American Journal of Physical Medicine & Rehabilitation Articles Ahead of Print
DOI: 10.1097/PHM.0000000000002409

Utility of Structured Oculomotor, Balance, and Exercise Testing in Civilian Adults with Mild Traumatic Brain Injury (mTBI)

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Data is available upon request of the corresponding author.

Acknowledgements

We thank Nicholas Guzowski for his work coordinating the study. This study was funded by the Medical College of Wisconsin Advancing a Healthier Wisconsin Endowment. The REDCap database used for the study was supported by The Clinical and Translational Science Institute (NIH grant #2UL1TR001436).

Mary Simons is in training.

Abstract

Purpose

Assessments of oculomotor, balance, and exercise function detect different responses to mild traumatic brain injury (mTBI) in sport-related mTBI. These assessments are understudied in the adult community mTBI population. We evaluated level 1 trauma center patients with non-sports related mTBI on oculomotor functioning (near point of convergence [NPC] and accommodation [NPA]), balance (Balance Error Scoring System [BESS]), and exercise tolerance (Buffalo Concussion Treadmill Test [BCTT]).

Methods

A prospective, cohort study of adults with mTBI (N=36) were assessed at 1 week and (N=26) 1 month post-mTBI using NPC, NPA, BESS, BCTT, and the Rivermead Post Concussion Symptoms Questionnaire [RPQ]. Prevalence of test impairment and association between performance and mTBI-related symptom burden (RPQ scores) were characterized.

Results

Participants demonstrated varying levels of impairment (e.g., 33.3% oculomotor, 44.1% balance, and 55.6% exercise impairment at 1 week). Participants displayed diverse impairment profiles across assessments. We observed medium-to-large correlations between poorer NPC and BCTT performance and greater mTBI symptom burden.

Conclusions

Clinical examinations of oculomotor function, balance, and exercise adopted from sport-related concussion assessments detect impairment in adult community members with mTBI. While findings warrant larger-scale replication, they imply that incorporating these simple, structured exams into the assessment of mTBI may facilitate more personalized management strategies.

Key Words

Brain concussion, traumatic brain injury, vestibulo-ocular, exercise tests

What is Known: Assessments of oculomotor, balance, and exercise function are purported to detect differences in response to mild traumatic brain injury (mTBI) and direct personalized treatments. Researchers have encouraged the use of multimodal clinical assessment to identify ways in which sports-related concussion impacts individuals, however utility of multimodal assessment in a community population has been understudied.

What is New: This study used clinical examinations of oculomotor, balance, and exercise function in adult community members with mTBI. The findings support distinct phenotypes of civilian mTBI discerned through brief assessments and imply that incorporating these exams into the assessment of mTBI may facilitate more personalized management strategies.

Introduction

In the United States, traumatic brain injury (TBI) is a growing public health concern. Every year, there are approximately 2.8 million new emergency department (ED) and hospital visits for TBI, of which 75% were attributable to falls and motor vehicle accidents. [1] Of all TBI-related hospital visits, 80% are categorized as "mild" (mTBI), a subset of TBI classified as Glasgow Coma Scale (GCS) score of 13-15 and sometimes a negative head computed tomography (CT-) scan. [1] Although CT- mTBI has a good prognosis, symptoms can last from months to years in some cases. Level 1 trauma center patients with mTBI are at particularly high risk of persisting mTBI symptoms (i.e., persisting post-concussive symptoms, PPCS). [2] In this subpopulation of mTBI, the majority of patients continue to endorse mTBI-related symptoms at 12 months post-injury, [2, 3] and a recent meta-analysis estimated the prevalence of PPCS (reflecting multiple mTBI symptoms at 3–6 months) to be 31.3%. [4] In comparison to orthopedic controls, who can also report mTBI related symptoms, patients with mTBI experienced over twice the symptom burden a year after injury. [3]

It is possible that improved systems of care for civilian mTBI could improve outcomes. [5] Prior work indicates that mTBI often goes undiagnosed in EDs. [6, 7] Moreover, in a U.S. multicenter study, less than half of participants with mTBI received educational materials at ED discharge or had outpatient follow-up within 3 months of injury. [8] Concerningly, this included patients with complicated mTBI (positive image findings). [8] This can be contrasted to other mTBI subpopulations such as athletes with sport-related concussion (SRC), for whom international consensus guidelines, laws, and athletic policies support systematic follow-up and management to ensure safe and adequate recovery. [9]

One of the improvements seen in the management of SRC in the last 20 years has been the increased adoption of active and targeted treatment to prevent persisting mTBI-related symptoms. [2, 9-12] Recognizing the heterogeneity in the clinical and physiological effects of SRC, researchers have encouraged the use of multimodal clinical assessment strategies to identify the unique ways in which SRC impacts individuals and to design more personalized treatment programs. For example, Leddy and colleagues have proposed the existence of several concussion phenotypes/subtypes that are detectable through relatively simple office-based assessments. This model postulates the existence of a physiologic concussion (resulting from impaired global metabolism and detectable through structured exercise testing), which may be distinguished from problems of vestibulo-ocular and cervicogenic origins through additional examination of postural stability and oculomotor function, other among other tests. [13] In fact, it appears that proper detection and targeting of symptoms in acute and chronic phases leads to a reduction in or resolution of symptoms. [2, 13-15] Nevertheless, these tests and their utility in detecting distinct phenotypes of mTBI have not been studied in the broader non-athlete adult ("civilian") trauma population.

The objective of this study was to evaluate the potential utility of oculomotor, postural-stability and exercise testing assessments in the management of mTBI within the level 1 trauma center mTBI population. Individuals with CT- mTBI were prospectively recruited and longitudinally followed from 1 week to 1 month post-injury. Our specific aims were to (1) estimate the prevalence and patterns of dysfunction detected through these clinical exams in this population and (2) to characterize the relationship between clinical exam findings and mTBI-

related symptom outcomes. We hypothesized that the sample would show substantial heterogeneity in the pattern of dysfunction similar to other studies. [16]

Methods

Participants

This was a secondary analysis of data from a study of 36 participants with mTBI who were treated in a level 1 trauma center emergency department in Southeast Wisconsin and enrolled prospectively into this longitudinal cohort study. The broader study recruited 37 persons with mTBI, but one was excluded due to not completing any of the primary outcomes for this secondary analysis. Results from other outcomes within this sample have been previously reported. [17] The Institutional Review Board at the Medical College of Wisconsin approved the study. This study conforms to all STROBE guidelines and reports the required information accordingly (see Supplementary Checklist, http://links.lww.com/PHM/C261).

Inclusion and Exclusion Criteria

Inclusion criteria for the broader study required participants to be age 18–65; English-speaking; able to provide informed consent; and have no history of concussion or TBI in the past 6 months; no history of serious cardiovascular, neurologic, autonomic or endocrine disease; no medical contraindications to participate; and not currently pregnant. Diagnoses of mTBI were established from the American Congress of Rehabilitation Medicine definition, involving head trauma with an admission Glasgow Coma Scale (GCS) score of 13–15 and evidence of a disruption in normal physiological brain function (operationalized here as acute alteration in consciousness as evidenced by unconsciousness of 0–30 minutes, posttraumatic amnesia of 0–24

hours, any retrograde amnesia, and/or other evidence of altered mental status such as confusion or disorientation). [18] The study additionally required that there be no acute intracranial findings if any neuroimaging was performed. An additional inclusion criterion for this secondary analysis was having completed at least one primary outcome of interest at one or more study timepoints.

Assessment Protocol

Patients were assessed at 1 week (7 ± 3 days) and 1 month (30 ± 5 days) post-injury. The testing protocols were conducted by a trained research coordinator or research assistant. Research visits took approximately 2 hours and comprised a variety questionnaire, interview, and performance-based assessments. A summary of each assessment relevant to the current investigation is provided below.

Near Point of Convergence (NPC)/Accommodation (NPA) exam. This test takes 1-2 minutes and utilizes the Gulden's Near Point Rule with accommodation card and slider. The rule measures up to 50 cm long and is a 10 mm square (also contains units of Inches, Diopter scales and Duane Age). Participants were asked to keep any corrective lenses on during the exam. Participants were asked to focus on a convergence rule card containing a series of letters that begins at a distance and then is brought toward the participant slowly by the examiner. Once the participant began to see double, the individual was instructed to blink. If the participant continued to see double, the convergence *break* (NPC-break) score was recorded. The card was then slowly moved by the examiner away from the participant, and once the subject began to see one image, *recovery* (NPC-recovery) was recorded. NPA was examined by moving the rule card toward the subject with one eye covered, measuring the distance at which the image became and

remained blurry. The exam was then repeated, and the best of the two break, recovery, and accommodation scores (in cm) were used as the final scores. Using recommended normative values for NPC from von Noorden's textbook as reference, we characterized performance as impaired if greater than 10 cm for NPC-break/recovery. [19] NPA was characterized as impaired if it exceeded the upper limit of normal using the age-stratified normative data in a large published study. [20]

Balanced Error Scoring System (BESS). The BESS is a 3–5 minute test that assesses postural stability while participants hold three positions on the nondominant leg with their eyes closed: double leg stance, single leg stance, and tandem stance. Each position is held for 20 seconds on both a firm surface and a foam surface. Up to 10 errors in maintaining posture are scored per trial, resulting in a total score ranging from 0–60. Errors include moving hands off the iliac crests, opening the eyes, stepping/stumbling, abduction or flexion of the hip past 30 degrees, lifting the distal foot or heel off of the testing surface, or remaining out of the testing procedure for greater than 5 seconds. In addition to using continuous BESS total scores in correlational analyses, we scored each assessment as impaired or not impaired based on a normative dataset collected at our institution using an independent sample as follows:

Normative dataset for BESS. BESS norms were established from a subsample of persons recruited in a prior published study from the same ED as the present study. [21] Participants in the prior study were age 18–45 years old and had either sustained a CT- mTBI or an orthopedic injury. For the purpose of establishing normative values for the BESS, we identified participants tested with the BESS at the study endpoint (45 days post-injury) who reported being completely

recovered from their injuries at the time of the exam (N=93) and who had valid BESS data at 45 days post-injury (N=60; 43.3% male, age M = 28.2 [SD = 7.6] years). Based on analyses demonstrating a relationship between gender (but not age) and BESS total score in this sample, we established impairment thresholds as the worst 9th percentile of scores within a participants' gender group (male ≥ 18 BESS total errors, female ≥ 20).

Buffalo Concussion Treadmill Test (BCTT). The BCTT is a 15 minute test that was developed to measure mTBI-related physiological dysfunction and exercise intolerance in individuals with mild traumatic brain injury (mTBI). Participants walked on a treadmill at 3.2 mph starting with a 0-degree incline, and the incline was increased 1 degree every minute until a discontinue criterion or the test endpoint (15 minutes) was reached. At the end of each minute, participants were asked to report their level of exertion using the Borg Scale (range 6–20, where higher ratings reflect greater perceived exertion). Severity of any mTBI-related symptoms was further monitored using the Visual Analog Scale (VAS). The VAS is a scale used evaluate discomfort or pain levels, ranging from 1–10. Participants were asked to use the VAS to rate any physical symptoms such as dizziness or headache they experienced during the assessment. This protocol was adapted from the original protocol in three ways: (1) the starting speed was held constant at 3.2 mph (whereas in the original protocol some participants start at a faster speed), (2) the maximum duration of the task was shortened from 20 to 15 minutes, and (3) to accommodate saliva collection not relevant to this paper, the treadmill was paused for 2 minutes after 5 minutes of walking and then restarted. Discontinuation criteria included: Borg rating of 18 (exhaustion) or higher, increase in VAS score of 3 points from a previous rating, any rapid

progression of complaints reported to the examiner (e.g., severe focal pain), or report of feeling unable to continue the test safely.

Examiners recorded the reasons for discontinuation. We categorized participants into one of the following categories based on completion of the BCTT and behavioral reasons the BCTT was not completed: Did not discontinue (completed exam; 13.9% at 1 week), mTBI symptom exacerbation (36.1% at 1 week), peripheral/other symptom exacerbation (25.0% at 1 week), exertion (22.2% at 1 week), and other (2.8%). Previous research has defined the resolution of physiological post-concussive symptoms as ability to voluntarily exercise to 85-90% of age predicted maximum HR without increase in mTBI symptoms. [22] Therefore, we characterized performance as impaired if the BCTT was discontinued early due to mTBI symptom exacerbation or if it was discontinued due to exertion before a participant's heart rate had reached 85% of their age-predicted maximum. [10]. In addition to the binary impaired versus not impaired outcome, analyses used the continuous variable of exam duration (number of minutes). [13]

Rivermead Post Concussion Symptoms Questionnaire (RPQ). The RPQ is a validated self-report inventory of 16 symptoms commonly experienced after mTBI. Symptoms experienced over the past 24 hours were rated according to the severity relative to any pre-injury symptoms on a 0–4 scale (0=not experienced at all, 1=no more of a problem [than pre-injury], 2=A mild problem, 3=A moderate problem, 4=A severe problem). Ratings of 1 were treated as 0 for summation. We computed total scores (sum of all items; range 0–64) as well as physical, cognitive, emotional, and visual symptom subscale scores.

Statistical Analysis

Statistical analyses were conducted using IBM SPSS Statistics (version 27, Armonk, NY). The UpSet plot was produced in R Statistical Software [[23], version 4.2.1] using the UpSet R package (version 1.4.0). [24] Sample demographic and injury characteristics were summarized as means (standard deviations) or frequencies (percentages). Factors that predicted retention (attendance at the 1-month post-injury appointment) were examined using logistic regression. We calculated the percentage of participants who performed in the impaired range on the aforementioned five tests: NPC-break, NPC-recovery, NPA, BESS, and BCTT. Associations between performance on these exams (in their original continuous scales) and RPQ symptom burden (total score and physical, cognitive, emotional, and visual subscales) were computed using Pearson correlations. Correlations were considered statistically significant if $p < .05$. With a sample size of 36 we would expect 80% power ($\alpha = 5\%$) to detect a Pearson correlation of $r = 0.45$.

Results

Participant Characteristics

Table 1 portrays the demographic and injury characteristics of our sample. Our sample was 50.0% male, 47.2% female, 2.8% other gender; 63.9% Black; and 88.9% Non-Hispanic with a mean age of 32.2 years (SD = 11.3; range 18–62). Common causes of injury included motor vehicle-traffic crash (77.8%), fall (11.1%), assault (2.8%), struck by/against (2.8%), other (5.6%). Although our inclusion criteria required some form of acute altered mental status, a minority of the sample experienced unconsciousness (27.8%) and posttraumatic amnesia (33.4%).

Attending the 1-month follow-up appointment was predicted by older age (p = .042; OR = 1.14 [95% CI 1.004 – 1.285]) but was not predicted by gender (p= .889), race (p = .199), ethnicity (p = .309), body mass index (p = .984), years of education (p = .808), or 1-week RPQ total score (p = .712).

Prevalence of Impairment on Oculomotor, Balance, and Exercise Tests

The prevalence of impairment on each individual clinical exam is reported in **Table 1**. At 1 week post-injury, impairment rates ranged from 14.7% (NPC-Break) to 58.8% (NPA). At 1 month, impairment rates ranged from 20.8% (NPC-Break) to 54.2% (NPA). Across time, impairment was most prevalent for NPA, followed by the exercise test (BCTT) and balance test (BESS) and, lastly, NPC-Break.

The prevalence of each profile of impairment observed across tests (within the cohort with complete data) is depicted in **Figure 1** (1 week) and **Figure 2** (1 month).

Displayed impairments emphasize heterogeneity in impairment profiles at both timepoints. In particular, 17 distinct profiles were found among the 33 individuals with complete data at 1 week post-injury; 12 profiles were found among 24 individuals who completed the 1-month follow-up exam. Impairments commonly co-occurred and displayed a variety of combinations across domains (i.e., oculomotor, balance, exercise). The percentage of domains impaired in different numbers of clinical domains (oculomotor, balance, exercise) at 1 week are as follows: 0 domains (3.0%) 1 domain (33.3%), 2 domains (54.5%), and 3 domains (9.1%). At one month, the percentages were as follows: 0 domains (12.5%) 1 domain (25.0%), 2 domains

(54.2%), 3 domains (8.3%). Among those who displayed an isolated impairment in one domain, it was most commonly the oculomotor domain (18.2% at 1 week and 20.8% at 1 month), followed by exercise (12.1% at 1 week and 4.2% at 1 month), and balance (3.0% at 1 week and 0.0% at 1 month).

Association Between Test Performance and mTBI Symptomatology

Figure 3 depicts a heat map of correlations between clinical assessments of mTBI and reported mTBI-related symptom (RPQ) domains over time.

Because of sample size restrictions at follow-up we focused our interpretation mostly on the 1-week data, but all correlations across time are provided. Overall, associations were most robust for NPC, with poorer (longer) break and recovery distance associated with higher mTBI symptom burden (e.g., NPC-break versus RPQ total score at 1 week $r = 0.46$). We also observed robust correlations between better BCTT performance (longer exam duration) and lower mTBI symptom burden (e.g., $r = 0.34$ at 1 week). Surprisingly, associations between NPC performance and symptom domains were stronger for physical, cognitive, and emotional symptom domains ($r = 0.36$–0.52 at 1 week).

Discussion

In this study, we evaluated how adult level 1 trauma center patients with mTBI performed on brief clinical assessments of oculomotor (NPC/NPA), balance (BESS), and exercise (BCTT) functioning. Considering these assessments are frequently used and increasingly recommended to direct the clinical management of sport-related mTBI, we aimed to

provide preliminary data that would inform the potential utility of these assessments in the assessment and management of the adult mTBI community. We found that a substantial proportion of our prospectively recruited sample met established thresholds for impairment on each exam across the first month post-injury (range 14.7%-58.8%) and that some impairments (particularly those on the NPC and BCTT exams) correlated robustly with diverse mTBI-related symptoms. These findings imply that these clinical assessments commonly detect physical/neurologic dysfunction that may be attributable to mTBI in level 1 trauma center ED patients.

Second, we observed diverse profiles of impairment across the tests administered, which indicates that these tests provide distinct information about the functioning of various systems that may be impacted by mTBI. Taken together, the findings support assertions that there are distinct clinical phenotypes of mTBI that can be discerned through brief assessments such as the NPC/NPA examination, BESS, and BCTT.[13]

Interestingly, we found that performance on the NPC exam correlated robustly with diverse mTBI-related symptoms measured by the RPQ. Unexpectedly, at 1-week post-injury, associations between NPC functioning and symptoms were strongest for physical, cognitive, and emotional symptoms and were trivial and nonsignificant with visual symptoms. This aligns with literature on other phenomenon (e.g., cognitive functioning, sleep) indicating a disconnect between subjective and objective tests and reinforces that subjective symptom assessments are not a substitute for performance-based tests. The magnitude of associations further implies that these performance-based exams are not redundant with subjective symptom assessments. The

findings hint at the potential for more detailed, multimodal clinical examinations to inform the detection and treatment of different sequelae of mTBI.

Considering future clinical evaluation, it is important to establish prognostic value. Aside from the aforementioned complexities in objective versus subjective reporting, we found strong correlations between initial assessments and reported symptoms at one month. Specifically, mTBI-related deficits on the BCTT and NPC were moderately to highly correlated with higher scores on the RPQ. However, BESS examination at 1 week did not have the same relationships with mTBI symptoms. This could be due to a variety of factors, such as variations in the reliability of these exams. The BESS exam, in particular, has been criticized for suboptimal repeatability and inter-rater reliability and limited capability to detect more subtle exam findings.[25, 26]

These findings support continued research into best practices for the evaluation and clinical management of civilian mTBI, for which coordinated systems of care are currently lacking.[7, 8] Targeted evaluations based on treating PPCS in young athletes highlight important potential future therapeutic targets. In a recent study of athletes suffering from sport-related concussion, individualized (based on BCTT performance) targeted heart rate sub-symptom threshold aerobic exercise prescribed 2–10 days from injury facilitated recovery when compared with stretching controls.[27] Consistent with other studies, they found that early treatment with exercise safely hastens recovery and, importantly, significantly reduced the risk for PPCS.[11, 28, 29]

Similarly, effective oculo-vestibular rehabilitation to address abnormalities has recently gained traction. Currently, the screening process involves a TBI-related symptom questionnaire and basic eye exam. Further treatment involves correction with lenses and office-based rehabilitation with home-reinforcement. [28] These studies demonstrate improvement in objective and subjective consequences of TBI with programs aimed at correcting specific dysfunction. [28, 30] Patient-tailored rehabilitation on a national scale is currently hindered due to lack of consistent methodologies and coordination among health professionals. [28] More insight into the benefit of treatment and refined protocols are the next step to translate these findings into practice to improve patient outcomes.

Limitations

Our sample was limited in size, which necessitated a descriptive approach and indicates a need for larger scale replication and validation. Further, generalizability of these findings is limited to other mTBI populations with similar characteristics (e.g., adults treated in level 1 trauma centers). Second, although we used independently developed norms to interpret the oculomotor and balance exams, the tests are lacking in widely established, validated normative data from which to interpret performance for adults ranging widely in age. Lastly, our study was not powered to examine clinically relevant questions such as the relationship between interventions and recovery of these clinical functions. On the other hand, the sample was unique in being among the first to undergo multimodal clinical assessments comprising oculomotor, balance, and exercise tolerance testing on a prospectively recruited level 1 trauma center adult mTBI sample.

Conclusions

Multimodal assessment of oculomotor function, balance, and exercise tolerance is widely accepted and recommended to assess youth with SRC but not routinely for adult community mTBI settings. We provide preliminary evidence that these assessments commonly reveal evidence of clinical impairments that are often unique from self-reported symptoms alone. Furthermore, multiple clinical impairments in oculomotor, balance, and exercise tests highlight the diversity of clinical findings in mTBI samples and the potential value of a multimodal assessment approach for adult community mTBI monitoring.

Conflict of Interest

The results of the present study do not constitute endorsement by ACSM. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The authors have no conflicts of interest with this work. Dr. Leddy received compensation as a member of the SAB for Neuronasal and Quadrant Biosciences as well as minority stock options in Highmark Innovations and 360 Concussion Care.

References

1. Taylor CA, Bell JM, Breiding MJ, Xu L. Traumatic Brain Injury-Related Emergency Department Visits, Hospitalizations, and Deaths - United States, 2007 and 2013. MMWR Surveill Summ. 2017;66(9):1-16.
2. Leddy JJ, Baker JG, Willer B. Active Rehabilitation of Concussion and Post-concussion Syndrome. Phys Med Rehabil Clin N Am. 2016;27(2):437-54.
3. Machamer J, Temkin N, Dikmen S, Nelson LD, Barber J, Hwang P, et al. Symptom Frequency and Persistence in the First Year after Traumatic Brain Injury: A TRACK-TBI Study. J Neurotrauma. 2022;39(5-6):358-70.
4. Cancelliere C, Verville L, Stubbs JL, Yu H, Hincapie CAA, Cassidy JD, et al. Post-concussion symptoms and disability in adults with mild traumatic brain injury: a systematic review and meta-analysis. J Neurotrauma. 2022.
5. In: Matney C, Bowman K, Berwick D, editors. Traumatic Brain Injury: A Roadmap for Accelerating Progress. Washington (DC)2022.
6. Cota MR, Moses AD, Jikaria NR, Bittner KC, Diaz-Arrastia RR, Latour LL, et al. Discordance between Documented Criteria and Documented Diagnosis of Traumatic Brain Injury in the Emergency Department. J Neurotrauma. 2019;36(8):1335-42.
7. Powell JM, Ferraro JV, Dikmen SS, Temkin NR, Bell KR. Accuracy of mild traumatic brain injury diagnosis. Arch Phys Med Rehabil. 2008;89(8):1550-5.
8. Seabury SA, Gaudette E, Goldman DP, Markowitz AJ, Brooks J, McCrea MA, et al. Assessment of Follow-up Care After Emergency Department Presentation for Mild Traumatic Brain Injury and Concussion: Results From the TRACK-TBI Study. JAMA Netw Open. 2018;1(1):e180210.

9. McCrea M, Guskiewicz K. Evidence-based management of sport-related concussion. Prog Neurol Surg. 2014;28:112-27.

10. Leddy JJ, Cox JL, Baker JG, Wack DS, Pendergast DR, Zivadinov R, et al. Exercise treatment for postconcussion syndrome: a pilot study of changes in functional magnetic resonance imaging activation, physiology, and symptoms. J Head Trauma Rehabil. 2013;28(4):241-9.

11. Leddy JJ, Haider MN, Ellis M, Willer BS. Exercise is Medicine for Concussion. Curr Sports Med Rep. 2018;17(8):262-70.

12. Leddy JJ, Willer B. Use of graded exercise testing in concussion and return-to-activity management. Curr Sports Med Rep. 2013;12(6):370-6.

13. Ellis MJ, Leddy JJ, Willer B. Physiological, vestibulo-ocular and cervicogenic post-concussion disorders: an evidence-based classification system with directions for treatment. Brain Inj. 2015;29(2):238-48.

14. Marshall S, Bayley M, McCullagh S, Velikonja D, Berrigan L, Ouchterlony D, et al. Updated clinical practice guidelines for concussion/mild traumatic brain injury and persistent symptoms. Brain Inj. 2015;29(6):688-700.

15. Kontos AP, Collins MW, Holland CL, Reeves VL, Edelman K, Benso S, et al. Preliminary Evidence for Improvement in Symptoms, Cognitive, Vestibular, and Oculomotor Outcomes Following Targeted Intervention with Chronic mTBI Patients. Mil Med. 2018;183(suppl_1):333-8.

16. Kontos AP, Sufrinko A, Sandel N, Emami K, Collins MW. Sport-related Concussion Clinical Profiles: Clinical Characteristics, Targeted Treatments, and Preliminary Evidence. Curr Sports Med Rep. 2019;18(3):82-92.

17. Musacchio S, Kallenbach, M. D., Huber, D. L., Raff, H., Johnson, B. D., Leddy, J., McCrea, M. A., Meier, T. B., & Nelson, L. D. (in press). . Salivary cortisol dynamics after mild traumatic brain injury. . Journal of Head Trauma Rehabilitation. 2022.

18. Rehabilitaion JoHT. Definition of Mild Traumatic Brain Injury: Aspen Publishers, Inc.; 1993.

19. Noorden GV. Physiology of the ocular movements. Binocular vision and ocular motility. 6th 2002. p. 52-84.

20. Duane A. Studies in Monocular and Binocular Accommodation, with Their Clinical Application. Trans Am Ophthalmol Soc. 1922;20:132-57.

21. Nelson LD, Furger RE, Gikas P, Lerner EB, Barr WB, Hammeke TA, et al. Prospective, Head-to-Head Study of Three Computerized Neurocognitive Assessment Tools Part 2: Utility for Assessment of Mild Traumatic Brain Injury in Emergency Department Patients. J Int Neuropsychol Soc. 2017;23(4):293-303.

22. Leddy JJ, Kozlowski K, Donnelly JP, Pendergast DR, Epstein LH, Willer B. A preliminary study of subsymptom threshold exercise training for refractory post-concussion syndrome. Clin J Sport Med. 2010;20(1):21-7.

23. Team RC. R: A language and environment for statistical computing. R package. 1.4.0 ed. Vienna, Austria: R Foundation for Statistical Computing; 2022.

24. Gehlenborg N. UpSetR: A More Scalable Alternative to Venn and Euler Diagrams for Visualizing Intersecting Sets. R package. 1.4.0 ed2019.

25. Bell DR, Guskiewicz KM, Clark MA, Padua DA. Systematic review of the balance error scoring system. Sports Health. 2011;3(3):287-95.

26. Murray N, Salvatore A, Powell D, Reed-Jones R. Reliability and validity evidence of multiple balance assessments in athletes with a concussion. J Athl Train. 2014;49(4):540-9.

27. Leddy JJ, Master CL, Mannix R, Wiebe DJ, Grady MF, Meehan WP, et al. Early targeted heart rate aerobic exercise versus placebo stretching for sport-related concussion in adolescents: a randomised controlled trial. Lancet Child Adolesc Health. 2021;5(11):792-9.

28. Fox SM, Koons P, Dang SH. Vision Rehabilitation After Traumatic Brain Injury. Phys Med Rehabil Clin N Am. 2019;30(1):171-88.

29. Leddy JJ, Haider MN, Ellis MJ, Mannix R, Darling SR, Freitas MS, et al. Early Subthreshold Aerobic Exercise for Sport-Related Concussion: A Randomized Clinical Trial. JAMA Pediatr. 2019;173(4):319-25.

30. Schlemmer E, Nicholson N. Vestibular Rehabilitation Effectiveness for Adults With Mild Traumatic Brain Injury/Concussion: A Mini-Systematic Review. Am J Audiol. 2022;31(1):228-42.

Figure Captions

Figure 1. Prevalence of distinct profiles of impairment across oculomotor, balance, and exercise tests in adult with mild traumatic brain injury (mTBI) at 1 week post-injury (complete case analysis; n=33; one subject had no impairments across assessments). BCTT, Buffalo Concussion Treadmill Test (impairment reflects early discontinuation due to mTBI-related symptom exacerbation or exertion before HR exceeded 85% of predicted maximum); BESS, Balance Error Scoring System; NPA, near point of accommodation; NPC, near point of convergence.

Figure 2. Prevalence of distinct profiles of impairment across oculomotor, balance, and exercise tests in adult with mild traumatic brain injury (mTBI) at 1 month post-injury (complete case analysis; n=24; three subjects had no impairments across assessments). BCTT, Buffalo Concussion Treadmill Test (impairment reflects early discontinuation due to mTBI-related symptom exacerbation or exertion before HR exceeded 85% of predicted maximum); BESS, Balance Error Scoring System; NPA, near point of accommodation; NPC, near point of convergence.

Figure 3. Pearson correlations between clinical exam performance and mTBI-related symptom burden. NPC, Near Point of Convergence; NPC-B, NPC break; NPC-R, recovery; NPA, Near Point of Accommodation; NPA-R, NPA right eye; NPA-L, left eye; BESS, Balance Error Scoring System; BCTT, Buffalo Concussion Treadmill Test Duration; mTBI, mild traumatic brain injury; RPQ, Rivermead Post Concussive Symptoms Questionnaire; White, Low correlation with assessment performance and reported symptoms; Black, High correlation with assessment performance and reported symptoms (* Indicates $p<0.05$.).

Figure 1

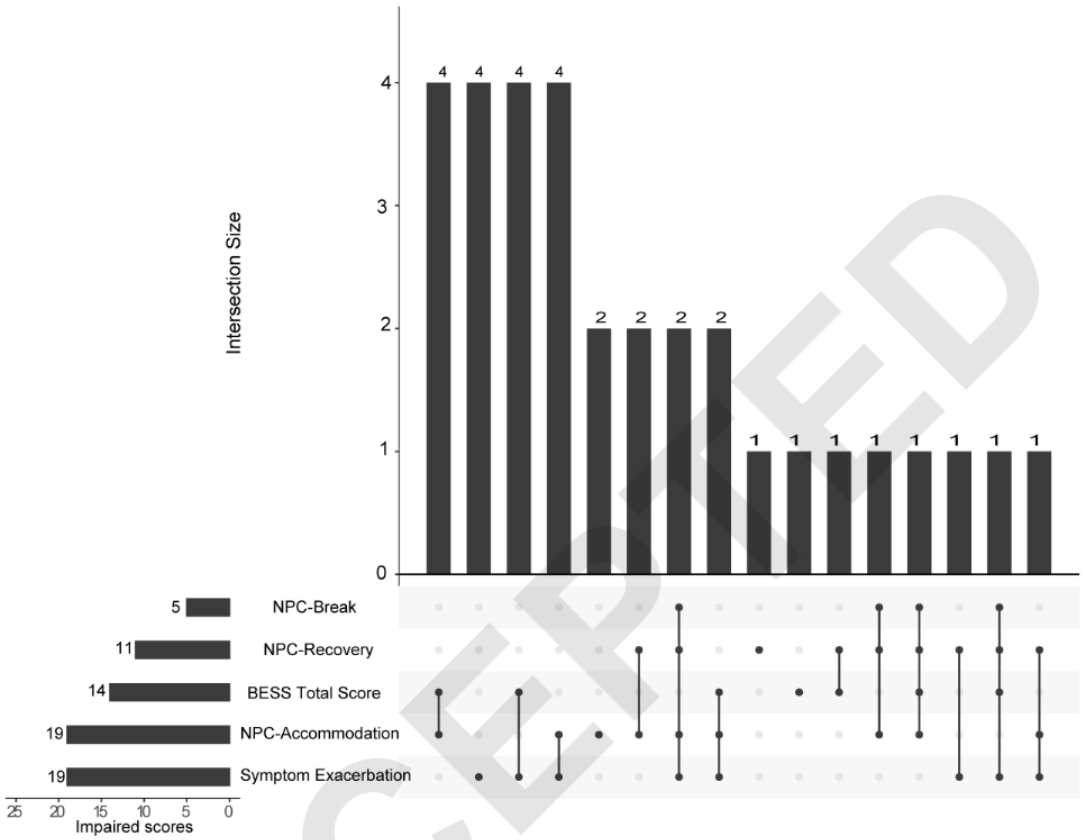


Figure 2

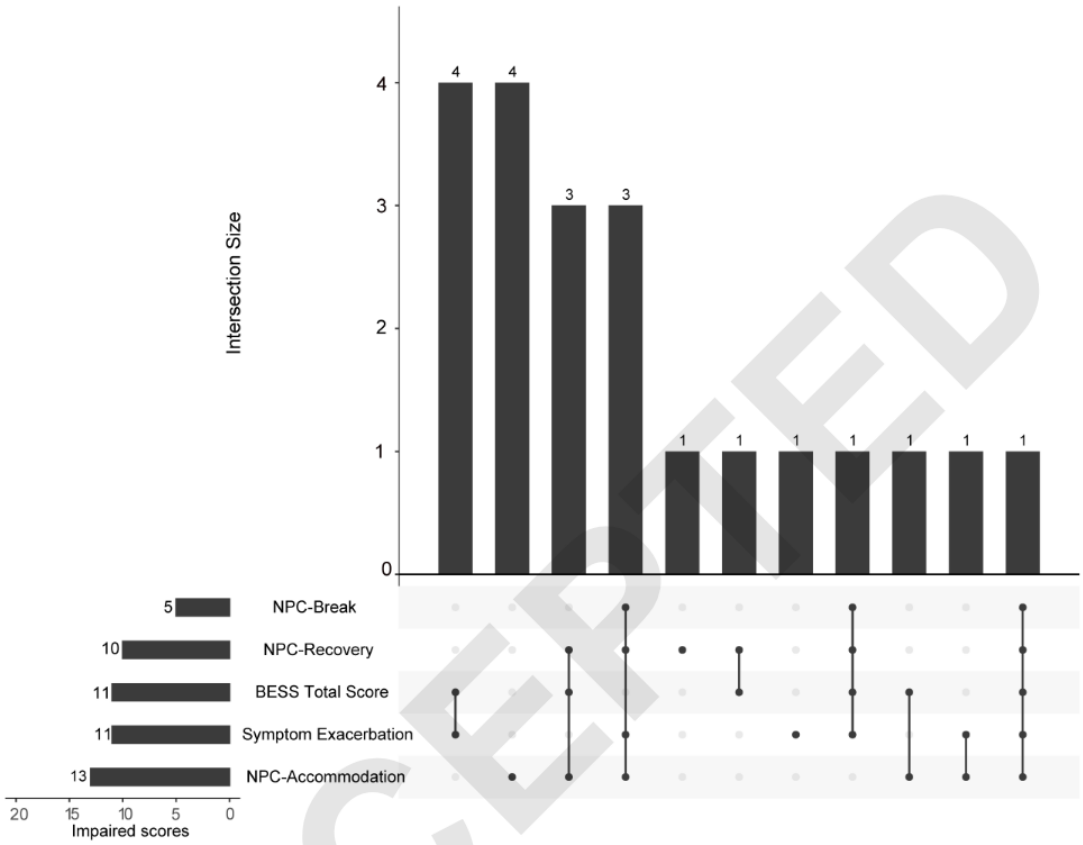
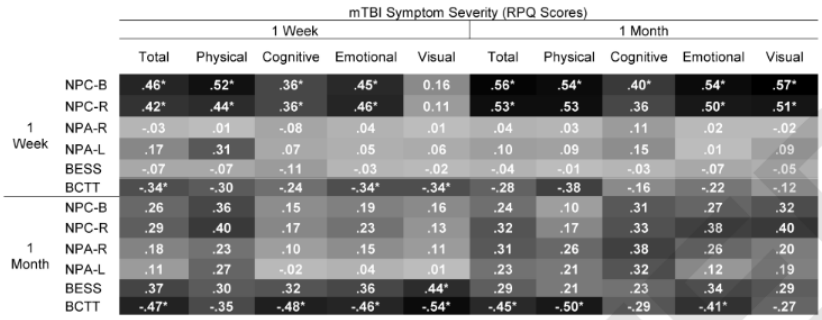


Figure 3



		mTBI Symptom Severity (RPQ Scores)									
		1 Week					1 Month				
		Total	Physical	Cognitive	Emotional	Visual	Total	Physical	Cognitive	Emotional	Visual
1 Week	NPC-B	.46*	.52*	.36*	.45*	0.16	.56*	.54*	.40*	.54*	.57*
	NPC-R	.42*	.44*	.36*	.46*	0.11	.53*	.53	.36	.50*	.51*
	NPA-R	-.03	.01	-.08	.04	.01	.04	.03	.11	.02	-.02
	NPA-L	.17	.31	.07	.05	.06	.10	.09	.15	.01	.09
	BESS	-.07	-.07	-.11	-.03	-.02	-.04	-.01	-.03	-.07	-.05
	BCTT	-.34*	-.30	-.24	-.34*	-.34*	-.28	-.38	-.16	-.22	-.12
1 Month	NPC-B	.26	.36	.15	.19	.16	.24	.10	.31	.27	.32
	NPC-R	.29	.40	.17	.23	.13	.32	.17	.33	.38	.40
	NPA-R	.18	.23	.10	.15	.11	.31	.26	.38	.26	.20
	NPA-L	.11	.27	-.02	.04	.01	.23	.21	.32	.12	.19
	BESS	.37	.30	.32	.36	.44*	.29	.21	.23	.34	.29
	BCTT	-.47*	-.35	-.48*	-.46*	-.54*	-.45*	-.50*	-.29	-.41*	-.27

Table 1. Sample characteristics (N = 36 persons with mild traumatic brain injury)

	M (SD) or n (%)	
N complete at 1 week | 1 month post-injury	36 | 26	
Age	32.2 (11.3)	
Gender		
Female	17 (47.2%)	
Male	18 (50.0%)	
Other	1 (2.8%)	
Race, n (%)		
Black	23 (63.9%)	
White	11 (30.6%)	
Other/not reported	2 (5.6%)	
Ethnicity		
Hispanic/Latino	4 (11.1%)	
Not Hispanic/Latino	32 (88.9%)	
Body mass index	28.15 (6.15)	
Years of education	12.6 (1.8)	
Cause of injury, n (%)		
Motor vehicle-traffic crash	28 (77.8%)	
Fall	4 (11.1%)	
Assault	1 (2.8%)	
Struck by/against	1 (2.8%)	
Other	2 (5.6%)	
Acute injury characteristics, n (%)		
Loss of consciousness	10 (27.8%)	
Post-traumatic amnesia	12 (33.4%)	
Retrograde amnesia	5 (13.9%)	
Other altered mental status[1]	36 (100%)	
mTBI-related symptom severity	1 Week	1 Month
RPQ total score	20.3 (15.6)	17.0 (15.2)
Prevalence of impairment	1 Week	1 Month
NPC-break	5/34 (14.7%)	5/24 (20.8%)
NPC-recovery	12/34 (33.3%)	10/24 (41.6%)
NPA	20/34 (58.8%)	13/24 (54.2%)
BESS	15/34 (44.1%)	12/25 (48.0%)
BCTT mTBI symptom exacerbation	20/36 (55.6%)	12/25 (48.0%)

Note. RPQ, Rivermead Post Concussive Symptoms Questionnaire.

[1]Other altered mental status includes signs other than unconsciousness and amnesia such as self-reported or observed confusion or disorientation.