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TITLE: The Sensor Technology and Rehabilitative Timing (START) Protocol: A Randomized Controlled Trial for the Rehabilitation of Mild Traumatic Brain Injury

RUNNING HEAD: Rehabilitation Timing and Wearable Sensors for Home Exercise in mTBI

TOC CATEGORY: Neurology

ARTICLE TYPE: Protocols

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KEYWORDS: Rehabilitation, mTBI, Concussion, Wearable Sensors, Balance, Gait

ACCEPTED: October 4, 2019

SUBMITTED: June 15, 2018

Background. Clinical practice for rehabilitation after mild traumatic brain injury (mTBI) is variable and guidance on when to initiate physical therapy is lacking. Wearable sensor technology may aid clinical assessment, performance monitoring and exercise adherence, potentially improving rehabilitation outcomes during unsupervised home exercise programs.

Objective. The objectives of this study were to 1) determine whether initiating rehabilitation earlier than typical will improve outcomes after mTBI; and 2) examine whether using wearable sensors during a home-exercise program will improve outcomes in participants with mTBI.

Design. This was a randomized controlled trial.

Setting. Academic hospital; Oregon Health & Science University, Portland Veterans Affairs Health Care System, and in the home environment.

Participants. This study will include 160 individuals with mTBI.

Intervention. The early intervention group (n = 80) will receive one-on-one physical therapy 8 times over 6 weeks and complete daily home-exercises. The standard care group (n = 80) will complete the same intervention after a 6 to 8-week wait period. Half of each group will receive wearable sensors for therapist monitoring of patient adherence and quality of movements during their home exercise program.

Measurements. The primary outcome measure will be the Dizziness Handicap Inventory score. Secondary outcome measures will include: symptomatology, static and dynamic postural control, central sensorimotor integration posturography, and vestibular-ocular-motor function.

Limitations. Potential limitations include variable onset of care, a wide range of ages, possible low adherence and/or withdrawal from the study in the standard of care group, and low DHI scores effecting ceiling for change after rehabilitation.

Conclusions. If initiating rehabilitation earlier improves primary and secondary outcomes post-mTBI, this could help shape current clinical care guidelines for rehabilitation. Additionally, using wearable sensors to monitor performance and adherence may improve home-exercise outcomes.

There is currently limited evidence supporting when rehabilitation for mild traumatic brain injury (mTBI) should be initiated, and as a result, clinical care guidelines for rehabilitation of mTBI lack consistency.[1-3] This lack of consensus means rehabilitative methods can vary post-mTBI. As an example, many individuals may not be referred to rehabilitation at all (eg, only 20% referred to rehabilitation),[4] while some may be prescribed rest within the first few days following injury[5]. Although prolonged or strict bedrest may be counterproductive,[6-8] guidelines are less clear when symptoms do not resolve after a few weeks. Nevertheless, preliminary evidence suggests that beginning subthreshold activity early, as part of a multimodal rehabilitation program, is safe and may be beneficial.[9-10]

Faster recovery of symptoms and earlier return-to-play has been found following progressive individualized physical therapy initiated approximately 10 days post-mTBI in comparison with controls that received sub-therapeutic, non-progressive therapy.[11] Though these findings suggest it may be safe to intervene around 10 days post-mTBI, they do not provide information on whether early intervention is of benefit over delayed rehabilitation. Given mTBI patients may not commence physical therapy until several months post injury (i.e. median time reported to be 61 days[12]), knowing if early initiation of physical therapy leads to better outcomes than delayed physical therapy, or vice-versa, is a pertinent question.

Another critical question relates to the performance of home exercises by patients undertaking physical therapy. With the majority of mTBI rehabilitation completed unsupervised at home, there is the potential for patients to perform exercises less than prescribed, and to perform them incorrectly.[13-14] These factors may impact a person's progression through rehabilitation.[15-16] People with vestibular pathology have impaired proprioception, such as perceived head relative to trunk position.[17] Given mTBI is a diffuse injury, where vestibular

problems may exist, persons with mTBI may be unable to successfully complete their prescribed movements. Further, these patients may exhibit avoidance behavior and develop maladaptive strategies such as limiting the head range-of-motion and turning speed to minimize symptoms. Unfortunately, subtle head and neck movement impairments may not be detected visually, even by clinicians.[18] One solution that may improve outcomes is to provide clinicians with objective feedback on the quality of the head and trunk movements that would otherwise be undetectable during the home exercise program. Advances in wearable technologies allow this information to be collected. Thus, using a wearable sensor during rehabilitation has the potential to: 1) provide objective measures of impairment, 2) monitor quality and rate of improvement in home-exercise performance, and 3) enable patients to eventually monitor their own progress to increase their adherence to home-exercise regimen.

The aims of this study are to: 1) determine whether initiating rehabilitation earlier than typical will improve outcomes after mTBI and 2) examine whether using wearable sensors to monitor adherence and performance during a home-exercise program will improve outcomes in participants with mTBI. We hypothesize that early intervention will lead to greater improvements in primary and secondary outcomes relative to standard care timing. Our second hypothesis is that a home-exercise program involving the use of wearable sensors that is reviewed weekly by the physical therapist will improve primary and secondary outcomes.

[H1] Methods

[H2] Design

This randomized controlled trial will include a total of 160 individuals with mTBI who will be randomly assigned to 1 of 4 groups: 1) early intervention (n = 80), with 40 assigned to

rehabilitation and 40 assigned to rehabilitation with wearable sensors; or the 2) standard care timing for rehabilitation (n = 80), with 40 assigned to rehabilitation and 40 assigned to rehabilitation with wearable sensors (Figure).

[H2] Setting

The testing sessions and physical therapy sessions will take place within an academic hospital setting at Oregon Health & Science University (OHSU), and Portland Veterans Affairs Health Care System (VAPORHCS). The home exercise portion will take place at each participant's home.

[H2] Participants

Individuals within 12 weeks of mTBI will be recruited using non-probability, convenience sampling methods. Recruitment flyers will be posted on community noticeboards throughout the Portland metropolitan and surrounding areas, including but not limited to locations such as hospitals and clinics, universities, community recreation centers, gymnasium and sporting facilities, cafes, and public noticeboards. In addition, flyers will be provided to patients being treated at the OHSU concussion clinic, as well as affiliated and supporting medical clinics. Study information will be accessible on the OHSU website, using search terms such as 'concussion' and 'mild Traumatic Brain Injury' or 'mTBI'. A phone screening call will be used to follow up with any interested participants.

Inclusion criteria will consist of participants: 1) having a diagnosis of mTBI within 12 weeks;[19] 2) being between 18-60 years old; 3) having sport concussion assessment tool version 5 (SCAT5) symptom evaluation sub-score $\geq$ 1 for balance, dizziness nausea, headache or vision AND a minimum total score of 15; 4) and having no or minimal cognitive impairment ($\leq$ 9 on the Short Blessed Test).[20] Exclusion criteria will consist of participants: 1) having other

musculoskeletal, neurological, or sensory deficits that could explain dysfunction; 2) having moderate to severe substance-use disorder within the past month[21]; 3) being in severe pain during the evaluation (≥7/10 subjective rating); 4) being pregnant; 5) being unable to abstain from medications that might impair balance 24 hours before testing; 6) having contraindications to rehabilitation such as unstable c-spine; and 7) actively participating in physical therapy for their concussion. Participants are permitted to undertake other forms of treatment for their symptoms such as massage, acupuncture, and counseling. The mechanism of injury will not be restricted, including whiplash if they pass the cervical screen.

Participants assigned to the early intervention will be within the acute to post-acute stage, while the participants in the standard care group will be in the post-acute period or at the beginning of the chronic stage. Previous work has defined 0 to 7 days post-mTBI to be the immediate period, 1 to 6 weeks the acute period, 7 to 12 weeks the post-acute period, and > 12 weeks to be the chronic period.[19] All mTBI diagnoses will be confirmed by a physician and will be defined with the following criteria: no CT scan (or a normal CT scan if obtained), loss of consciousness not exceeding 30 min, alteration of consciousness/mental state up to 24 h, and post-traumatic amnesia not exceeding one day.[19]

[H2] Blinding and Randomization

Key researchers involved in testing and data analysis will be blinded to group assignment. The study coordinator, physical therapists (JW and NP), and principal investigator (LK) will be unblinded and will not be involved in the testing or analysis of the results. The study coordinator will be responsible for group allocation, scheduling, and answering participant queries. Group assignment will be identified to participants in a sealed opaque envelope.

The unblinded study coordinator will use an adaptive randomization design, prepared by the statistician (CM), to balance the distribution of age and sex covariates. The standard care group may improve during the wait period and may be more apt to withdraw from the study. Accordingly, we are randomly allocating 60% and 40% of the participants to the standard care and early intervention groups, respectively, such that final participant counts will be approximately equal (ie, n = 40 per group). The randomization procedure will distribute the use of wearable sensors equally within the two care groups (early and standard care). Arm allotment will begin by seeding the first 10% of participants to one of the four groups using a two-step, balanced arm approach, first to treatment assignment, then to wearable sensors assignment, with a preference towards group sizes with the described proportions. After seeding has set demographics for the four treatments, adaptive randomization based on age and sex will be used to maintain demographic equity between the groups. In cases where participants are assigned to any arm without disruption to demographic distribution, randomization will default to the previously described balanced arm approach. While arm and demographic balanced randomization will be carried out, should other demographic variables be different between groups at study completion, they will be controlled for as covariates.

[H2] Data collection

All participants who are eligible after an initial phone screen will complete informed consent, and demographics (age, gender, race and ethnicity, education, occupation, zip code, time since injury etc.), predictive comorbidities (e.g. migraine, anxiety, depression) and concussion symptoms (SCAT symptom evaluation) will be recorded.

A physical therapist will then perform a cervical screen to determine if there is a need for physician referral and/or imaging based on the Canadian C-Spine Rule.[22] If cleared, participants will complete baseline testing.

Two days of baseline testing will be undertaken in the Balance Disorders Laboratory at OHSU and Vestibular Laboratory at the VA Portland Health Care System. Participants will complete a standard vestibular and oculomotor testing battery, a series of validated questionnaires, cognitive assessment (a computerized neurocognitive testing), motor assessment (static and dynamic balance testing) and visual tracking assessments (see Tab. 1 and Tab. 2 for detailed list of measures). Second baseline testing (standard care group), post testing, and retention testing will be completed at OHSU (see Figure).

[H3] Primary Outcome Measure. The primary outcome measure will be the Dizziness Handicap Inventory (DHI)[23], and will be collected as part of the validated questionnaires. Our decision was based on the following rationale: 1) We were interested in having a participation level outcome (International Classification of Functioning, Disability and Health, ICF) as the primary outcome measure[24]; 2) It was the outcome measure of choice given the focus on vestibular rehabilitation within this study. Although minimal detectable change has not been established for patients with mTBI, DHI has been shown to be sensitive to vestibular rehabilitation,[25-26] have excellent test-retest reliability (r = 0.97) in vestibular populations[23], and

be a reliable measure to track improvement after vestibular rehabilitation post-concussion.[27]; 3) DHI is a common data element[28] for the TBI sub-disease category of concussion/mild TBI in the adult population. Where dizziness is a concern, the DHI is listed as highly recommended during the period 72 hours to 3 months and persistent timelines[29]–this is a timeline that we will be working with patients; and 4) content validity for DHI has been established, as higher scores were consistent with complaints of unsteadiness and imbalance after mTBI.[30-31]

[H3] Secondary Outcome Measures. Secondary outcome measures will be derived from questionnaires, cognitive and motor testing, and eye-tracking assessment. Standard testing procedures in these domains will be performed according to cited work in Table 1. Additional information regarding collection procedures for our more novel measurements, including instrumented measurement of balance and gait, dynamic balance assessment using the Central Sensory Motor Integration test (CSMI), and eye-tracking assessment are provided below.

For the instrumented measures of balance and gait, participants will wear five synchronized wireless Opal V2 sensors (APDM, Inc., Portland, OR, USA), attached to the head, sternum, lumbar, and left and right feet using elastic straps. Data will be collected at 128 Hz and transferred to a laptop for automatic generation of balance and gait measures by Mobility Lab software (APDM, Inc., Portland, OR, USA) as well as additional analyses of the raw time-series data.

The CSMI[32-33] test for dynamic balance assessment will be performed on a NeuroCom platform (SMART Equitest CRS, Natus Medical Inc, Clackamas, OR, USA) using custom-designed, low-amplitude (2° peak-to-peak) pseudorandom stimuli that continuously applies seven 20 second cycles of wide bandwidth surface-tilt and/or visual-tilt stimuli in the sagittal plane with eyes open or closed, and individual tests lasting less than 3 minutes. The surface and

visual surround rotation angles, and the participants' center of pressure displacements will be recorded and used to estimate the center of mass sway angle. Center of mass displacement will be calculated from center of pressure by filtering using a phaseless second order lowpass filter with cutoff frequency 0.47 Hz[33]. A frequency response function analysis will calculate the response sensitivity (gain) and timing (phase) changes that relate the angular tilt of the center of mass relative to the tilt of the surface and/or visual scene as a function of stimulus frequency. Participants' balance control characteristics will be quantified by estimating parameters (sensory weights, time delay, and sensory-to-motor transformation) of a balance control model to account for the experimental frequency response functions.[33]

To collect information on the visual system while performing functional tasks including the vestibular-ocular-motor screening test (VOMS), a binocular mobile eye-tracker (100Hz, Tobii pro Glasses 2, Falls Church, VA, USA), with prescription lenses for those who require them, will be synchronised with the sensors and worn during the dynamic balance tasks to record eye movements.[34]

[H2] Intervention

[H3]*Physical therapy treatment.* All participants will receive rehabilitation, with half of the participants completing rehabilitation immediately after baseline testing (early initiation) and half after 6 weeks (standard care). Once initiated, participants will be seen by a physical therapist twice a week for the first 2 weeks, and once a week for the remaining 4 weeks, for a total of 8 sessions. The rehabilitation will take place for 60 minutes and will be comprised of cardiovascular, cervical, static and dynamic balance exercises incorporating vestibular challenges (Table 3), as these rehabilitative strategies have been effective in post-mTBI.[12, 35] If participants test positive on the Dix-Hallpike test,[36] the Epley/canalith repositioning maneuver

will be performed at each rehabilitation session until associated symptoms resolve. We have included our full protocol and materials required in Supplementary Appendix 1 (available at https://academic.oup.com/ptj).

[H3]*Home exercise.* The home exercise program will be completed for 30 minutes and is based on the same domains performed during the supervised sessions (see Suppl. Appendix 2, available at https://academic.oup.com/ptj for full program). Half of the participants will use wearable sensors during home exercises and half will use only a custom computer interface to guide exercises. Neither group will receive feedback during their home exercises. Participants will be trained on their respective equipment by the physical therapists, and will be asked to complete the home program every day except for days that they are seen by their physical therapist. Physical therapists and participants in both groups will be asked about the usability of the intervention equipment at the end of the intervention phase. The differences between the wearable sensor group and no-sensor computer interface group are as follows:

The wearable sensor group:

- Will be sent home with sensor equipment (one sensor for the head and one for the sternum) and a laptop pre-installed with custom software designed to track head and trunk movement.
- At each physical therapy session, physical therapists will upload the participant's sensor data to assess progress in head and trunk ROM and turning speed for each exercise as well as adherence.

The no-sensor computer interface group:

- Will be provided with a custom designed web-interface, equipped with the same exercise instructions as the wearable sensor group but with a 30 second timer.

- No home data will be collected for this group aside from self-reported adherence logs and the computer log in time.

[H3]*Physical therapy and home exercise progression.* Both programs will be individualized and progressive using a point system (see Suppl. Appendix 1, available at https://academic.oup.com/ptj) to measure and guide the progress of the patient. Participants' begin with Green (1 point) exercises, and physical therapists will advance the level of difficulty when participants have correctly performed the exercise and there is no more than a 2 out of 10 change in self-reported symptoms during the exercise. Progression through the program toward the most challenging exercises (Yellow, 3 points) is based on the physical therapists' discretion. The points are used to help track and objectify the level of progression through the exercises, however, they are used to guide the physical therapists only and are not seen by the participants. The physical therapists will also meet regularly to ensure consistency in the progression of exercises and level of care across participants.

[H3]*Exercise adherence.* Exercise adherence will be monitored in both groups using daily logs kept by the participants that will be handed in and discussed with the physical therapists weekly. Additionally, weekly logs will be checked against data from the sensors (for the sensor group) or from the computer log in (from the non-sensor group). Where necessary, physical therapists will discuss adherence with participants if their daily logs do not match sensor data or log in data.

[H2] Sample Size Calculation

Sample size was determined a-priori using effect sizes calculated from previously published differences in DHI between early and late treatment in people with vestibular

dysfunction (Cohen's *d*=0.432).[25] While these effects are noted in a sample of vestibular patients, we expect our population to be equally, if not more symptomatic, given the acute stage in which they are being seen. Thus, assuming this effect size, a significant group effect (contrasting early physical therapy and standard of care therapy) on change in DHI will be observed at α=0.05 with 80% power with a sample size of 36 per group.

Based on participant retention in previous studies,[35, 37-39] an overall dropout rate of ~20% across the study period is a reasonable assumption. Therefore, the expected on-treatment effect sizes calculated above would be observed as significant with a final recruitment of 40 participants for each of the four groups; totaling 160 people with mTBI.

[H2] Statistical Analysis

Adherence measures will be calculated per participant using the self-reported daily logs. A percentage of the number of days completed (numerator) out of all days possible (denominator) will be calculated and reported for all of the exercises. If necessary, adherence (%) will be used in further analysis in the adjustment of linear models, as described below.

An intention-to-treat evaluation will be used within the study, where all available data, including data from participants lost to follow-up will be used. Any missing data will be treated using multiple imputations. A sensitivity analysis will be performed post-hoc to determine how much the model estimates differ between imputed and observed datasets.

A linear mixed-effects model will be used to analyze whether the primary outcome measure differed across groups (early versus late intervention, sensor and non-sensor) over the recovery period (1). Results will be considered significant at α=0.05.

(1)

Three fixed-effects will be included in the model: 1) a fixed effect of Onset group will be included as a dichotomous categorical variable, used to compare the effect of early versus standard of care intervention (Aim 1); 2) a fixed effect of Sensor group will be included as a dichotomous categorical variable, used to compare the effect of rehabilitation with wearable sensors versus rehabilitation without sensors (Aim 2); 3) a fixed effect of Time will be included as a continuous linear covariate. The interaction between Onset group, Sensor group and Time will also be included. Independent random effects terms for intercept and slope will be fit for each subject to account for within-subject correlations across time. Differences amongst the groups (Onset group/ Sensor group) will also be explored using contrast comparisons to provide a sense of effect size and precision.

Each of the linear mixed-effects models will also test covariates found to influence study outcomes (e.g. age, gender, vestibular function, and adherence) by assessing adjusted models with covariates inserted as factors within the model. Assessment of model fit and integrity will be examined using a combination of formal fit criteria and visual inspection of residual plots to determine which covariates should remain within the model.

Secondary outcome measures will be assessed using the same mixed-effects framework. As part of an exploratory analysis, we will assess subgroups within the primary outcome including the 3 domains of the DHI (functional, physical and emotional) as well as mild, moderate and severe levels of handicap.

[H2] ROLE OF THE FUNDING SOURCE

Dr Horak, Dr El-Gohary, Mr Pearson, and Mr VanDerwalker have a significant financial interest in, and are employees of APDM, a company that has a commercial interest in

the results of this research and technology. This potential institutional and individual conflict has been reviewed and managed by OHSU and the VA Portland Health Care System.

[H1] Discussion

This manuscript describes the protocol for a randomized control trial that aims to evaluate whether the timing of rehabilitation (early vs standard care), and whether the use of wearable sensors during a home exercise program will improve outcomes in participants with mTBI. Currently there is limited evidence, and a lack of consensus guiding when rehabilitation should start following an mTBI. Assessing the differences in recovery of symptoms, neuromotor, neurocognitive and other measures between people who have completed early versus standard care has the potential to inform clinical practice on the timelines for initiating rehabilitation. In addition, wearable technologies are becoming more accessible, and allow the monitoring of exercises performed by patients. Data gained from these devices may provide critical information to clinicians about the quality of exercises performed during home programs, as well as allow clinicians to monitor whether patients are complying with programs. Evaluating whether the use of wearable sensors during rehabilitation improves recovery outcomes will provide information to service providers on the efficacy of these devices to supplement current care. Collectively, this study may provide meaningful evidence to improve best practices for rehabilitation post-mTBI.

[H2] Potential benefits and risks

Aim 1: A stepwise return to activity, assisted with rehabilitation, within days of injury may be more beneficial than strict rest following an mTBI.[7] Thus, it is possible, that those who

partake in early intervention benefit through greater improvements in recovery than those in the standard care group. With delayed rehabilitation, there is a risk of adopting maladaptive compensatory mechanisms after injury, by avoiding movements that provoke discomfort (eg, dizziness, imbalance).[40] Therefore, it is possible that those who partake in the standard care group may experience more maladaptive compensatory strategies than the early intervention group.

Aim 2: Recent research has shown reduced head turn velocity when walking while horizontally rotating the head from side to side in mTBI compared with healthy controls.[18] It is possible that feedback about reduced capability such as this, may be helpful for clinicians to make informed decisions regarding mTBI rehabilitation. The use of wearable sensors may therefore benefit participants by providing physical therapists with information about home-exercise performance, and allowing informed decisions to be made regarding exercise progression. There is a risk, however, that using wearable sensors will deter participants from completing their exercises, due to the participants being required to set up and use the equipment each home exercise session. Of benefit to the wider rehabilitation community, should wearable sensors improve the quality of performance of prescribed exercises and exercise adherence, then this study provides the first step in developing a biofeedback system that can be used by persons during rehabilitation, and in particular rehabilitation for mTBI.

[H1] **Limitations**

The time to first physician visit may vary among participants. While there is no evidence that early intervention can reduce long-term dysfunction, we acknowledge that the variable onset of care may be a limitation, and we will only enroll participants who are <12 weeks post-injury to help account for this. The wide age range presents a possible confounding variable since

younger people may recover at different rates than older persons. Although this makes our sample more heterogeneous, we believe it will be of clinical relevance, and, where necessary, the effect of age will be assessed statistically.

There is a possibility that persons within the standard care group recover during the wait period, and as a result, decide to withdraw from the study. This may particularly be the case for those with less severe concussion symptoms, which has the potential to introduce bias and should be acknowledged as a potential limitation. To minimize chances of withdrawal from this group, we will keep the participants actively engaged in the study throughout this period by contacting them weekly and asking them to fill out the SCAT symptom checklist. Additionally, all participants will be reimbursed for their time using an incremental system.

We will be using an intention-to-treat analysis, which is supported by the CONSORT guidelines.[41] This style of analysis provides a more reliable estimate of true treatment effectiveness by replicating 'real world' issues such as non-adherence. We acknowledge that low adherence to the home exercise program poses potential limitations such as more conservative estimates of the effect of treatment. However, as exercise adherence will be monitored in all study participants through daily logs, and discussed with physical therapists weekly, we have the ability to assess any effects and adjust for this statistically. While using multiple imputations if, and when necessary, is generally regarded as a valid method for handling missing data in randomized control trials,[42] we do acknowledge that any missing data can be a limitation.

Finally, there is a possibility that patients will have low DHI scores at baseline, which may cause a ceiling effect in the potential change of our primary outcome. Although the DHI is used for clinical relevance, with the diffuse nature of mTBI, we are assessing multiple domains

within our secondary measures and believe low subjective reporting of DHI will not affect the ability to see changes in more objective measures.

[H1] Conclusion

This study aims to address a gap in clinical care guidelines after mTBI, as initiating rehabilitation early has the potential to provide improvements in outcomes in individuals with mTBI. Should wearable sensors create improved outcomes, these findings may open new avenues for rehabilitation of individuals' post-mTBI.

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The authors thank audiologists Sean Kampel and Daniel Putterman, physical therapist Kate Scanlan, research coordinator Shelby Martin, and research assistants Sharna Donovan, Rachel Schneider, Alexandra Beeson, and Nicholas Kreter for assisting in setup, coordination, and data collection.

Ethics Approval

All protocols have been approved by a joint Oregon Health & Science University (OHSU) and VA Portland Health Care System Institutional Review Board (study no. 00017370). Informed written consent will be obtained from all participants. An investigator will verbally explain the consent form to the participant, then allow the person ample time to read through the consent form. In signing the form, the participant will confirm their consent to participate.

Funding

This work was supported by the Assistant Secretary of Defense for Health Affairs under award no. W81XWH-17-1-0424. Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the US Department of Defense.

Clinical Trial Registration

This trial is registered at ClinicalTrials.gov (NCT03479541).

Disclosure and Presentations

The authors completed the ICMJE Form for Disclosure of Potential Conflicts of Interest. Dr Horak, Dr El-Gohary, Mr Pearson, and Mr VanDerwalker have a significant financial interest in, and are employees of, APDM, a company that has a commercial interest in the results of this research and technology. This potential institutional and individual conflict has been reviewed and managed by OHSU and the VA Portland Health Care System. No other authors have reported a competing interest.

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Table 1. List of Secondary Outcome Measures by Domain That Will Be Administered Across Testing Sessions

Domain	Test	Description	Outcomes
Static balance	Modified Balance Error Scoring System (mBESS)[43]	20 s of stance with feet together, single leg stance, and in tandem stance.	Subjective error count, root mean square of mediolateral sway.
Dynamic balance	Mini-Balance Evaluation Systems Test (Mini-BESTest)[44]	14-item test battery, each item is rated on a scale of 0 (lowest level of function) to 2 (highest level of function for a maximum of 28 points.	Composite score and subcategories (anticipatory balance, reactive balance, sensory orientation and dynamic gait).
	Self-selected gait with and without a secondary task[45]	1 minute of walking at a self-selected pace with and without an auditory Stroop.	Gait speed and change between single-task and dual-task[a] gait speed. Spatiotemporal gait measures.
	Self-selected and fast turning gait with and without a secondary task[46]	Walking at a self-selected pace around a complex course with and without auditory Stroop, and without an auditory Stroop at a fast pace.	Gait speed, time to complete the course and change between single-task and dual-task[a] gait speed, time to complete the course, and turning velocity.
Central Sensorimotor Integration	Central Sensorimotor Integration (CSMI) Test[32-33]	Quantifies sway evoked by continuously applied balance disturbances caused by rotations of the stance surface and/or visual scene. Provides a set of parameters that characterize the balance control system.	Sensory weights and sensory-to-motor transformation properties (stiffness, damping and time delay).
Vestibular-Ocular-Motor System	Vestibular-Ocular-Motor Screening (VOMS)-instrumented [47]	Participants will complete a battery of tasks including: horizontal and vertical smooth pursuits, horizontal and vertical saccades, convergence, horizontal and vertical vestibular ocular reflex, and the visual motion	Total symptom score of headache, dizziness, nausea, and fogginess. Measurement of convergence distance (cm).

		sensitivity test.	
Neurocognition	Automated Neuropsychological Assessment Metrics (ANAM)[48]	Computerized battery of neurocognitive tests examining attention, concentration, reaction time, memory, processing speed, and decision-making.	Composite score, reaction times, throughput, percentage correct.
Symptomology	Quality of Life After Brain Injury Questionnaire[49]	Questionnaire related to quality of life.	Total score.
	Head Impact Test-6[50]	Questionnaire of headache severity.	Total score.
	Insomnia Severity Index[51]	Questionnaire related to sleep.	Total score.
	Neurobehavioral Symptom Inventory[52]	Questionnaire of common symptoms associated with mTBI.	Total score.
	Symptom Evaluation from Sport Concussion Assessment Tool 5 (SCAT5)[53]	Questionnaire of common symptoms associated with mTBI.	Total score.
	Patients' Global Impression of Change[54]	One question rated on a seven-point Likert scale to evaluate perceived impression of change in health.	Total score.

[a]Dual-task = simultaneously performing two tasks

Table 2. List of Covariates and Comorbidities Assessed at Baseline

Domain	Test	Description
Ocular-motor tests	Random saccades	Assesses the ability to make accurate saccadic eye movements to random visual targets.
	Predictive saccades	Examines the ability to recognize when visual target motion becomes repetitive.
	Anti-saccades	Assesses the ability to inhibit eye movements with saccades in the opposite direction.
	Smooth pursuit	Evaluates the ability to visually track a sinusoidal target.
	Optokinetics	Assesses the optokinetic reflex with full-field stimulation to generate visually-evoked nystagmus.
Vestibular Tests	Cervical vestibular evoked myogenic potential (cVEMP)	Assesses the function of the saccule and inferior branch of the vestibular nerve.
	Ocular vestibular evoked myogenic potential (oVEMP)	Assesses the function of the utricle and superior branch of the vestibular nerve.
	Dix-Hallpike	Examines for benign paroxysmal positional vertigo (BPPV) of the posterior semicircular canal.
	Computerized rotational head impulse test	Assesses the function of the lateral semicircular canals and superior vestibular nerve branches.
	Visual suppression of the vestibular-ocular reflex	Assesses the ability to use vision to suppress vestibular-ocular reflex eye movements during rotations that evoke horizontal eye movements.
	Sinusoidal harmonic acceleration	Tests the vestibular-ocular reflex during horizontal rotations at various frequencies.
Sensory and perceptual tests	Proprioception	Assesses the ability to detect directional movement of right and left hallux when moved passively by a PT.
	Light touch	10 g monofilament protocol to feet performed by a PT.
	Hearing	Audiogram and tympanometry performed by an audiologist.
	Auditory perception	Quantification of auditory processing using spatial cues of interaural time and level differences.
	Vision	Measures static visual acuity and contrast sensitivity using vision

		charts.
	Subjective visual vertical	In the rotary chair, participants will orient a line to vertical and the deviation from true vertical will be measured.
Post-traumatic stress	Post-Traumatic Stress Disorder checklist (either military or civilian version)	A 17-item standardized self-report rating scale for post-traumatic stress disorder.

Table 3. Rehabilitation Program

Domain	Description
Cardiovascular Exercise	Walking on treadmill at 80% of heart rate as determined by the Buffalo Treadmill Protocol. Heart rate increased by 5 bpm every 5 minutes if symptoms do not increase more than 2 points by increasing speed or incline.
Cervical Exercises	Manual therapy Joint position sense Strengthening Stretching Motor control exercises
Static Balance Exercises with Vestibular Challenges	Quiet stance including oculomotor and vestibular-ocular exercises; changes in support surface, eyes open/closed, head turns and dual-tasking
Dynamic Balance Exercises with Vestibular Challenges	Walking with vestibular-ocular exercises; changes in support surface, eyes open/closed, head turns, base of support and dual-tasking[a] Bending forwards with eyes open/closed Squatting with eyes open/closed

[a]Dual-tasking = simultaneously performing two tasks

Figure. Flow diagram illustrating the study design.