyes closed, and C2) 2° surface rotations - eyes open. The CSMI analysis yields measures of sensory weights (W, the relative contribution of vestibular information to balance in C1 and the vestibular + visual contribution to balance in C2), and measures of sensorimotor stiffness (Kp) and damping (Kd) parameters, indicating the corrective ankle torque generated in proportion to the body sway angle and sway angular velocity, respectively. Consistency of the CSMI test was assessed using Intraclass Correlation Coefficients (ICCs). Changes in the mTBI group were assessed using effect sizes. Reported values for W range between 0 and 1, while Kp and Kd were normalized by each person's height and weight.

Results: Good to excellent consistency was found for each measure; C1: W, $ICC = .92$, $CI [.42, .99]$; Kp, $ICC = .88$, $CI [.12, .98]$; Kd, $ICC = .97$, $CI [.80, .99]$; C2: W, $ICC = .80$, $CI [.14, .97]$; Kp, $ICC = .93$, $CI [.59, .99]$; Kd $ICC = .93$, $CI [.60, .99]$. Following rehabilitation, W increased in both conditions toward control values (C1: pre= $.41 \pm .05$, post= $.47 \pm .08$, $d = .92$; C2: pre= $.53 \pm .04$, post= $.60 \pm .05$, $d = 1.64$). Kp increased in C1 (pre= $1.58 \pm .23$, post= $1.66 \pm .25$, $d = .34$) but decreased in C2 (pre= $1.94 \pm .41$, post= $1.77 \pm .28$, $d = -.52$), while for Kd, effects indicated an increase in Kd for C1 and C2, respectively. (C1: pre= $.48 \pm .06$, post= $.55 \pm .03$, $d = 1.50$; C2: pre= $.50 \pm .06$, post= $.52 \pm .08$, $d = .31$). DHI improved in 5/6 patients, with an overall decrease in symptoms (pre= 43 ± 17 , post= 36 ± 23 , $d = -.36$).

Conclusions: CSMI test-retest results were highly consistent suggesting it may be an effective way to identify specific abnormalities and track changes in balance control. Increased W in the mTBI group toward control values suggests that rehabilitation changed reliance on sensory systems for balance. Differences in Kp and Kd following rehabilitation indicate adaptation in motor response to the stimuli. Decreased DHI suggests improvement in dizziness symptoms after rehabilitation.

Clinical Relevance: Understanding how sensory and sensorimotor contributions to balance change with rehabilitation may help drive evidence-based programs.

References: 1. Haran FJ, Slaboda JC, King LA, Wright WG, Houlihan D, Norris JN (2016) Sensitivity of the balance error scoring system and the sensory organization test in the combat environment. *J Neurotrauma* 33.7: 705-711. 2. Kolev OI, Sergeeva M (2016) Vestibular disorders following different types of head and neck trauma. *Funct neurol* 31,22: 75-80. 3. Alsalaheen BA, Mucha A, Morris LO, Whitney SL, Furman JM, Camiolo-Reddy CE, Collins MW, Lovell MR, Sparto PJ (2010) Vestibular rehabilitation for dizziness and balance disorders after concussion. *J Neurol Phys Ther* 34.2: 87-93. 4. Assländer L, Peterka RJ (2016) Sensory reweighting dynamics following removal and addition of visual and proprioceptive cues. *J Neurophysiol* 116.2: 272-285. 5. Fino PC, Peterka RJ, Hullar TE, Murchison C, Horak FB, Chesnutt JC, King LA (2017) Assessment and rehabilitation of central sensory impairments for balance in mTBI using auditory biofeedback: a randomized clinical trial. *BMC Neurol* 17: 41.

Funding:

This research was funded by the United States Department of Defense and US Army (W81XWH-15-1-0620)

Research Week Abstract

Vestibular function following chronic mild traumatic brain injury: examining the association between otolith function, sensorimotor integration, and posture

Jehu DA, Kempel S, Stuart S, Parrington L, Fino P, Hullar T, King LA

Mild traumatic brain injury (mTBI) is common in sport as well as following motor vehicle accidents and falls. Previous work has examined saccular function of the otolith organ using Cervical Vestibular-Evoked Myogenic Potential (cVEMP) in mTBI patients; however, the Ocular Vestibular-Evoked Myogenic Potential (oVEMP), a recent technique, examines utricular function and may provide further insight into the overall otolith organ function following concussion. The purpose of this study was to measure otolith function and explore its relationship with postural sway and sensorimotor integration in chronic mTBI. Fifty-one controls and 22 chronic mTBI participants completed the cVEMP, oVEMP, Sensory Organization Test (SOT), and quiet stance as measured by an inertial sensor. Vestibular dysfunction was observed by a lower amplitude ($p<0.05$) and a trend for greater asymmetry ($p=0.07$) of the cVEMP in the mTBI compared to controls. No differences in the amplitude or asymmetry of the oVEMP were observed between groups ($p>0.05$). Deficiencies in sensorimotor integration, as detected by the composite score of the SOT ($p<0.001$), and poor postural control, as evidenced by a trend for greater root mean square in the medial-lateral direction during standing ($p=0.06$), were apparent in the mTBI compared to controls. Although all of the cVEMP and oVEMP parameters were correlated ($p<0.05$), and the SOT was correlated to sway ($p<0.001$), no relationship between vestibular parameters and sensorimotor integration or sway were exposed ($p>0.05$). These results suggest that deficits in sensorimotor integration and posture may stem from other central or peripheral mechanisms.

Key words: brain injury, vestibular function, sensorimotor integration, posture

#299 Dual-task cost and cognition in patients with chronic mTBI

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Dysfunction following mTBI has been previously described in cognitive and motor domains, however, limited study has been conducted across both areas in populations with persistent balance symptoms following injury. In this abstract we provide preliminary findings comparing 15 persons with chronic mTBI (10 female, 40 ± 13 years, 67 ± 3 kg, 1.7 ± 0.4 m) with 15 healthy controls (9 female, 40 ± 13 years, 67 ± 4 kg, 1.7 ± 0.5 m). Chronic mTBI participants had self-reported balance complaints persisting more than 3 months following a clinically diagnosed mTBI. Participants completed the Automated Neuropsychological Assessment Metrics (ANAM) test and a dual-task of walking while completing a continuous Auditory Stroop. Prior to undertaking the dual-task walk, baseline single-task walking and a seated Auditory Stroop condition were collected in order to calculate the dual-task cost. ANAM composite score, dual-task cost on cognition (reaction time and a throughput score of accuracy/ correct response time), and dual-task cost on gait speed were assessed. Between group differences were assessed using Cohen's d effect sizes. Medium effects suggested that the chronic mTBI group performed worse on the ANAM composite score (control = $.27 \pm 1.26$, mTBI = $-.47 \pm .99$, $d = .66$) and experienced a greater dual-task cost on cognition (reaction time [control = $-1 \pm 11\%$, mTBI = $9 \pm 22\%$, $d = -.57$] and throughput score [control = $2 \pm 5\%$, mTBI = $-6 \pm 27\%$, $d = .51$]), while a small effect suggested healthy controls may have incurred a greater dual-task cost on gait speed (control = $-4 \pm 6\%$, mTBI = $-1 \pm 6\%$, $d = -.39$). Preliminary findings suggested cognitive differences, and difficulty in dual-task function may persist in chronic mTBI patients who complain of balance impairment. Of note is the lack of dual-task cost on gait speed in chronic mTBI – although the chronic mTBI walked slower in both conditions (single-task $d = -.55$, dual-task $d = -.29$), their dual-task gait speed was not as compromised as their cognitive response. These results help explain functional deficits contributing to difficulties in complex activities in chronic mTBI patients. Funding source: This work was supported by the Assistant Secretary of Defense for Health Affairs under Award No. W81XWH-15-1-0620. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the Department of Defense.

#299 Dual-task cost and cognition in patients with chronic mTBI

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NASPSA Abstract

Exploring the relationship between otolith function, sensorimotor integration, and posture in chronic mild traumatic brain injury

Jehu DA, Kempel S, Parrington L, Fino P, Hullar T, King LA

Mild traumatic brain injury (mTBI) is common in sport contexts as well as following motor vehicle accidents and falls. Previous work has examined saccular function of the otolith organ using Cervical Vestibular-Evoked Myogenic Potential (cVEMP) in mTBI patients; however, the Ocular Vestibular-Evoked Myogenic Potential (oVEMP), a recent technique, examines utricular function and may provide further insight into the overall otolith organ function following concussion. Utricular dysfunction has been linked to poor postural control and sensorimotor integration in individuals with vestibular loss, but this has not been reported in the mTBI population. Therefore, the purpose was to measure otolith function and explore its relationship with postural sway and sensorimotor integration in chronic mTBI. Fifty-one controls and 22 chronic mTBI participants completed the cVEMP, oVEMP, Sensory Organization Test (SOT), and quiet stance as measured by an inertial sensor. Vestibular dysfunction was observed by a lower amplitude ($p<0.05$) and a trend for greater asymmetry ($p=0.07$) of the cVEMP in the mTBI compared to the control group. No differences in the amplitude or asymmetry of the oVEMP were observed between groups ($p>0.05$). Deficiencies in sensorimotor integration, as detected by the composite score of the SOT ($p<0.001$), and poor postural control, as evidenced by a trend for greater root mean square in the medial-lateral direction during standing ($p=0.06$), were apparent in the mTBI compared to the control group. Although all of the cVEMP and oVEMP parameters were correlated ($p<0.05$), and the SOT was correlated to sway ($p<0.001$), no relationship between vestibular parameters and sensorimotor integration or sway were exposed ($p>0.05$). Globally, the saccule seems to be more sensitive to damage than the utricle following head trauma. Moreover, no link between otolith function and posture or sensorimotor integration was observed, suggesting that deficits in sensorimotor integration and posture may stem from other central or peripheral mechanisms.

Key words: brain injury, vestibular function, sensorimotor integration, posture

Turning the tide: real-world turns are more sensitive to mild traumatic brain injury deficits than daily activity measures.

(275 words limit)

Objective

This study aimed to compare real-world mobility measures (activity and turning) of healthy and mild traumatic brain injury (mTBI) participants using a wearable sensor.

Design

Cross sectional study.

Setting

Community.

Participants

Real-world mobility was examined in seven healthy control (52.7 ± 16.2 years) and twelve mTBI (43.1 ± 11.1 years) participants (>3 month post injury, who reported balance deficits) over one week, using an Opal inertial sensor placed at the waist.

Interventions

None.

Main Outcome Measure(s)

Outcomes included measurements across the week of daily activity and turning. Daily activity measures were: walking bouts per hour, bout duration, coefficient of variation (CV) of bout duration, and activity rate. Instrumented turning measures were: average turn angle, CV of turn angle, turn duration, and peak velocity. Symptoms were assessed using Dizziness Handicap Inventory (DHI) and Symptom Impact Questionnaire (SIQ).

Results

The mTBI group had similar daily activity to controls (walking bouts per hour, $p=.159$; bout duration, $p=.342$; CV bout duration, $p=.680$; activity rate, $p=.912$). However, mTBI participants made larger turns, had longer turning durations, and had slower peak velocities (all $p<.001$) compared to controls. MTBI participants also had more variable turning angles ($p<.001$), durations ($p<.001$), and peak velocities ($p=.002$) compared to controls. Slower peak velocities and longer turn durations were associated with more severe symptoms (DHI-physical sub-score; $r=-.69$, $p=.028$, SIQ; $r=.66$, $p=.037$, respectively).

Conclusion(s)

Our preliminary data show that people with mTBI have deficits in real-world turning, but not in measures of daily activity, compared to controls, and that real-world turning deficits were related to symptom severity. Real-world turning may therefore be more sensitive to mTBI symptoms than daily activity measures. Further work on a larger cohort will establish findings.

Key Words: continuous monitoring, concussion, turning, wearable sensor, daily activity

TEST-RETEST RELIABILITY OF THE SENSORY ORGANIZATION TEST AND CENTRAL SENSORIMOTOR INTEGRATION (CSMI) TEST

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INTRODUCTION

The collection and integration of information from the vestibular, visual and somatosensory systems are an integral aspect of balance control. Balance dysfunction can arise from damage to sensory systems (e.g. somatosensory decline following lower limb injury) or from central integration issues (e.g. neuromotor impairment following mild traumatic brain injury). Tests such as the Sensory Organization Test (SOT), and the Central Sensorimotor Integration (CSMI) Test [1] have been developed to try to identify contributions to balance dysfunction in patients. Both of these tests collect anterior-posterior sway data under different sensory conditions (e.g. moving surface, moving visual surround, eyes open or closed). One of the key differences between the two tests, is that the surface or visual surround movement during the SOT is dependent upon an individual's sway, and thus the amplitude of surface or visual surround movement is not fixed, while movement of the surface and visual surround in the CSMI is determined by continuous pseudorandom stimuli at fixed peak-to-peak amplitudes of 2° and 4°.

Although the SOT has been recognized as a reliable tool for the assessment of sensory contribution to balance in a number of populations [2,3], one of the recognized limitations is the effect of learning with repeated exposures [4]. Comparatively, there is limited information about the test-retest reliability of the CSMI test, and whether or not the CSMI test is subject to learning effects. In this abstract we present preliminary data on the test-retest reliability of the SOT and CSMI test measures focusing on four comparable conditions across the two tests: 1) surface movement with eyes closed, 2) surface movement with eyes open, 3) visual surround movement, and 4) both surface and visual surround movement. We hypothesize that a) both the SOT and

the CSMI will have good to excellent reliability, and b) that the participants will improve on the SOT, but will not improve on the CSMI – suggesting learning effects occur in the SOT but not CSMI test.

METHODS

Participants were 14 healthy volunteers (26.3 ± 2.8 years) recruited from Oregon Health & Science University (OHSU). Exclusion criteria included any history of injury, surgery or medical condition that would impair cognition or motor ability. All participants gave written informed consent, and procedures were approved by the OHSU Institutional Review Board. Participants completed two testing sessions, conducted six-weeks apart – a timeline chosen to reflect a reasonable test-retest interval in a balance intervention program. Participants completed the SOT and the CSMI test in a custom modified SMART Balance Master (Neurocom International Inc.), adapted to collect CSMI test data (Figure 1). For the SOT, participants completed the standard SOT clinical protocol of three 20-s trials per six conditions. For the CSMI test, participants completed randomly ordered trials at amplitudes of 2° and 4°, making eight total trials. Outcome measures were the Equilibrium Score (E, SOT) and the Sensory Weight presented as sensory weight*100 (W, CSMI) per condition.



Figure 1: Custom modified SMART Balance Master

Test-retest reliability was assessed using Intraclass Correlation Coefficients (ICCs) using a 2-way mixed effects model (ICC_{3,1}) with absolute agreement. 95% confidence intervals were calculated, and interpretations (<.5=poor; .5-.75=moderate; .75-.9=good; >.9=excellent) were based off Koo & Li [5]. Paired t-tests were also assessed to evaluate any mean differences between testing sessions.

RESULTS AND DISCUSSION

Except for the 2° visual condition, the ICC values for the CSMI were on average higher than the SOT (Table 1). SOT equilibrium score significantly improved in the visual movement condition (mean±SD, E₁=92±3, E₂=94±2, $p=.041$), and the surface plus visual movement condition, (E₁=64±18, E₂=74±15), $p=.001$), but no significant changes to performance in the surface movement with eyes open condition (E₁=86±5, E₂=88±6, $p=.050$) or surface movement with eyes closed condition (E₁=66±14, E₂=72±12, $p=.168$).

Table 1: ICC values, 95% confidence intervals and interpretation of ICC for each condition tested.

		95% CI			Interpretation
		ICC _{3,1}	Lower	Upper	
SOT	S, EC	0.475	-0.46	0.83	Poor
	S, EO	0.733	0.20	0.91	Moderate
	V	0.451	-0.36	0.81	Poor
	S + V	0.867	0.10	0.97	Good
CSMI	S, EC 2°	0.854	0.55	0.95	Good
	S, EC 4°	0.655	0.03	0.89	Moderate
	S, EO 2°	0.557	-0.46	0.86	Moderate
	S, EO 4°	0.878	0.61	0.96	Good
	V 2°	0.392	-0.69	0.80	Poor
	V 4°	0.705	-0.05	0.91	Moderate
	S + V 2°	0.849	0.52	0.95	Good
	S + V 4°	0.882	0.61	0.96	Good

*S = surface movement; V = visual movement; EC = eyes closed; EO = eyes open

The only significant change in performance for the CSMI test was in the 4° visual movement condition, $W_1=5\pm3$, $W_2=3\pm1$, $p=.004$. No significant changes in performance occurred in any other condition (2° surface movement, eyes closed condition, $W_1=49\pm8$, $W_2=50\pm7$, $p=.448$; 4° surface movement, eyes closed condition, $W_1=39\pm10$, $W_2=35\pm4$, $p=.063$; 2° surface movement, eyes open condition, $W_1=72\pm4$, $W_2=72\pm5$, $p=.697$; 4° surface movement, eyes open

condition, $W_1=19\pm4$, $W_2=19\pm3$, $p=.864$; 2° visual movement condition, $W_1=10\pm5$, $W_2=8\pm2$, $p=.178$; 2° surface and visual movement condition, $W_1=53\pm7$, $W_2=54\pm6$, $p=.814$; 4° surface and visual movement condition, $W_1=44\pm9$, $W_2=41\pm7$, $p=.063$).

Our results suggest better test-retest reliability of the CSMI than the SOT for the surface movement with eyes closed condition, while being comparable for surface movement with eyes open, and surface plus visual surround movement. Test-retest reliability was low for the SOT visual condition and the low amplitude CSMI visual movement condition. Repeat test performance improved in the SOT visual movement and surface plus visual movement conditions, while for the CSMI a decrease in the sensory weight occurred in the visual movement condition. Overall reliability of the SOT and CSMI were somewhat lower than expected. This may be an outcome of the repeat trial occurring six weeks following the initial testing block. The general improvement in SOT performance is consistent with a learning effect.

CONCLUSIONS

Test-retest reliability ranged from poor to good for both the SOT and CSMI test, with the CSMI test performing slightly better overall. The observed test-retest changes in performance in healthy young adults provide a benchmark for judging whether rehabilitation interventions are effective in improving balance function in patients.

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ACKNOWLEDGEMENTS

Funding was provided by the US Department of Defense (W81XWH-15-1-0620). Thank you to Ms. Alexa Beeson for her assistance with data collection.

Free-living mobility outcomes improve with balance rehabilitation following mild traumatic brain injury

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Background

Balance and mobility issues are common non-resolving symptoms following a mild traumatic brain injury (mTBI). Traditionally, balance and mobility following an mTBI are assessed within clinic using subjective clinical rating scales (e.g. SCAT, BESS etc.) that may not be sensitive to subtle deficits. With the advancement of wearable inertial sensor technology, it is now possible to assess a range of sensitive balance and mobility outcomes in a more objective manner within natural free-living environments. This provides a unique opportunity to assess patient symptom variability usually not captured within a single clinic visit. Generally, free-living mobility is reported in terms of physical activity (i.e. steps per day), however recent evidence has demonstrated that turning may be sensitive to mTBI and can be monitored in free-living. Visual, vestibular and proprioceptive system input are required for balance and mobility, especially for complex tasks such as turning that requires control of dynamic balance and sequential, whole-body coordination. Therefore, free-living physical activity and turning measures may improve with balance rehabilitation that targets these systems.

This study aimed to examine free-living mobility (physical activity and turning) in mTBI participants using a wearable sensor pre and post balance rehabilitation. We hypothesized that turning measures would be more sensitive to improvement following balance rehabilitation than general physical activity outcomes.

Methods

Free-living mobility was examined in fourteen mTBI (aged 42.4±12.8 years) participants (>3 months post injury, who self-reported balance deficits) over one week pre and post balance rehabilitation, using continuous monitoring with an Opal (APDM Inc.) inertial sensor placed at the waist. Primary outcomes were instrumented measurements of daily activity and turning across the week. Daily physical activity measures included walking bout duration (sec), coefficient of variation (CV) of bout duration, total number of steps per day and active rate. Turning measures included average turn angle, CV of turn angle, turn duration, and peak velocity. The 6-week balance rehabilitation program involved progressive exercises for gaze stabilization, vestibular function, balance, and proprioception. Pre-intervention symptoms were also rated using the dizziness handicap inventory (DHI), including the physical, emotional and functional sub-scales.

Results

Following balance rehabilitation, a number of free-living mobility metrics modified in the mTBI participants, but turning rather than physical activity metrics appeared to be more sensitive to improvement. Increased turn angle ($p=.013$), reduced turn angle variability (CV: $p=.002$) and increased peak velocity ($p=.004$) were observed post-rehabilitation. However, no significant change occurred for turn duration ($p=.155$). In terms of physical activity measures, an improvement of longer and less variable walking bout durations ($p=.004$, CV: $p<.001$) was observed. However, there was no significant change in the total number of steps per day ($p=.665$) and there was significant reduction in active rate ($p=.002$).

More severe symptoms pre-rehabilitation related to greater improvement in free-living mobility metrics post-rehabilitation. Specifically, greater DHI physical sub-scale score pre-rehabilitation related to increased turn velocity and reduced turn angle CV ($\rho=.70$, $p=.006$, $\rho=-.56$, $p=.039$, respectively), and reduced CV of walking bout duration ($\rho=-.59$, $p=.027$) post-rehabilitation.

Conclusion

In conclusion, free-living mobility improves following balance rehabilitation in mTBI, particularly in those who experience greater physical symptoms. Specifically, turn quality measures may be more sensitive than general daily physical activity measures to balance rehabilitation in mTBI participants. Future analysis will establish these findings within a larger cohort.

Improvements in turning speed but not gait speed in people with mild traumatic brain injury following vestibular rehabilitation

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Background: Recent studies have shown turning is impaired in people with mild traumatic brain injury (mTBI) and residual symptoms. Additionally, abnormal turning may be more sensitive to patient-reported symptoms than traditional mobility measures such as gait speed. Our previous research has shown that individuals with mTBI turn slower, and those who report more severe somatic symptoms have the largest impairments. However, it is unclear whether markers of turning quality, such as peak turning velocity, can improve with treatment. While measures of turning have potential to serve as a clinical outcome measures for return-to-duty decisions, the responsiveness to intervention needs to be investigated. This preliminary analysis assessed whether turning can serve as a useful outcome measure by examining the change in peak angular velocity after six weeks of vestibular rehabilitation in people with chronic mTBI. We hypothesized that individuals with chronic mTBI would improve their peak turning velocity and following rehabilitation.

Methods: Seventeen adults (8 mTBI, 9 controls) provided informed consent. All mTBI participants had self-reported complaints of imbalance >3 months following a diagnosed mTBI. Each participant completed two walking tasks while wearing inertial sensors on their feet, lumbar region, trunk, and head. To obtain straight gait, participants walked at their self-selected pace for approximately four minutes between two lines marked 14 m apart. Gait speed was calculated using Mobility Lab v2 (analysis version 3, APDM, Inc.) based on the inertial sensors on the feet. To obtain turning data, participants completed 12 self-paced continuous laps around a custom-designed course containing two 45° turns, four 90° turns, and two 135° turns. The first and last laps were excluded from analysis. Lap time was determined from the average lap completion time. Peak angular velocities for each turn were identified and extracted for the head, trunk, and lumbar inertial sensors. The mTBI group was assessed before and after completing a six-week long progressive vestibular rehabilitation. The healthy control group was assessed at two sessions separated by six weeks to match the timeline of the mTBI group. To compare the change over time between the groups, linear mixed models were fit for gait speed and the peak angular velocities of the head, trunk, and lumbar. Linear mixed models were adjusted for group, testing session, and the group*session interaction to determine if the mTBI group changed significantly compared to controls. Models for turning velocity were also adjusted for turning angle.

Results: Participants with mTBI had significantly slower peak angular velocities of the lumbar region ($p<0.01$, $\beta=-0.38$, $SE=0.13$) and head ($p=0.03$ $\beta=-0.37$, $SE=0.17$) compared to the control group at baseline. A significant group*session interaction was found for peak lumbar angular velocity ($p=0.03$ $\beta=0.12$, $SE=0.05$), where the mTBI group increased their peak lumbar turning velocity more than controls over time. Gait speed did not differ between groups at baseline ($p=0.39$ $\beta=-0.37$, $SE=0.17$), and no group*session interaction was found indicating gait speed did not improve over time with respect to controls ($p=0.74$ $\beta=-0.01$, $SE=0.03$).

Conclusions: Peak turning velocity during a clinical turning task improved in people with mTBI after vestibular rehabilitation. Baseline deficits and the sensitivity to intervention suggest that turning velocity, more so than other standard gait outcomes such as gait speed, has high potential as an outcome measure for return-to-duty assessments. Further work is needed to examine other clinometric properties of turning and to refine clinical turning tasks to enable rapid and easy assessments in clinical and operational environments.

Learning Objectives:

Describe gait and turning deficits in people with mTBI

Describe the effect of vestibular rehabilitation on gait and turning in people with mTBI

Analyze the effectiveness of rehabilitation with turning-based outcome measures

Military Health System Research Symposium (MHSRS) Abstract

Assessment of balance after mild traumatic brain injury: Are vestibular and ocular-motor testing capturing all balance deficits?

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Background: Mild traumatic brain injury (mTBI) has been challenging to both diagnose and treat, as symptoms are diverse in nature and subtle in presentation. Impairments post-mTBI have spanned multiple domains, such as vestibular [1], ocular-motor [2], balance [3], and sensory integration [4]. However, it is unclear whether vestibular, ocular-motor, and balance testing are redundant in identifying individuals with mTBI, or whether unique deficits can be captured across domains.

Aim and Hypothesis: The purpose of this study was to evaluate the prevalence of abnormalities in vestibular and ocular-motor testing in comparison with clinical tests of balance in people with chronic balance deficits after mTBI relative to healthy young adults. We also investigated the relationship between vestibular, ocular-motor, and balance abnormalities in people with chronic mTBI. We hypothesized that a similar prevalence of abnormalities would exist across vestibular, ocular-motor, and balance domains, and that abnormalities in vestibular and ocular-motor domains would be associated with abnormalities in balance domains.

Methods: Twenty-eight individuals with chronic mTBI (age: 39.2 ± 12.0 years, 19 females) and 51 healthy young adults (age: 35.5 ± 12.5 years, 19 females) completed a battery of 1) vestibular tests, 2) ocular-motor tests, and 3) clinical balance tests. Specifically, the vestibular examination included the evaluation of otolith function (i.e., Cervical Evoked Myogenic Potential (cVEMP), Ocular Evoked Myogenic Potential, (oVEMP)), and semi-circular canal function (i.e., Calorics, Dix-Hallpike). Ocular-motor function was evaluated via Saccade, Gaze, Smooth Pursuit, and Convergence testing. Participants were classified by an audiologist as normal or abnormal based on clinical norms. The balance assessment included the Sensory Organization Test (SOT) and the Modified Balance Error Scoring System (mBESS) test. Participants were further classified using the root mean square of medial-lateral acceleration (ML-RMS), measured by an inertial sensor worn on the lower lumbar region, when standing with feet together on a firm surface with eyes closed. ML-RMS acceleration has been previously shown to be effective for classifying individuals post-mTBI [5]. Participants were deemed abnormal on the clinical balance tests if their data were outside of 2 standard deviations from the average of the controls.

Results: Descriptively, in our participants with chronic mTBI, 7.1 % exhibited abnormalities in one or more of the vestibular tests, 3.6 % presented with abnormalities in one or more of the ocular-motor tests, 17.9 % had abnormalities in one or more of the balance tests, 0 % showed abnormalities in both vestibular and ocular-motor tests, 35.7 % displayed abnormalities in

vestibular and balance tests, 17.9 % had abnormalities in ocular-motor and balance tests, and 7.1 % revealed abnormalities across vestibular, ocular-motor and balance tests, while 10.7 % showed no abnormalities. Proportions tests demonstrated significantly more abnormalities in mTBI participants compared to controls in ocular-motor tests (mTBI: 29.6 %, Control: 9.8 %; $p=0.03$) and in clinical balance tests (mTBI: 78.6 %, Control: 9.8 %; $p<0.001$), while no differences between groups were observed for otolith tests (mTBI: 25.9 %, Control: 23.5 %; $p>0.82$) or semi-circular canal tests (mTBI: 29.6 %, Control: 27.4 %; $p=0.75$). No associations were found between vestibular function and the SOT ($r_{\phi}=-0.03$, $p=0.86$), the mBESS ($r_{\phi}=0.04$, $p=0.84$), or ML-RMS sway ($r_{\phi}=-0.28$, $p=0.15$). No relationships were exhibited between ocular-motor tests and the SOT ($r_{\phi}=0.07$, $p=0.71$), the mBESS ($r_{\phi}=0.19$, $p=0.33$), or ML-RMS sway ($r_{\phi}=-0.16$, $p=0.40$).

Conclusion: A greater proportion of individuals with mTBI presented with ocular-motor and clinical balance abnormalities relative to healthy young adults, suggesting that mTBI deficits are primarily attributed to central dysfunction. Specifically, our results did not demonstrate that tests designed to detect peripheral vestibular dysfunction were helpful in distinguishing between mTBI and controls. However, performing only ocular-motor or only balance tests will fail to detect a portion of individuals with mTBI. That is, the lack of relationships between vestibular function and clinical balance, as well as between ocular-motor function and clinical balance indicate that vestibular, ocular-motor, and balance testing offer unique information and may all be necessary to sensitively detect mTBI. These findings further the knowledge on best practices of mTBI assessment and emphasize the importance of including a multifaceted battery of tests to accurately classify mTBI.

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Key words: brain injury, vestibular function, ocular-motor function, clinical balance, accurate detection

Learning Objectives:

1. Learners will be able to identify peripheral compared to central impairments post- mild traumatic brain injury (mTBI)
2. Learners will be able to describe the prevalence of abnormalities in vestibular, ocular-motor, and balance function following mTBI
3. Learners will be able to apply the knowledge that a multifaceted testing battery may be necessary to accurately detect a mTBI into military and clinical practice

Central Sensorimotor Integration Test: Test-retest reliability and learning effects

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Background: Balance and sensory integration deficits are common problems after mild traumatic brain injury and often require balance rehabilitation. Judging the effectiveness of an intervention requires practitioners to know both the retest reliability of a tool, and whether or not repeat testing is subject to learning effects. The Sensory Organization Test, a gold standard test for measuring sensory integration and balance, has been shown to be a reliable way to assess sensory contributions to balance, but is also recognized as being subject to learning effects. As an alternative, our group has utilized the Central Sensorimotor Integration (CSMI) test to identify sensory contributions to balance control. The CSMI test uses continuous pseudorandom rotations of the surface, visual surround, or paired surface and visual surround at fixed peak-to-peak amplitudes of 2° and 4° rather than the sway-evoked rotations (i.e., sway-referencing) used in the SOT. Because of the unpredictable nature of pseudorandom stimuli, it is plausible that the CSMI will not be subject to learning effects, making it a promising tool to investigate changes following rehabilitation. Also, in addition to providing measures of the relative contribution of proprioceptive, vestibular or visual systems to balance (Sensory Weights, W_s), the CSMI provides functionally meaningful sensory-to-motor transformation parameters (Stiffness, K_p and damping, K_d). The purpose of this investigation was to assess test-retest reliability and identify performance changes that may indicate learning effects in a sample of healthy controls.

Methods: Fourteen healthy participants (age: 26.3 ± 2.8 years, 9 female) were recruited from Oregon Health & Science University. Participants were excluded if they had a history of injury, surgery or medical condition that would impair cognition or motor ability. Procedures were approved by the Institutional Review Board, and all participants provided written informed consent prior to testing. Testing was comprised of two sessions completed six-weeks apart. This timeline was chosen to reflect the interval used in our vestibular rehabilitation program. The CSMI was completed in a customized SMART Balance Master (Natus Medical Inc.). Four conditions that target reliance on the 1) vestibular system (surface movement with eyes closed, SEC), 2) combined vestibular and visual systems (surface movement with eyes open, SEO), 3) combined proprioceptive and vestibular systems (visual surround movement, VEO); and 4) vestibular system with conflicting visual and proprioceptive information (paired surface and visual surround movement, S+V) were tested at 2° amplitudes in random order. Two-way mixed effects Intraclass Correlation Coefficients ($ICC_{3,1}$) with absolute agreement and 95% confidence intervals were calculated for W , K_p , and K_d . Test-retest reliability was interpreted as $ICC_{3,1} < 0.5$ =poor; $0.5-0.75$ =moderate; $0.75-$

0.9=good; >0.9=excellent. Paired t-tests were used to assess changes (learning effects) in performance between testing sessions.

Results: Test-retest reliability: Test-retest reliability was best in SEC and S+V conditions, and lowest in the VEO condition. Test-retest reliability ranged from good to excellent in the SEC condition (W, $ICC_{3,1}=0.854$, CI=0.554, 0.953; Kp, $ICC_{3,1}=0.922$, CI=0.759, 0.975; Kd, $ICC_{3,1}=0.851$, CI = 0.534, 0.952), and ranged from moderate to good for SEO (W, $ICC_{3,1}=0.557$, CI=-0.457, 0.860; Kp, $ICC_{3,1}=0.810$, CI=0.401, 0.939; Kd, $ICC_{3,1}=0.689$, CI=0.044, 0.900). In the VEO condition, test-retest reliability was poor to moderate (W, $ICC_{3,1}=0.392$, CI=-0.692, 0.797; Kp, $ICC_{3,1}=0.241$, CI=-0.645, 0.717; Kd, $ICC_{3,1}=0.677$, CI =0.018, 0.896), and was good in the S+V condition (W, $ICC_{3,1}=0.849$, CI=0.521, 0.952; Kp, $ICC_{3,1}=0.875$, CI=0.570, 0.961; Kd, $ICC_{3,1}=0.814$, CI=0.347, 0.943). Learning effects: There were no significant changes over time to W in any of the conditions ($p=0.08$ to 0.81), however, significant changes occurred in Kp and Kd in the VEO condition (Kp, $M_{diff}=-0.098$, $p=0.031$; Kd, $M_{diff}=0.033$, $p=0.017$), and in the S+V condition (Kp, $M_{diff}=-0.051$, $p=0.044$; Kd, $M_{diff}=0.029$, $p=0.024$).

Discussion and Conclusion: Test-retest reliability was best across outcome measures in the SEC and S+V conditions, while being moderate in the SEO condition. The VEO condition had the lowest test-retest reliability. This low reliability is likely related to the very low amplitudes of sway evoked by the visual stimulus, resulting in parameters estimates with higher variability compared with the other conditions that evoked greater sway. The non-significant changes in W in each condition suggests that subjects do not alter how they use sensory information for balance over time. However, changes to Kp and Kd in VEO and S+V indicate potential changes to stiffness and damping –an indication that the mechanism of control may have adjusted in some participants. Based on these findings, SEC, which challenges the vestibular system, may be the most effective condition to monitor changes following rehabilitation. Further investigation is needed to determine the minimal detectable change for each of the CSMI conditions.

Acknowledgements: Funding was provided by the US Department of Defense (W81XWH-15-1-0620). Thank you to Ms. Alexa Beeson for her assistance with data collection.

Title: Exploring outcomes measures after vestibular rehabilitation in chronic concussion patients

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Abstract/Body:

Purpose: Current recommendations to measure change after vestibular rehabilitation in chronic concussion patients include measures ranging from single question symptom scores to complex objective balance tests. Such measures utilize both patient-oriented and objective outcomes. This study examined 4 common tests, both patient oriented and objective, that are used in concussion rehabilitation. We also explored the relationship between the change in these tests after vestibular rehabilitation.

Materials/Methods: Eighteen participants (14 females and 4 males, mean age 39.6 years old (± 12.5 SD)) participated in this study. On average, participants were 2.4 ± 2.4 years post injury and had prolonged complaints of imbalance. Participants engaged in vestibular rehabilitation 2x/week for 6 weeks under the supervision of a physical therapist. Outcome measures included both patient-oriented and objective outcomes. Specifically, Dynamic Handicap Inventory (DHI) and Sports Concussion Assessment Tool (SCAT) symptom checklist, as well as the modified Balance Error Scoring System (mBESS) and Sensory Organization Test (SOT).

Results: There were significant changes in both patient-oriented and objective measures. The SCAT symptom checklist ($p=0.001$) and the SOT ($p<0.001$) showed significant change after rehabilitation. The change in SOT (18.3 ± 12.5 SD) exceeded the MDC of 8 points. The change in SCAT symptoms was 16.8 ± 18 . There were no changes in the DHI ($p=0.191$) or the mBESS ($p=0.125$) after rehabilitation.

Of the 2 patient-oriented scales (SCAT and DHI), there was a moderately significant correlation ($r=0.49$, $p=0.046$). Of the 2 objective tests (mBESS and SOT), there was a moderately significant correlation ($r=0.47$, $p=0.050$). Interestingly, there was no significant correlation between either of the patient-oriented measures with either of the objective measures.

Conclusions: Vestibular rehabilitation can improve both patient-oriented and objective measures in subjects with a concussion > 1 yr. Clinicians should include both patient-oriented and objective testing to fully capture change in the chronically concussed patient. The SCAT symptom checklist and SOT were most sensitive to change after vestibular rehabilitation compared to the DHI and mBESS in this chronic population.

Test-retest reliability of systems assessing sensory contributions to balance

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Balance is controlled through the integration of information from the visual, vestibular, and somatosensory systems. Testing batteries such as the Sensory Organization Test (SOT), and more recently, the Central Sensorimotor Integration Test (CSMI), have been developed to help characterize balance dysfunction. A primary difference between these tests is that the CSMI evokes sway through pseudorandom stimuli, while the SOT does not. Little is known about how these two systems compare on test-retest reliability, and whether they are subject to learning effects. Our aim was to examine the test-retest reliability of the SOT and CSMI over a six-week period using two comparable conditions, both involving surface movement with eyes open (EO) and with eyes closed (EC). Fifteen healthy volunteers (25.8 ± 3.13 years) participated. Intraclass correlation coefficients ($ICC_{3,1}$) and paired t-tests were calculated for the SOT equilibrium score and CSMI sensory weight. The test-retest reliability of the SOT equilibrium scores were moderate (EO, $ICC_{3,1}=0.749$, EC, $ICC_{3,1}=0.577$), while the test-retest reliability for the CSMI sensory weight were moderate (EO, $ICC_{3,1}=0.557$) and good (EC, $ICC_{3,1}=0.854$). Participants significantly improved performance in the SOT EC condition ($p=0.043$), but not in the EO condition. No significant differences were found for either CSMI condition over six weeks ($p>0.05$). Although the SOT showed moderate reliability, the increased performance may indicate learning effects not present in the CSMI test. Given comparable reliability, CSMI testing may provide a beneficial alternative to the SOT when assessing the efficacy of interventions as it does not appear to be confounded by learning effects.

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Activity: Scientific Abstract

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Sensory weighting in chronic mTBI with vestibular and oculomotor dysfunction

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Abstract:

Background: Mild traumatic brain injury (mTBI) is known to disrupt balance control and has been linked to abnormal use of the vestibular and visual systems. Peripheral vestibular and oculomotor dysfunction may affect how patients rely on information from these systems. We used a test of central sensorimotor integration (CSMI) to determine the relative contribution of one or more sensory systems to balance in patients with chronic mTBI. **Objective:** To compare Sensory Weight scores in people with chronic mTBI with and without vestibular and/or oculomotor dysfunction (VOD), compared to healthy controls. **Setting:** Oregon Health & Science University and the Portland VA balance and vestibular laboratories. **Participants:** Twenty-six mTBI patients with chronic balance complaints lasting more than 3 months (65% f, age=39.4 ±12) and 24 healthy controls with no history of mTBI, and no VOD (67% f, age=31.8 ±11) participated.

Design: Participants completed a battery of vestibular and oculomotor tests (calorics, cVEMP, oVEMP, VHIT, convergence, and saccades) and were rated as abnormal (n=18) or normal (n=8). All control subjects had normal function. Participants then completed the CSMI test; a test that uses pseudorandom rotations of the surface and/or visual surround to elicit sway. For this analysis we focused on two conditions: surface movement eyes closed, used to assess reliance on the vestibular system, and surface movement eyes open, to assess reliance on both the vestibular and visual system. Difference in Sensory Weight across groups was assessed using a one-way ANOVA. **Main Outcome Measure:** Sensory Weight (W, range 0 - 1). **Results:** A significant difference in W was found between groups for both reliance on the vestibular system, $F(2,44)=6.269$, $p=0.004$, and reliance on vestibular and visual systems together, $F(2,45)=5.848$, $p=0.006$. W was significantly smaller in mTBI with VOD than controls in both conditions (reliance on vestibular system, W mean(SD) mTBI VOD=0.38(0.10), control=0.47(0.08), $p=0.006$; reliance on paired vestibular and visual systems, $p=0.004$, W mTBI VOD=0.62(0.07), control=0.69(0.06)). There were no significant differences between controls and the mTBI group without VOD, or between the mTBIs with and without VOD in either condition ($p>0.05$). **Conclusions:** Differences in sensory weighting occurred only in the mTBI group with measurable VOD suggesting balance problems in mTBI patients without measurable vestibular and/or oculomotor deficits may have different mechanism. Such underlying differences may affect rehabilitation efficacy.

Gait velocity variances in chronic mild Traumatic Brain Injury (mTBI) subjects through single and dual-task activity

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Walking requires dynamic postural control, whole body coordination and timing of movement, which may be impaired in people suffering chronic mTBI. The aim of this study was to analyze walking velocity in patients with chronic mTBI and healthy controls. Specifically, we were interested in the differences between single and dual-task walking (addition of secondary activity). Fifty-one mTBI participants (age 40 ± 11.8 years, 66% female) with chronic and non-resolving balance deficits (>3 months) and 54 matched control participants (age 37 ± 12.6 years, 58% female) with no recent history of mTBI were recruited. All participants completed a single-task (ST) and a dual-task (DT) walk, in which participants walked down a hallway toward a line then turned around and walked back, covering a distance of 26.10m. During the DT walk, participants additionally completed an auditory Stroop task. The time taken was recorded using a stop-watch, and clinical gait velocity was calculated using the formula $\text{velocity} = \text{distance}/\text{time}$. Independent samples t-tests were used to examine significant differences between groups, and paired samples t-tests were used to compare between conditions ($\alpha=0.05$). The mTBI group walked significantly slower than the controls during both conditions ($p<0.001$), however, there were no significant differences in either groups between the ST and the DT walking conditions. Results suggested that assessing walking under simple and complex cognitive conditions may be a cost effective and widely accessible tool for detection of dynamic balance deficits following mTBI.

Assessing the Relationship between Symptom Severity and Gait Performance in a Symptomatic, Chronic mTBI Population Before and After Vestibular Rehabilitation

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Background: Evidence suggests that subtle gait deficits persist in chronic mild traumatic brain injury (mTBI) beyond one year post injury. To date, there is little known about the relationship between symptom severity and possible gait performance deficits in people with symptomatic, chronic mTBI. Dizziness, a commonly reported symptom in people with mTBI, as well as mobility, have been shown to improve following vestibular rehabilitation. However, the effects of vestibular rehabilitation on symptom reporting and gait performance is not well understood in the symptomatic, chronic mTBI population.

The purpose of these preliminary analyses were to examine 1) the differences in gait performance between symptomatic, chronic mTBI and healthy control groups 2) the relationship between symptoms and gait performance in the mTBI group 3) the possible effects of vestibular rehabilitation on symptom severity and gait performance in the mTBI group and 4) the possible relationship between the change in symptom severity and gait performance after vestibular rehabilitation in the mTBI group. We hypothesized that the mTBI group would have worse gait performance than the controls before rehabilitation and that symptom severity would be to gait performance. Additionally, we hypothesized that the rehabilitation would improve both symptom severity and gait performance in the mTBI group, and the change in symptom severity would be related to the change in gait performance.

Methods: Sixty healthy participants (age: 36.9 ± 12.6 years, 35 female) and 54 participants with symptomatic chronic mTBI (age: 39.6 ± 11.2 years, 38 female, 2.3 ± 2.7 years since mTBI) were recruited from Oregon Health & Science University and the Portland area. Participants were excluded if they had a history of injury, surgery or medical condition that would impair cognition or motor ability, beyond an mTBI. The Institutional Review Board approved procedures and all participants provided written informed consent prior to testing. Testing included symptom evaluation using the Sport Concussion Assessment Tool (SCAT) 3 and gait characterization using inertial sensors (APDM Inc.) during single (ST) and dual task (DT) walking. The secondary task was the auditory Stroop test. Dual task cost (DTC) was calculated for each gait and secondary task variable. This testing battery was done before and after a six week, standard vestibular rehabilitation in the mTBI group only. Independent samples t-tests were used to compare between group differences. Paired t-tests assessed changes in symptom reporting and gait performance between pre and post rehabilitation sessions

in the mTBI group. Pearson's Correlations assessed the relationship between symptom scores and gait performance.

Results: There were no age or gender differences between groups. Before rehabilitation, the mTBI group walked slower than the control group (ST: 1.1 ± 0.1 vs 1.2 ± 0.1 m/s; $p < 0.01$; DT: 1.1 ± 0.2 vs 1.2 ± 0.2 m/s; $p < 0.01$), had slower peak turn velocity (ST: 161 ± 34 vs 198 ± 43 deg/s; $p < 0.01$; DT: 162 ± 37 vs 204 ± 48 deg/s; $p < 0.01$), and spent a greater percent of gait cycle in double stance (ST: $21 \pm 3\%$ vs $19 \pm 3\%$; $p < 0.01$; DT: $22 \pm 3\%$ vs $19 \pm 3\%$; $p < 0.01$), while exhibiting increased stance time variability (ST: 0.7 ± 0.1 vs 0.6 ± 0.1 ; $p = 0.03$; DT: 0.7 ± 0.2 vs 0.6 ± 0.1 ; $p = 0.02$). Further, the mTBI group had slower response times to the secondary task than the control group both seated (927 ± 156 vs 853 ± 154 ms; $p = 0.02$) and walking (991 ± 159 vs 8463 ± 150 ms; $p < 0.01$). Secondary task response time DTC (mTBI: -7.5 ± 16.4 ; control: -0.7 ± 10.7 ; $p = 0.02$) differed between groups. No other DTC variables were different between groups. There were no significant correlations between total symptom score and gait performance in the mTBI group before rehabilitation.

Post rehabilitation, only peak turn velocity (ST: 173 ± 37 vs 198 ± 43 deg/s; $p < 0.01$; DT: 174 ± 43 vs 204 ± 48 deg/s; $p < 0.01$) and secondary task response time DTC (-9.9 ± 14.0 vs -0.7 ± 10.7 ; $p = 0.01$) were different between groups. Paired t-tests yielded a significant decrease in total symptom score (pre: 36 ± 20 ; post: 28 ± 21 ; $p = 0.01$) following rehabilitation. Further, faster gait speed (pre: 1.1 ± 0.2 m/s; post: 1.2 ± 0.1 m/s; $p < 0.01$), less time in double stance (pre: $22 \pm 3\%$; DT: $20 \pm 3\%$; $p < 0.01$), and less stance time variability (pre: 0.7 ± 0.3 std; post: 0.6 ± 0.1 std; $p = 0.01$) during DT gait was observed. Pearson's correlations only yielded a significant relationship between the change (decrease) in total symptom score (SCAT3) and change (increased) ST gait speed (Pearson's $r = -0.38$; $p = 0.04$) in the mTBI group following vestibular rehabilitation. No other relationships were observed.

Discussion and Conclusion: This symptomatic, chronic mTBI group exhibited more symptoms, poorer gait performance, and slower secondary task response times than the control group before rehabilitation. Following rehabilitation, the mTBI group improved in all measures of gait performance, except for turning velocity and the DTC in secondary task response time compared to the control group. Though correlation analyses revealed a relationship between change in total symptom score and change in ST gait speed, there were no other relationships of note. The sparsity of relationships between total symptom score and gait performance suggests that symptoms may not be related to gait performance improvements following vestibular rehabilitation in this group. Ultimately, vestibular rehabilitation appears to improve gait performance independently of symptom severity, highlighting the importance of multimodal assessment in a symptomatic chronic mTBI population.

Acknowledgements: Funding was provided by the US Department of Defense (W81XWH-15-1-0620).

Central sensorimotor integration delays: does response latency to pseudorandom balance perturbations relate to reaction time?

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Background and Aim

The Central Sensorimotor Integration (CSMI) test identifies parameters that characterize mechanisms contributing to balance control. The identified parameters include a system time delay (TD) that represents the combined delays associated with sensory transduction, neural transmission, central processing, and muscle activation. We sought to determine if TD from the CSMI test correlated with two computerized measures; a simple reaction time (sRT) and a recognition reaction time (rRT) determined from a Go/No-Go task. We hypothesize that a chronic mild traumatic brain injury (mTBI) group will be slower than control subjects across both RTs and CSMI TDs, and that slower RT will be related to slower CSMI TDs.

Methods

Subjects included 52 controls (mean age 36.7 years) and 22 people with chronic (>3 month) balance complaints following a clinically diagnosed mTBI (mean age 39.1 years, mean time from injury 70.0 months). Participants completed the CSMI test and the Automated Neuropsychological Assessment Metrics (ANAM). The CSMI is performed using a modified Neurocom CRS (Natus Medical Inc.), adapted to deliver pseudorandom surface and/or visual tilt stimuli and collect sway data. The CSMI presents 2° and 4° (peak-peak) stimuli, respectively, in four sensory conditions: surface tilts with eyes closed (C1 and C2), surface tilts with eyes open (C3 and C4); visual tilts (C5 and C6), and combined surface-visual tilts (C7 and C8). The outcome variable for each CSMI condition is TD. The ANAM is a computerized clinical assessment of acute mTBI which provides sRT and rRT. Independent samples t-tests assessed group differences. Pearson's correlations assessed relationships between the RTs and CSMI TDs.

Results

There were no group differences for the RTs or CSMI TDs. Significant correlations were found between sRT and CSMI TD for C1($r=0.27$; $p=0.02$), C2($r=0.28$; $p=0.02$), C3($r=0.33$; $p<0.01$), C4($r=0.43$; $p<0.01$), C7($r=0.25$; $p=0.03$), and C8($r=0.35$; $p<0.01$). At the group level, only the control participants had a significant relationship between sRT and CSMI TD, but only for C2($r=0.44$; $p<0.01$), C3($r=0.42$; $p<0.01$), C4($r=0.55$; $p<0.01$), and C8($r=0.43$; $p<0.01$). Weaker, yet still significant, relationships were found between the rRT and CSMI TD for C3($r=0.26$; $p=0.02$), C4($r=0.36$; $p<0.01$), and C7($r=0.24$; $p=0.04$). At the group level, only the control participants maintained a significant relationship between rRT and CSMI TD for C2($r=0.37$; $p=0.01$), C3($r=0.38$; $p=0.01$), C4($r=0.51$; $p<0.01$), C7($r=0.31$; $p=0.03$), and C8($r=0.41$; $p<0.01$).

Conclusions

The chronic mTBI group did not perform differently than the control group in any RT or TD outcome measure. When assessing the relationship between RTs and CSMI TDs, the sRT yielded the strongest and most consistent relationships with the TDs. Only the control group exhibited significant relationships between RTs and TDs. Our future work will determine what factors alter the relationship between sRT and CSMI TD in people with chronic mTBI.

straight walking requiring dynamic coordination of the body and anticipatory control mechanisms. The complexity of turning may make it more susceptible to the negative effects of DT cognitive interference in HD. Furthermore, wearable inertial sensors show promise as a practical means to objectively assess gait deficits and disease severity in a clinical and research setting and to provide clinically meaningful motor outcome measures in clinical trials.

P2-H-69 Sensory contributions to head and lumbar sway in healthy individuals and those with mild traumatic brain injury

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BACKGROUND AND AIM: Balance deficits are a common clinical sign following mild traumatic brain injury (mTBI). Balance control involves the integration of visual, vestibular, and proprioceptive sensory information to control the motion of the center of mass (CoM). However, sensory information does not directly encode CoM motion; e.g., visual and vestibular information assess head motion. Thus head stability may be critical for balance when visual or vestibular information is important. Postural stability deficits and abnormal sensory integration in people with mTBI may manifest in different sway at the head. The purpose of this study was to address two primary questions: do individuals with mTBI exhibit greater sway at the CoM and head compared to controls, and is the relationship between sway at the head and CoM different between those with mTBI and controls. **METHODS:** Forty-two individuals with chronic (>3 months) balance complaints after a clinically diagnosed mTBI [28 females, mean(SD) 38 (2) years] and 54 healthy controls [31 females, mean (SD) 28 (4) years] participated in the study after providing consent. Subjects wore two inertial sensors (APDM Inc.) on the lumbar spine (approximate CoM) and across the forehead. Participants completed four balance tasks for 60 seconds each: (1) standing on firm ground with eyes open (EO-Firm), (2) and eyes closed (EC-Firm), (3) standing on foam surface with eyes open (EO-Foam), (4) and eyes closed (EC-Foam). The root mean square (RMS) of acceleration in AP and ML directions was calculated for the head and lumbar sensors. The ratios of head to lumbar sway were calculated in each direction for all conditions and normalized to body height. Linear mixed models assessed the effect of group, condition, and the group x condition interaction using $\alpha = 0.05$. **RESULTS:** Subjects with mTBI exhibited greater sway at both the head and lumbar for all conditions and directions ($p < 0.05$). Compared to baseline sway levels on the EO-Firm task, subjects with mTBI had larger AP and ML head sway than controls on all other conditions ($p < 0.03$), and larger AP and ML lumbar sway during EC conditions ($p < 0.03$). The ratio of head-to-lumbar AP sway did not differ between groups or conditions. However, the ML head-to-lumbar sway ratio was smaller in the Foam conditions compared to EO-Firm ($p < 0.001$), but this ratio was larger in subjects with mTBI than in controls, particularly in the EC-Foam condition ($p < 0.04$). **CONCLUSIONS:** People with mTBI exhibit greater postural sway at the head

and CoM, particularly when vision is removed. When relying on head-related sensory information (foam conditions), control subjects reduced the relative head-to-lumbar ML motion more than those with mTBI. The higher relative head motion in mTBIs than controls may indicate that subjects with mTBI exhibit abnormal sensory integration and balance strategies that impair head stabilization, particularly when accurate proprioception is compromised.

P2-H-70 Bridging the callosal gap in gait: A mechanistic evaluation of white matter's role in bilateral coordination

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BACKGROUND AND AIM: An essential part of mobility is bilateral coordination of the legs during locomotion. In the lower extremities, coordinated patterns produce locomotive actions with each leg operating in its own spatial and temporal pattern. The corpus callosum, the anatomical structure bridging the two hemispheres of the brain, is integral for the coordination of such complex, coordinated movements. Both coordinated movement and corpus callosum structural integrity are substantially compromised in persons with multiple sclerosis (PwMS). Thus, this aim of this project was to assess MRI-derived measures of transcallosal sensorimotor fiber tract microstructural integrity (via diffusion imaging) and identify the relation to gait coordination using novel methods of ecologically-valid mobility assessments in PwMS and age and gender-matched neurotypical adults. **METHODS:** Neurotypical adults (1 male and 6 females; 44 ± 18 years) and PwMS (3 males and 12 females; 52 ± 12 years) underwent three, two-minute walks at a self-selected pace, fast pace, and while dual-tasking. Lower limb asymmetries were quantified via the Phase Coordination Index (PCI), a comprehensive metric to evaluate bipedal coordination by assessing both the accuracy and consistency of phase generation in locomotion. White matter microstructural integrity of transcallosal tracts connecting homologous regions of the sensorimotor cortices was evaluated with diffusion tensor imaging. Radial diffusivity, an indirect marker of myelination, was utilized as the primary outcome. **RESULTS:** In our current sample, we report no significant main effect for condition ($p = 0.556$) or group ($p = 0.109$) with regards to PCI, nor a significant group by condition ($p = 0.846$) interaction. For transcallosal sensorimotor fiber tract microstructural integrity, we report a significant main effect for fiber tract ($p < 0.001$) and for group ($p = 0.013$), as well as a group by tract interaction ($p = 0.017$). Although not significant, PCI during self-selected walking was correlated with quality of fiber tracts connecting the primary motor cortices ($r = 0.39$; $p = 0.076$). Furthermore, PCI during dual-task walking was correlated with quality of fiber tracts connecting the supplementary motor areas (SMA; $r = 0.4$; $p = 0.065$) and pre-SMA ($r = 0.37$; $p = 0.088$). **CONCLUSIONS:** In this preliminary analysis of an ongoing data collection, results indicate that PwMS have increased impairment of bilateral coordination during over-ground walking and poorer transcallosal white matter microstructural integrity in comparison to an age and gender matched neurotypical cohort. Further, transcallosal fiber tract integrity