TRACKING FUNCTIONAL RECOVERY FOLLOWING CONCUSSION USING COGNITIVE-MOTOR INTEGRATION

ALANNA PIERIAS

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Abstract

This research examines cognitive-motor integration (CMI) (thinking and moving) during eye-hand coordination, a skill commonly required in sport. This study examines CMI in varsity athletes during their return-to-sport protocol following concussion. Participants were tested on two novel visuomotor transformation tasks using a computer touch-sensitive tablet attached to a second external touchpad. Tasks consisted of a standard interaction condition, and a plane change and reversal condition, in which perception and action were decoupled, therefore requiring CMI. We observed that these athletes showed performance impairments at the time they were cleared to return to their sport based on current protocols. We found a lack of improvement compared to that of control athletes measured at the same time points. As well, some athletes showed deficits as late as three months following injury. These data suggest that more work needs to be done in order to better assess and understand the underlying effects of concussion.

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Introduction

Concussion

Concussion, a form of mild traumatic brain injury (mTBI) induced by biomechanical forces, has recently been referred to as a silent epidemic by the Centers for Disease Control and Prevention (CDC).[1] Concussions affect an estimated 1.6-3.8 million Americans[2] and 653/100,000 Ontario residents[3] per year. However, given the numbers that remain undiagnosed and unreported, the actual number of concussions occurring each year is hypothesized to be even larger.[2,4] Many researchers have indicated that concussions may affect a person's ability to return to their daily life and may result in long-term consequences such as difficulty with memory and persistent symptoms.[1,3,6,7] To be diagnosed with a concussion, an individual must have a mechanism of injury (MOI) and at least one sign or symptom.[3,7] Mechanisms of injury include a direct blow to the head, neck, face, or elsewhere on the body causing linear or rotational forces to be transmitted to the brain.[4,5,7] These mechanisms of injury are suggestive of the inertial response of the brain within the skull, which can be direct or indirect.[4,5] Brain areas thought to be commonly affected in concussion include the upper part of the brain stem, the fornix, the corpus callosum and the frontal and temporal lobes.[6,8]

Pathophysiology of Concussion

The pathophysiology of concussion is still not fully understood. One of the main difficulties with diagnosis and recovery from concussion is that microscopic neural damage cannot be detected when using standard diagnostic imaging techniques.[3,7,9,10] However, it is speculated that the functional disturbances observed following concussion result from neurometabolic effects which cause significant changes in cerebral glucose metabolism.[11-12] It has been found in both humans and animals that mTBI can alter the brain's physiology for as little as a few hours to as long as several years.[13,14] In an attempt to restore ionic and cellular homeostasis, the increased demand for energy coupled with the decreased supply of cerebral blood flow results in a mismatch between energy supply and demand.[9, 11] During this time of energy crisis, it is speculated that the human brain is at an increased vulnerability to the effects of another concussion.[15] Along with neurometabolic changes there may also be damage involving neurotransmission. Specifically, damage to the cytoskeleton of axons results in decreased axonal transport and therefore, impaired functioning due to slowed conduction.[9] Recently, studies using diffusion tensor imaging (DTI) have found decreased white matter integrity in both the acute and chronic stages of concussion.[16,17,] The brain areas in which this decreased integrity was observed include the corpus callosum, superior longitudinal fasciculus (SLF), and corticospinal tract (CST). The damage to these areas suggest a decreased connectivity within the frontoparietal network.[18-20]

Current management and recovery standards

The current diagnosis for sport related concussion is based mainly on the judgment of physicians[3,6,7, 21, 22] with input from athletic therapists/trainers and coaches. In order to clinically diagnose a concussive head injury, there are many features to look for. These features include: a direct blow to the head, face, or neck; a direct blow elsewhere on the body which transmits a force to the head; rapid onset of neurological function impairment; and a presentation of a number of symptoms in the absence of structural abnormailites on standard structural neuroimaging.[3,7,9,10] Symptoms of concussion are generally grouped into four main categories: physical, emotional, cognitive, and sleep disturbances[3,7] (see Table I in Appendix A for a full list of symptoms). Symptoms of concussion typically resolve within 7-10 days.[7] Any symptoms lasting longer than this are considered persistent symptoms and may progress into post-concussion syndrome (PCS).[4,23]

Current standards of management for sport related concussions and symptoms follow a Return-to-sport (RTS) protocol.[7] This consists of 6 stages following diagnosis of concussion, and 24-48 hours of physical and cognitive rest: 1) Symptom limited activity (daily activities), 2) Light aerobic exercise, 3) Sport-specific exercise, 4) Non-contact training drills, 5) Full-contact practice, 6) Full return to sport (see Table II in Appendix A for further detail of the RTS protocol). These steps are to be monitored by a licensed health care professional. Following diagnosis, each step requires the athlete to be asymptomatic for 24 hours before proceeding to the next stage. However, the objective progression of these stages remains difficult as the identification of signs and symptoms can be complicated due to the lack of abnormalities on structural neuroimaging.[9,10,24] This makes it difficult for clinicians to accurately determine if the brain has completely healed following injury. Instead, the majority of Athletic Trainers in the USA (71.2%) currently use a battery of neurocognitive tests to assess concussion and monitor the stages of recovery. [25] As well, a multifaceted approach has recently been adopted to include assessment of balance, cognitive and mental status, neuropsychological performance, and self-reported symptoms. [26]

One major issue with the current concussion assessments is the sequential analyses of cognitive and motor abilities, rather than simultaneous assessment. It is well known that an important aspect of most sports is the ability to think and move at the same time. For example, movements must be made while incorporating information about the rules of the game, other players' positions, and past experiences in specific situations. Therefore, testing cognitive and motor abilities separately is not a good reflection of the brain networks required during actual play. As well, it has been found that the sensitivity of any one of the domains, when tested separately, fails to exceed 70 percent.[26] This lack of sensitivity may lead to the inappropriate management of concussion; which includes things like failure to identify the presence of concussion, premature return to participation, and increased potential for second impact syndrome. [26] Athletes are being tested on cognition and motor abilities separately, and then returning to sport situations in which they are expected to use them together. Previous research in this area has shown that a proportion of athletes who have been returned to sport based on the current standards continue to display deficits when tested in areas which require integrative brain processing, such as cognitive-motor integration. [27, 28, 29]

Management Tools

A common tool used to evaluate an injured athlete for concussion is the Sport Concussion Assessment Tool (SCAT). This currently consists of a Glasgow Coma Scale and Maddocks Score, as well as a symptom evaluation, cognitive assessment, neck examination, balance examination, and coordination examination, for use during sideline assessment (see Appendix C for full SCAT5).[7] Over recent years, the SCAT tool has been developing and changing in order to better identify, and assist with tracking recovery from concussion. However, there is still controversy as to the validity and effectiveness of the tool. In 2014, Snyder & Bauer (2014) found a significant age effect on SCAT2 performance such that older adolescents and teenagers produced higher (better) total scores than younger. These authors suggest that clinical utility may be limited in children under age 11. As well, Carson, et al., (2014)[30] found that 43.5 percent of concussion cases were returned to play and school too soon. Since then, an updated version (SCAT3) has been developed in order to improve upon the SCAT2. This included adding the Glasgow Coma scale to assess the initial severity of injury, and an independent score for each component as opposed to an overall composite score.[31] As well, this included introducing a modified SCAT3 for children under the age of 12.[3] (See Appendix C for full SCAT3) However, critisisms remained concerning the lack of indication about specific timing of administration following concussion[32], and the variability in symptom scales in the absence of concussion.[33] While the protocol has once again been updated recently, research continues to suggests that the current version (SCAT5) is still insufficient in detecting lingering neurological issues following concussion in athletes given that it continues to measures cognitive and motor abilities subsequently . [27, 28, 29] The SCAT5 is currently considered the most well-established instrument available for sideline assessment of concussion, which consists of immediate removal of the athlete from play and assessment of concussion after a mechanism of injury occurs during play, but the value of the tool decreases significantly beginning 3 days following concussion.[7] Therefore, it is best to consider the SCAT a useful tool for the immediate assessment and diagnosis of concussion, but to remain wary of using it as a continual tracking tool to monitor the stages of recovery, and clear individuals for return to play.

Other management tools are commonly used in conjuction with the SCAT to monitor the stages of recovery from concussion. The Immediate Post-Concussion Assessment and Cognitive Testing Test battery (ImPACT) is a battery consisting of six modules to evaluate attention, memory, reaction time, and processing speed.[34] This test has been found to have 81.9 percent sensitivity, and 89.4 percent specificity, deeming it a useful tool to aid in the diagnosis of concussion.[35] However, as mentioned above, this test measures the specified domains separately, and therefore is not meant to be used in the assessment of recovery. The Balance Error Scoring System (BESS) is a static posture test consisting of three stances on two different surfaces in order to test postural stability. While balance itself has been found to be affected by many forms of brain injury, including concussion[36], the BESS has been found to have issues with intrarater and interrater reliability.[37,38] These issues make it difficult to rely on BESS scores for assessment of recovery, especially if more than one individual is administering the test. Many other test batteries exist and may be used by clinicians to aid in the diagnosis and assessment of recovery following concussion. However, to our knowledge all of these test batteries continue to test multiple facets separately, creating a lack of completeness to properly deem concussed athletes recovered.

Cognitive Motor Integration

The brain is often required to integrate information to properly execute tasks in everyday life. The ability to perform movements guided by vision requires visual information from the environment to be transformed into programed motor outputs, known as visuomotor integration. There are two main forms of visuomotor integration which we experience: standard mapping (where the targets of eye and limb movements are spatially congruent), and non-standard mapping (where there is a spatial dissociation between movements of the eyes and limb and a rule is required in order to successfully execute the appropriate motor command).[39] It is thought that the brain concurrently processes information for the eye and hand, simplifying planning and allowing for quick and accurate movements; this is commonly referred to as the default reaching network.[39,40] This network is utilized in standard mapping visuomotor transformations. These transformations involve looking at the target with which we are directly interacting. For example, when picking up a coffee cup both our gaze and our reach occur towards one target. However, if the visual information from the environment does not align with the required motor program, the brain must use rules to execute an appropriate motor response. [29, 41] This type of visuomotor integration requires non-standard mapping and therefore, the integration of spatial and cognitive rules.[39] The decoupling of hand and eye coordination, in combination with rules required to signfy the association between perception and action[5], requires cognitive-motor integration (CMI)[42]. Non-standard mapping can be decoupled in two ways: 1) There is an arbitrary relationship between the stimulus and the action (e.g. Red traffic light means step on the brake), 2) There is a transformational dissociation between gaze, spatial attention, or limb movements, and the target (ex. using a computer mouse when looking at a computer screen.[39] This decoupling can then be further separated by two possible recalibrations: spatial or strategic. Spatial recalibration requires the adaptation of the brain to changes in spatial orientation in order to align motor output with sensory input.[43-45] For example, when using a computer mouse your gaze is directed at the screen on a vertical plane, but you are interacting with the mouse on a horizontal plane. This adaptation is slower and occurs without conscious awareness and therefore, is considered to be implicit.[43-46] The implicit recalibration is thought to occur through movement inaccuracies signaling an internal error and resulting in correction.[46] Conversely, strategic control requires the integration of a rule that is task-dependent in order to align the motor response with the target.[43-46] For example, rotating the computer mouse input 180^{o} such that you would need to move your hand in the opposite direction of the target in order to successfully complete the task. This adaptation is considered explicit in nature, given that it requires external feedback to overcome movement errors. These types of visuomotor dissociations requiring cognitive-motor integration provide a means of assessing the brain's ability to think and move at the same time.

Brain networks involved in CMI

Visuomotor integration is thought to involve a transformation between reference frames from extrinsic (based on external cues) to intrinsic (based on required joint and muscle activations).[47-49] The combination of this information is required to create an appropriate plan of motor action in order for successful goal directed reaching movements to occur.[48,50] This combination of information may be due to reciprocal connections within the frontoparietal network – a network that is organized both hierarchically and in parallel in order to produce coordinated movement. [48,51] The frontoparietal network has been established as crucial for the visuomotor integration required for reaching.[50, 52] Hierarchically, visual information enters through the primary visual cortex (V1) of the occipital lobe and is further processed through the extrastriate cortex. A reaching movement requires the visual information to pass through the parieto-occipital extrastriate cortex (PO) to the posterior parietal cortex (PPC). The PPC includes the superior parietal lobule (SPL), inferior parietal lobule (IPL), the median dorsal parietal area (MDP), and areas of the intraparietal sulcus (IPS); including medial (MIP), lateral (LIP), and ventral (VIP) intraparietal areas.[49, 52] It has been determined that these areas are responsible for creating a spatial representation of both limb and stimulus by receiving information from both visual and motor areas.[47, 49, 52, 40] The areas where motor plans are created – premotor cortex (PMC); including medial supplementary motor area (SMA), and cingulate motor area (CMA), as well as the lateral dorsal (PMd) and ventral (PMv) premotor areas – receive information from the PPC and provide output to the primary motor cortex (M1) in order to create motor execution.[49, 52] The activity within the frontoparietal network is responsible for gradually transforming extrinsic visuospatial information into motor commands for reaching. However, it is not as simple as described above. This processing required depends on local communication and extensive reciprocal corticocortical projections that act both serially and in parallel.[48,49,52] Changes in the pattern of activity of the frontoparietal network, specifically within the PMd[54] and SPL[42], have been noted during a non-standard mapping visuomotor task. (see Figure 1 for diagram of pathways)

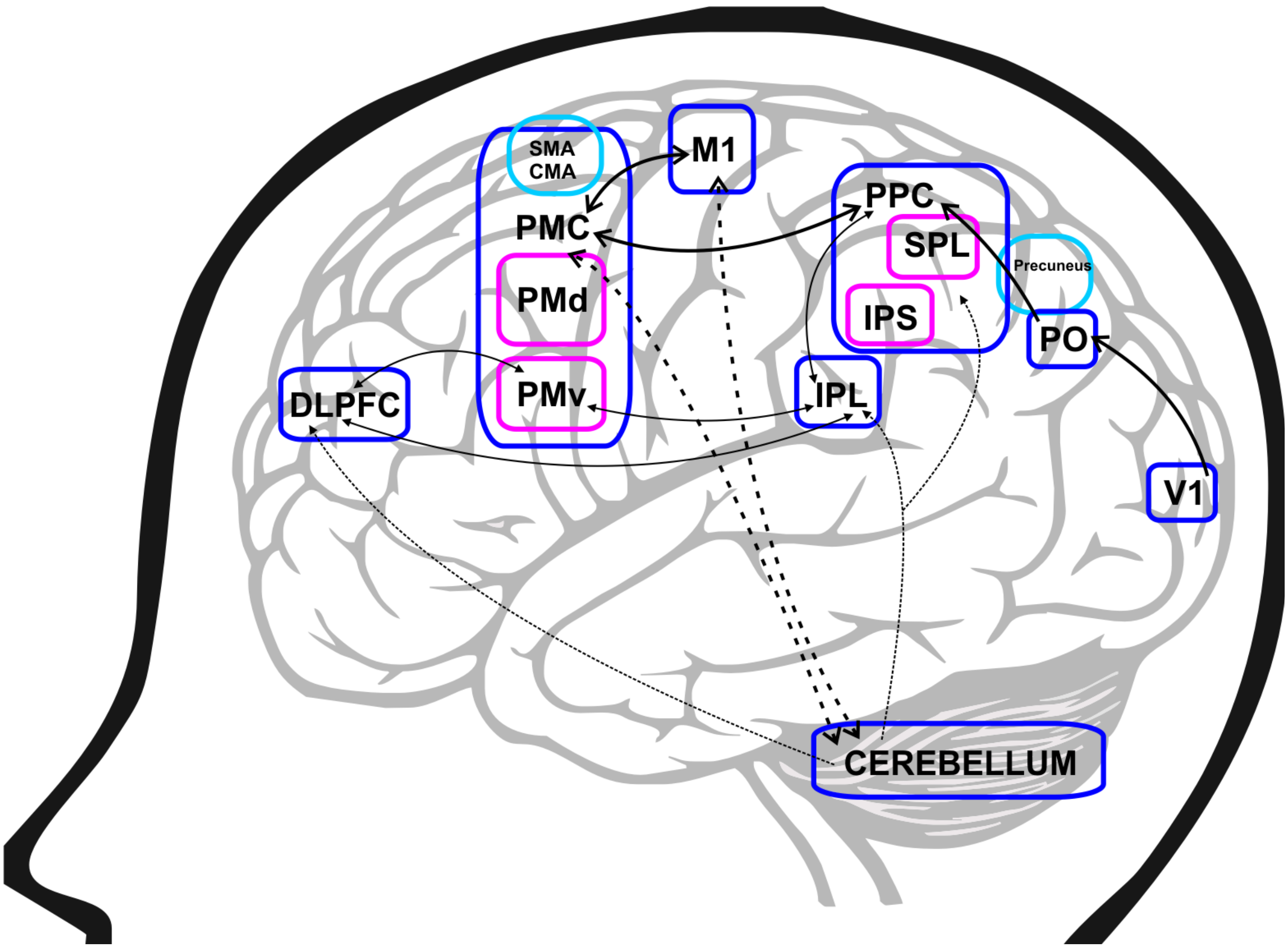

Figure 1. Simplified overview of brain regions involved in both standard and non-standard visuomotor transformation. Dark blue boxes refer to lateral brain areas, pink boxes represent a subdivision within a brain region, and light blue boxes represent areas found on the medial aspect of the brain. Thick black arrows denote the hierarchical organization for reaching as described in the paper, while thin black arrows characterize connections that may play a role in non-standard reaching. Dotted lines symbolize cerebellar connections within this network. It is important to note that connections are often reciprocal and act in parallel as well as hierarchically.

Primary visual cortex (V1), parieto-occipital extrastriate cortex (PO), posterior parietal cortex (PPC), superior parietal lobule (SPL), intraparietal sulcus (IPS), inferior parietal lobule (IPL), premotor cortex (PMC), dorsal premotor cortex (PMd), ventral premotor cortex (PMv), supplementary motor area (SMA), cingulate motor area (CMA), primary motor area (M1), dorsolateral prefrontal cortex (DLPFC)

The cerebellum – important for motor coordination, motor learning, and spatial attention[51,55]– also plays an essential role in both standard and non-standard reaching tasks.[40, 45, 56] Functionally, the cerebellum can be divided into the vestibulocerebellum, the spinocerebellum, and the cerebrocerebellum. For the proposed study described below, it is important to note that lesions to the deep nuclei of the spinocerebellum result in disrupted accuracy, hand path, and timing errors in reaching movements; while lesions to the deep cerebellar nucleus of the cerebrocerebellum result in delays in initiating movements and irregularities in movement timing.[51] In particular, it has been shown that cerebellum function is important during the corrective movement stages, when sensory feedback is accessed and utilized.[50, 51, 57] Accordingly, it is not surprising that increased cerebellar activity has been noted in non-standard compared to standard visuomotor tasks, resulting from the need for corrective movements or possibly due to a role in the actual dissociation of eye and hand.[55]

CMI in the healthy versus concussed brain

Along with differences in brain activation, behavioural differences have also been noted during non-standard tasks. The previously mentioned required recalibration is thought to be the reason for these behavioural differences. When vision and action are decoupled, decreased accuracy and increased movement and reaction time have been noted.[39,40] While these behavioural effects are generally well understood in healthy populations, they are less well understood in those with altered brain function. It is important to understand how these behavioural differences are linked to functional differences in order to improve prevention, progression, and rehabilitation for these individuals.

The effects of CMI in mild cognitive impairment (MCI)[58] and Alzheimer's patients[59-61] has been noted. These studies found that both MCI and Alzheimer's patients performed at the same level as healthy age-matched and young controls on a standard mapping task. However, the patient population showed signs of difficulty when attempting the decoupled tasks in which CMI is required.[58,41,61] It is also interesting to note that those with MCI only showed impaired reaction time and movement time when both spatial calibration and strategic control were required.[58]

As the frontoparietal network is highly susceptible to the effects of concussion given the lobe's anatomical locations, it seems likely that behavioural deficits would become evident during visuospatial transformation tasks, particularly when cognitive rules are required. Previous work in from this lab has shown impaired reaction time and movement time in previously concussed athletes when both spatial recalibration and strategic control were required. [27,28,29] However, the previous work compared concussed participants to control participants at one time-point and therefore, did not refer back to participants' baseline measures. Therefore, further work investigating the longitudinal behavioural impact of concussion on cognitive-motor integration is needed in order to improve methods of diagnoses, assessment, and recovery.

Current Study – Purpose and Hypotheses

Previous research from this laboratory has shown cognitive-motor integration declines in elite, university-level, child, and adolescent athletes who have a history of concussion (but were deemed recovered at the time of evaluation) [27,28,29]. To extend the research into concussion recovery, the current study examines cognitive-motor integration over a three month period in young adult athletes going through their clinically-monitored Return-to-Sport (RTS) protocol following diagnoses of suspected concussion. The purpose of this study is to expand on prior research by examining CMI changes in concussed athletes throughout the progression of their recovery period, and compare them with non-concussed athletes at corresponding time points in order to improve current tracking tools to monitor recovery from concussion.

In accordance with previous findings,[27,28,29] we believe using a CMI task will expose lingering deficits in cognitive-motor performance not detectable by current RTP standards. We predict that athletes following current RTP protocols will not return to their baseline levels (scored prior to obtaining concussion) at the time they are deemed safe to begin their return to play. This prediction would support our hypothesis that our task is affecting diverse brain networks combining cognition and action, and that these networks are an improved reference point for indicating neural healing following concussion.

As well, we predict that athletes will have impaired CMI performance following concussion, as compared to non-concussed controls measured at equivalent time points on the same tasks.

Materials and Methods

Participants

A total of twelve participants were included in the study (Concussion Group n=7, Control Group n=5). Demographic information and the make-up of the groups can be found in Table 1.

Table 1. Demographic information including age, sex, sport played, and number of previous concussions, for concussed and non-concussed control participants. Groups consist of return to play (RTP) and/or three months post concussion (3mos post) - - denotes a missing value

	Participant Number	Age	Sex	Sport	Number of previous concussions	Data included in
Concussed	1	19	Male	Football	0	RTP
	2	20	Male	Football	1	RTP 3mos post
	3	19	Male	Football	0	RTP 3mos post
	4	22	Male	Football	--	RTP 3mos post
	5	19	Female	Rugby	0	RTP
	6	19	Female	Women's Hockey	0	RTP 3mos post
	7	22	Female	Women's Hockey	0	3 mos post
Non-concussed Controls	1	18	Female	Field Hockey	0	RTP
	2	22	Male	Soccer	0	RTP
	3	21	Male	Soccer	0	RTP Time 3
	4	20	Male	Football	0	RTP
	5	21	Female	Field Hockey	0	RTP Time 3

Participants were recruited through York University Varsity athletics and the Gorman/Shore Sport Injury Clinic, located on York University Campus. The concussed athletes (Concussion group), as diagnosed by a health care professional, were recruited from York's Varsity Football, Men's Hockey, Women's Hockey, and Women's Rugby teams. All rookie players from York University's Varsity Football, Men's Hockey, Women's Hockey, and Women's Rugby were baseline tested prior to the start of their season. As a pilot, control participants (Control group) were recruited from Varsity level athletes who have no history of concussion. All participants completed two visuomotor transformation tasks (described below). Concussion group athletes completed these tasks at timepoints corresponding with their progress through the stages of RTS(stage 2 -Light aerobic exercise; and three months post conussion) as well as prior to the start of season (baseline). Control group athletes were measured at average timepoints signifying a typical progression through the stages of RTS (day 0 - baseline, day 7-10 – return to play, and day 90-100 – 3 months post concussion) for a total of 3 sessions. For clarity, Control group timepoints will be refered to as baseline, time 2 (corresponding with time of return to play), and time 3 (corresponding with three months post concussion). Ethics has been approved through York University's Research Ethics Board human participants subcommittee.

Baseline testing

Baseline testing consisted of a questionnaire and two visuomotor transformation tasks executed on the Brain Dysfunction Indicator (BrDI™) system (explained below).

The questionnaire was used to determine a) age, sex, sport, position, b) number, time, and approximate severity of previous concussions, c) video game use, and d)diagnosed neurological disorders, and family history of dementia or other neurological disorders. During the questionnaire, participants were verbally informed as to what neurological disorders were. They were provided with examples such as: Attention Deficit Disorder (ADD), Attention Deficit Hyperactivity Disorder (ADHD), Epilepsy, and Migraines. Please see Appendix B for full questionnaire.

No participants analyzed had been diagnosed with neurological disorders.

Experimental task

All participants were tested on two visuomotor transformation conditions per session, executed using the Brain Dysfunction Indicator (BrDI™) software. These tasks were presented on a tablet computer (ASUS Transformer Book T100 2 in 1 tablet) in a vertical position, and an external touchpad (Keytec™, 28.5cm x 21.5cm, 60Hz sampling rate) situated perpendicular (i.e. in the horizontal plane) to the tablet screen (see Figure 2 for diagram). Participants sat at a desk such that they could comfortably reach both the table touchscreen, and the external touchpad. Each session consisted of one standard (direct interaction) and one non-standard (indirect interaction) task.

In the standard task, the participants were required to directly interact with the targets on the vertically oriented touchscreen while wearing a capacitive-touch glove on their preferred hand. A central yellow target with a diameter of 7.5mm appeared in the center of the screen. Prior to the initiation of the experiment the participant was instructed to slide their finger on the touchscreen in order to move a white cursor to the center of the yellow target. Once achieving this, the center target turned green. After a delay period of 4000ms, a red peripheral target was presented 55mm away from center (up, down, left, or right) and the central target disappeared. This served as the "GO" signal for the participant to slide their finger along with the cursor across the screen directly to the presented peripheral target. After reaching the peripheral target and remaining there for 500ms, the peripheral target disappeared. This served as the signal for the end of the trial. Following a delay of 2000ms, the central target reappeared, signaling the participant to return to the center to begin the next trial. A total of 16 trials were completed for each condition. (see Figure 2)

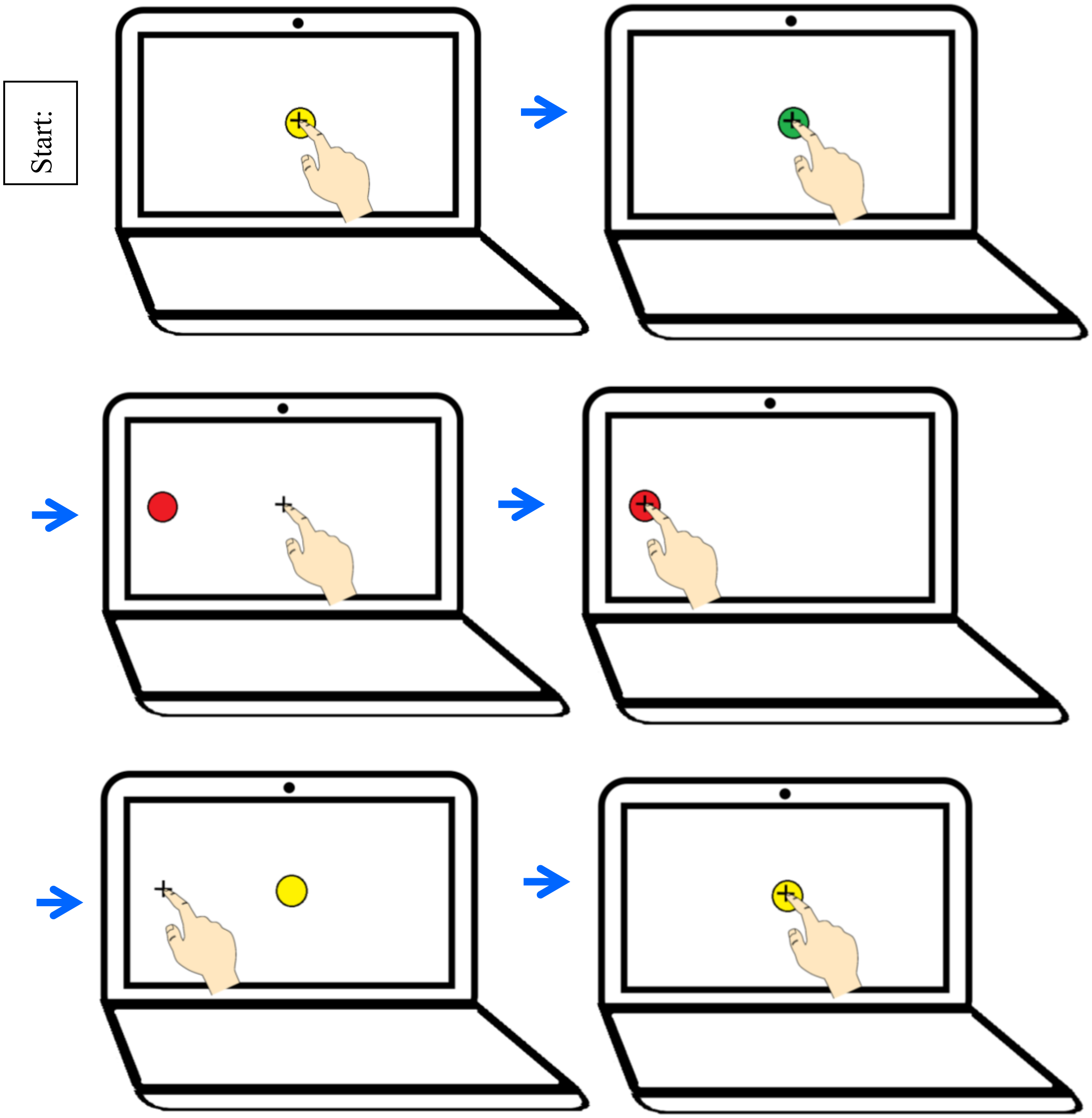

Figure 2. Sequence of events during one trial of the standard BrDI task. The yellow circle denotes the center, or home, target in which all movements begin. Target changes from yellow to green to signify a movement preparation signal. After 4000ms a red peripheral target appears in one of four peripheral directions (90° to top, bottom, left or right of center) which signifies the 'Go' cue. The yellow center home target reappears after an inter-trial interval of 2000ms, signaling the end of the trial. Participant is looking at and moving on the screen where targets appear.

In the non-standard (indirect interaction) task, measurement and timing of presentation of targets remained the same. However, in this task participants were instructed to maintain their eye focus on the vertically oriented tablet touchscreen, while manipulating the cursor using the horizontally oriented touchpad. This created a decoupling of vision and action. As well, the feedback for this task was rotated 180^{o} (i.e. in order to move the cursor left, you slide your finger right). This created the strategic control requirement. These two levels of decoupling are referred to as Plane Change and Feedback Reversal, respectively. (see Figure 3)

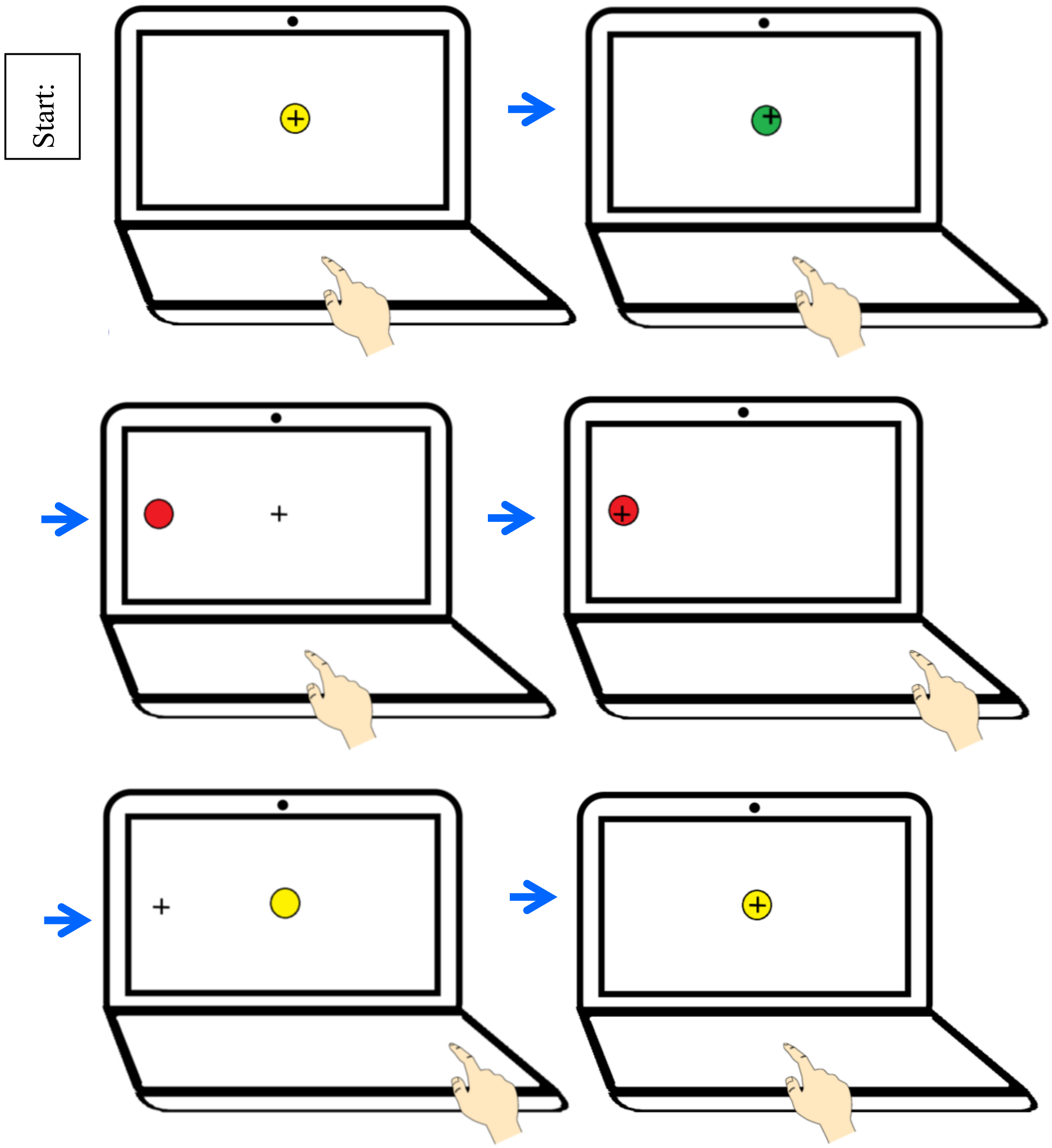

Figure 3. Sequence of events during one trial of the plane change and feedback reversal (non-standard) BrDI task. The yellow circle denotes the center, or home, target in which all movements begin. Target changes from yellow to green to signify a movement preparation signal. After 4000ms a red peripheral target appears in one of four peripheral directions (90° to top, bottom, left or right of center) which signifies the 'Go' cue. The yellow center home target reappears after an inter-trial interval of 2000ms, signaling the end of the trial. Participant is looking at the vertical screen but moving on the screen perpendicular to where targets appear and in the opposite direction.

In all conditions, participants were instructed to look to the target circle and to move as quickly and as accurately as possible.

Each participant completed 4 trials per target (n=4), per condition(n=2) for a total of 32 trials per participant, per session. An example of individual movement trajectories on both the standard and non-standard tasks can be found in Figure 4 and Figure 5.

Data processing

Kinematic measures, including timing, finger position, and error data were recorded by the BrDI software for each trial and converted into a MATLAB readable format using a custom written C++ application. Unsuccessful trials were detected by the data collection software and resulted in trial termination if the finger left the home target too early (<4000ms), Reaction time (RT) was too short, (<150ms), RT was too long, (>8000ms), or movement time was too long (>10000ms). Trials in which the first ballistic movement exited the boundaries of the center target in the wrong direction (greater than 45° from a straight line to target) were coded as direction reversal errors and were analyzed as a separate variable.

Velocity profiles were computed for each successful trial and displayed alongside a Cartesian plot illustrating finger position data and target locations using a custom analysis program.

The movement onsets and ballistic movement offsets (the initial movement prior to path corrections) were scored at 10 percent peak velocity, while total movement offsets were scored as the final 10 percent peak velocity point once the finger position plateaued within the peripheral target. In situations where the initial movement successfully brought the finger to the peripheral target, the ballistic and total movement offsets were equivalent. These profiles were then verified by visual inspection, and corrections to the movement onset, ballistic movement offsets, and final finger position were performed by the author when necessary. The scored data was then processed to compute 8 different movement timing and execution outcome measures, described in detail below. Individual trials which exceeded 2.5 standard deviations from the participant's mean for each of the outcomes measures was eliminated prior to the calculation of outcomes.

Dependent measures

The kinematic dependent measures in this study have been divided into categories of movement timing and movement execution. These measures were computed using a custom-written analysis software (MATLAB®)

Movement Timing

The measured kinematic variables for movement timing were as follows:

1) Reaction Time (RT): The time interval between the central target disappearance and movement onset (milliseconds; ms).

2) Movement Time: The time between movement onset and offset (millisecond; msec). Calculated as both total movement (MTf, full movement time) as well as ballistic movement (MTb, initial movement time). If no corrected movements were made, ballistic movements were equal to full movement times.

3) Peak Velocity (PV): The maximum velocity obtained for each trial (mm/ms).

Movement Execution

Kinematic variables for movement execution were:

1) Normalized path length : the normalized distance travelled between movement onset and offset (percentage of total path length; %). Calculated as both the normalized full path length (PLfN, -percentage of straight line between starting positing in center target and ending position in

peripheral target) as well as the normalized ballistic trajectory (PLbN, percentage of straight line between starting positing in center target and position at initial movement offset).

2) Absolute Error (AE, end-point accuracy): The average distance from the individual movement endpoints ($\sum x/n$, $\sum y/n$) to the actual target location (millimeters; mm).

3) Variable Error (VE, initial-point precision): The distance between the individual movement ballistic endpoints ($\sigma 2$) from each other (millimeters; mm).

4) Percent Direction Reversal errors (%DR): The percentage of total trials that constituted a deviation of greater than ±45° from the direct line between the center of the central and peripheral targets.

5) Percentage of Error Trials (%Err): The percentage of total trials in which the participant did not successfully complete the trial for any reason (other than manual deletion).

Trials were manually deleted based on notes kept during testing sessions. Reasons for manual deletion included: unresponsive touchscreen, unavoidable distraction causing participant to lose focus on the trial, removal of finger from the screen, and any other mishaps with the technology deemed non-reflective of the participant's performance. Please see Table IV in Appendix A for summary of number of trials deleted.

Statistical analysis

Statistical analyses were performed using SPSS statistical software (SPSS 24, IBM). In general, variables were assessed to determine whether concussed athletes had returned to baseline levels at time of beginning the return to sport protocol as initiated by a physician, and three months following initial diagnosis of concussion. As well, controls were used to determine whether there was a learning effect on the task by comparing rate of improvement on all variables with those recovering from concussion, and if there was a difference in performance between concussed individuals and controls at any one timepoint during their recovery process.

The comparison groups were as follows:

- Concussion group at Return to play vs. Concussion group at Baseline
- Concussion group at 3 months post concussion vs. Concussion group at Baseline
- Control group at time 2 vs. Control group at Baseline
- Control group at 3 time 3 vs. Control group at Baseline
- Concussion group at Baseline vs. Control group at Baseline
- Concussion group at Return to play (time 2) vs. Control group at time 2
- Concussion group at 3 months post concussion (time 3) vs. Control group at time 3

A Shapiro-Wilk's test was done to test for normal distribution on each variable. Repeated-measure t-tests were used on those normally distributed variables. Non-parametric analysis – specifically, Wilcoxon signed-rank tests – were used to compare the differences in means on the non-normally distributed variables. See Table III in Appendix A for distribution of variables.

A Kruskal-Wallis H test was used to compare the Concussion group to the Control group at all time points in order to compare level of improvement of scores.

As well, z-scores were calculated and used to determine overall scores on related groups of variables for the Concussion and the Control group. These scores were calculated by subtracting the individual participant scores at RTP(Time 2), and then three months post concussion, from the mean of their respective group at baseline and dividing by the standard deviation at baseline. The overall scores were used to create three groups: Trajectory (absolute error, variable error, and normalized full path length), Movement timing (Reaction time, and movement time), and Success (Percentage direction reversals and percentage errors).

Additionally, a Pearson's correlational analysis was executed to determine whether a correlation was present between reaction time and percentage error, and full movement time and percentage of error, at baseline, return to play, and three months post concussion time points for the Concussion and Control groups.

Results

Sample Trajectories

An illustration of the motor behaviour demonstrated by one concussed and one control participant is shown in Figures 4 and 5. These examples of trajectories for a concussed participant and a non-concussed control participant on the standard condition (Figure 4) and the non-standard condition (Figure 5) illustrate that overall concussed participants continue to show a difficulty in performance while control participants remain relatively consistent.

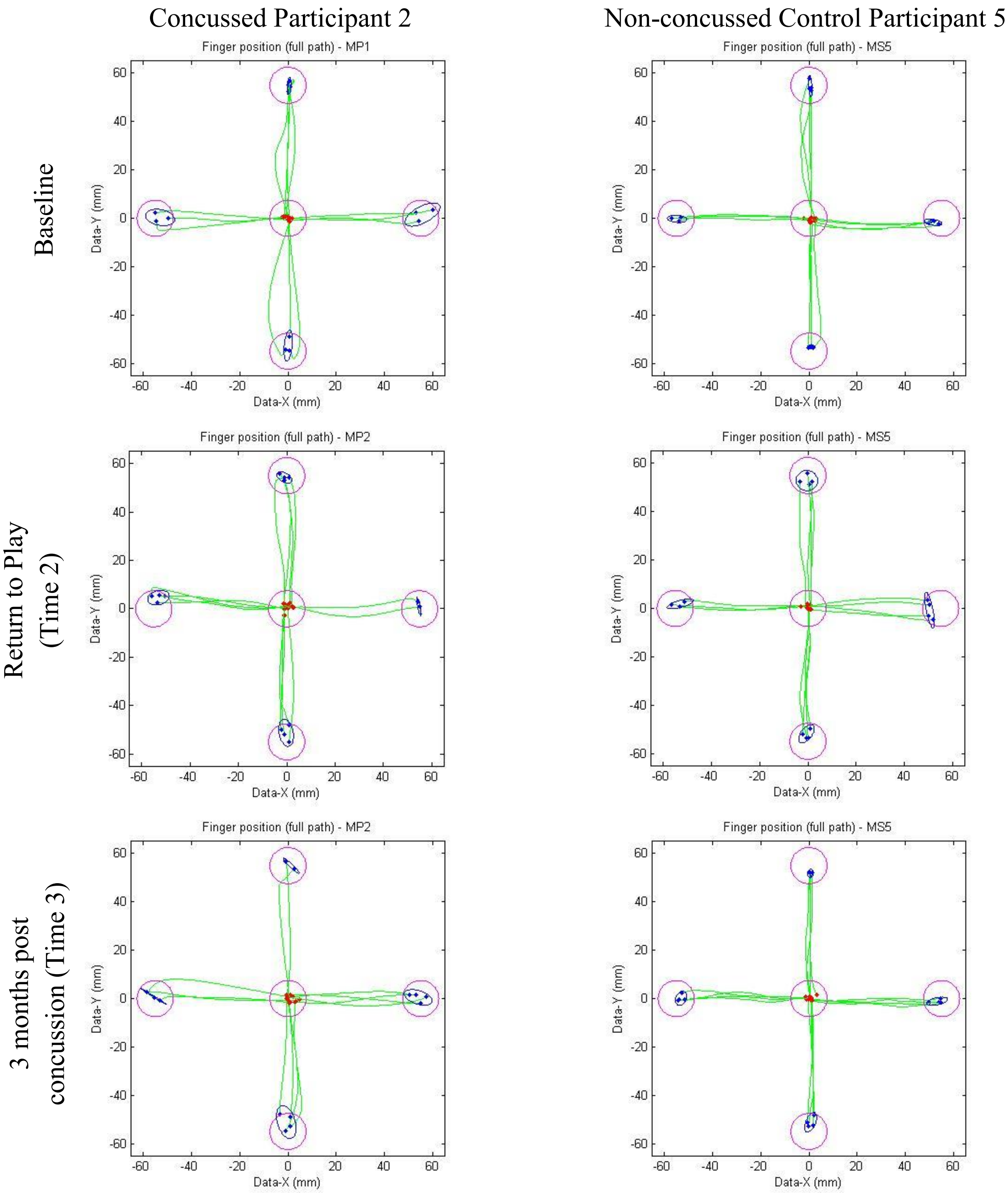

Figure 4. Sample Trajectories for Participant 2 (Concussion group) and Participant 5 (Control group) for the standard condition at baseline, return to play (time 2), and three months post concussion (time 3). Red dots indicate finger starting position, green lines indicate finger trajectory along the touch screen, purple circles indicate the targets, blue dots indicate finger ending position.

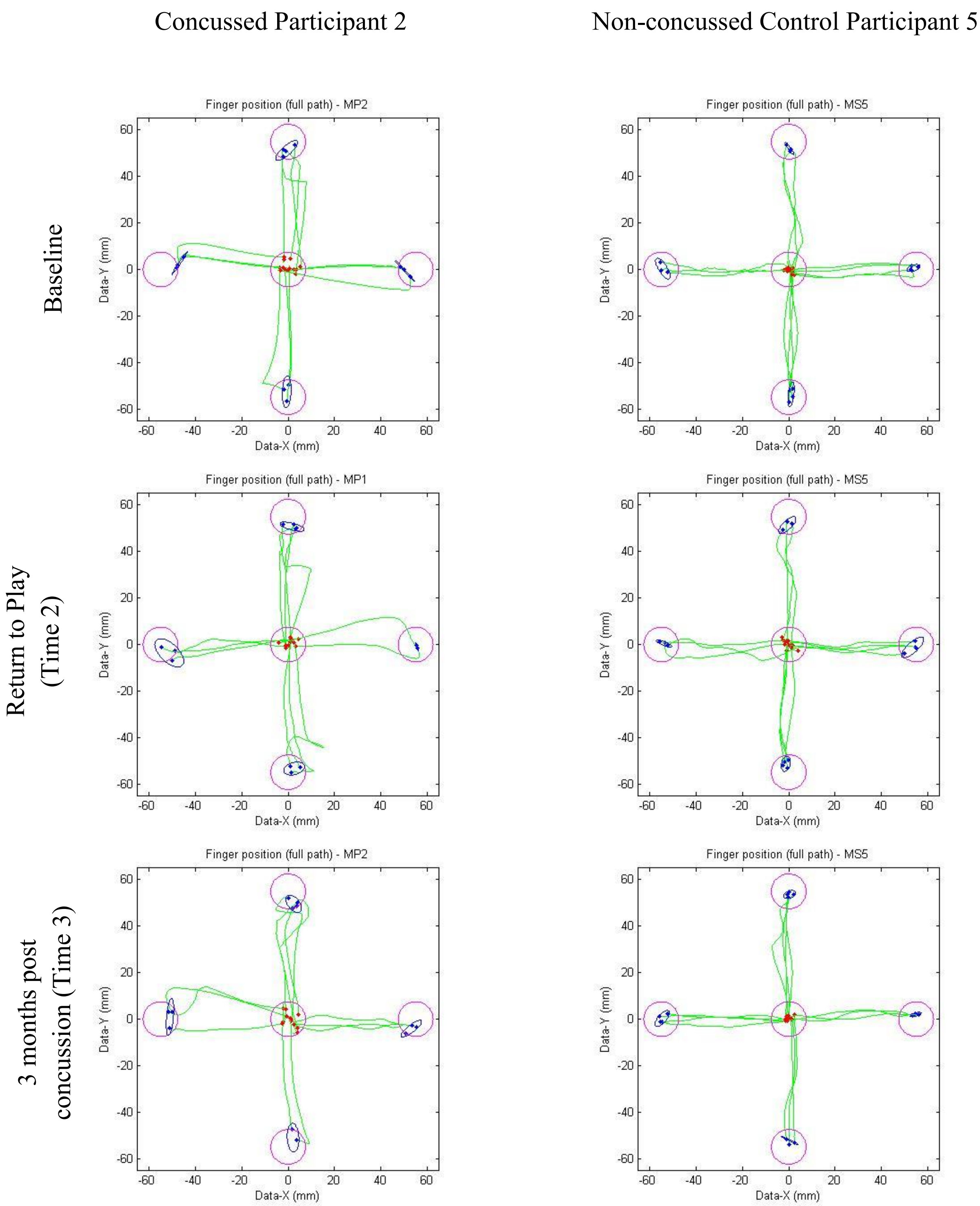

Figure 5. Sample Trajectories for Participant 2 (Concussion group) and participant 5 (Control group) for the non-standard condition at baseline, return to play (time 2), and three months post concussion (time 3). Red dots indicate finger starting position, green lines indicate finger trajectory along the touch screen, purple circles indicate the targets, blue dots indicate finger ending position.

Percentage of direction reversals

The concussion group exhibited zero direction reversals at time of return to play on the standard condition.The control group exhibited zero direction reversals at baseline, time 2, and time 3 on the standard condition, and time 3 on the non-standard condition.

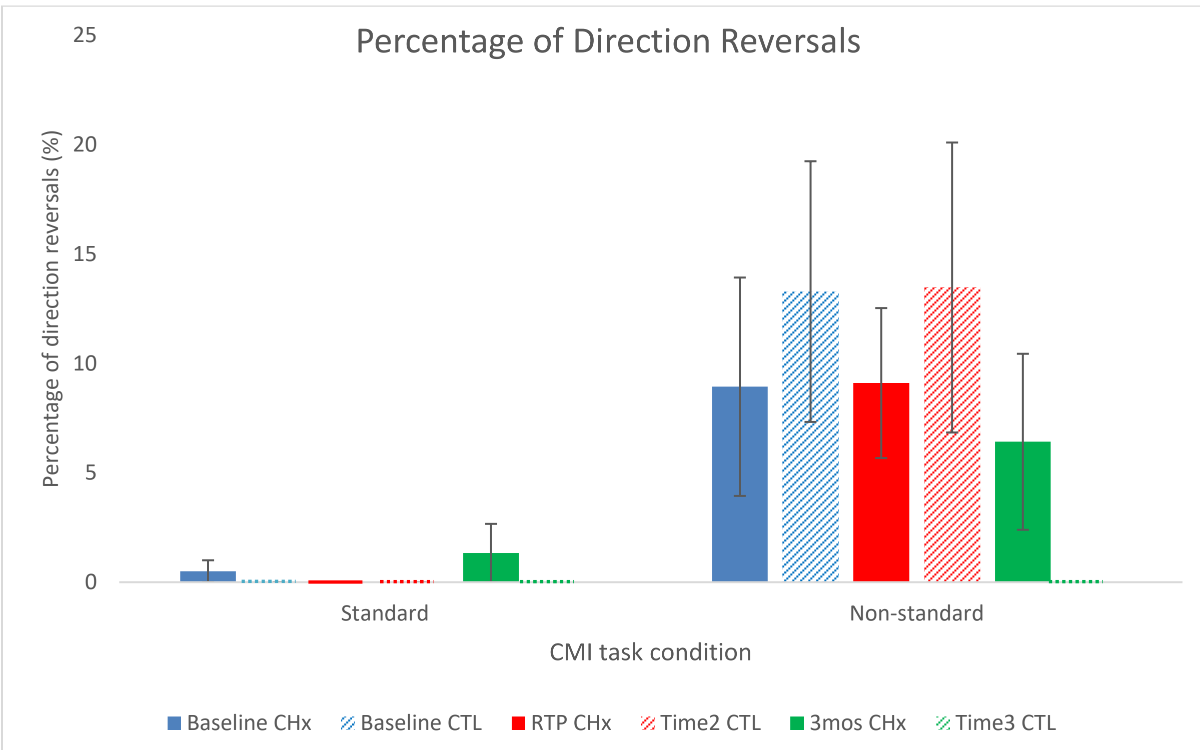

Figure 6. Histogram showing percentage of direction reversals (%) as a function of cognitive-motor integration (CMI) task condition (standard or non-standard) measured for concussion group (CHx) and control group (CTL) at baseline, return to play (RTP) (Time2) and three months post concussion (3mos)(Time3) time points. Error bars represent standard error of the mean (*p<0.05).

Percentage of error trials

When comparing baseline to return to play, we observed that Concussion group athletes had a significantly smaller overall percentage of error trials ($z = -2.232$, $p=0.026$) in the standard condition (Figure 7).

When comparing baseline to return to play, we observed that Concussion group athletes had a significantly smaller overall percentage of error trials ($z= -2.214$, $p= 0.027$) in the non-standard condition (Figure 7). This was unexpected given that our group's previous work showed lingering difficulties for athletes with a history of concussion on the non-standard task.

When comparing the Concussion group to the Control group, we observed a significant difference in percentage of error trials ($\chi^2=4.168$, $p=0.041$) on the standard condition at time of return to play (Time 2), with a mean rank score of 4.08 for the Control group, and 7.63 for the Concussion group (Figure 7), indicating that controls were actually executing more errors than Concussion group

Control group athletes exhibited zero errors at Time 3 in both the standard and non-standard condition, indicating all trials were executed correctly

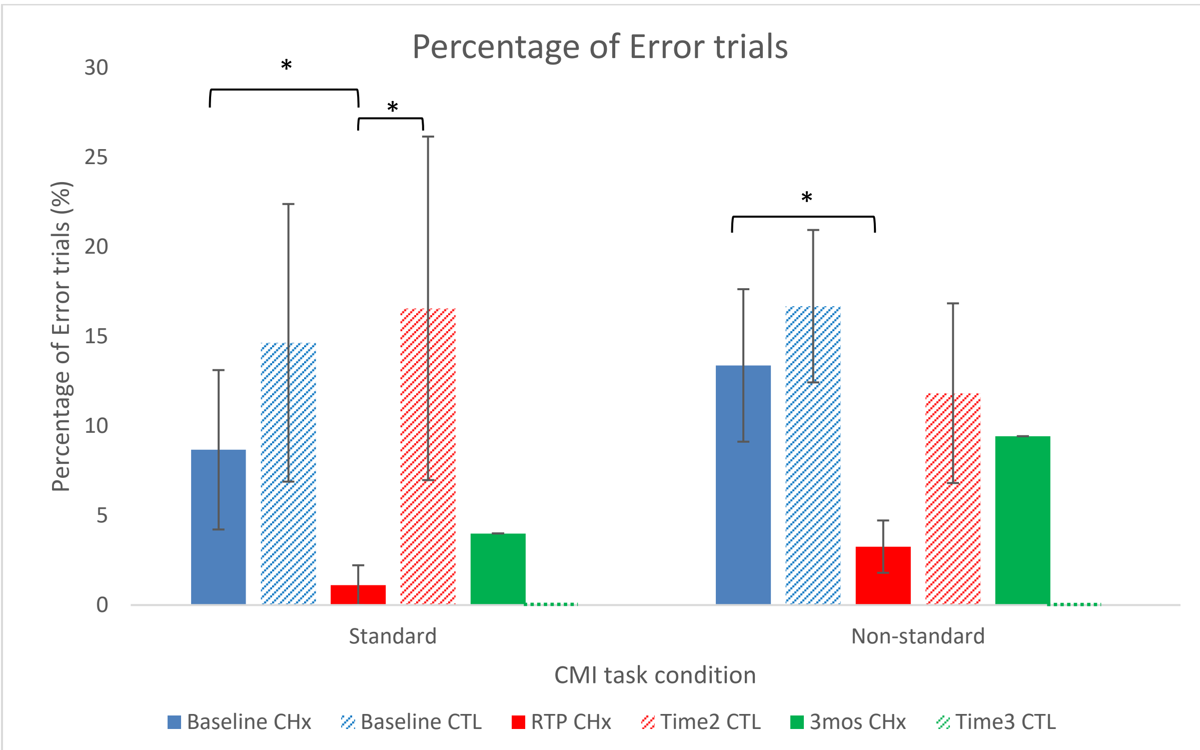

Figure 7. Histogram showing percentage of error trials (%) as a function of cognitive-motor integration (CMI) task condition (standard or non-standard) measured for concussion group (CHx) and control group (CTL) at baseline, return to play (RTP)(Time2) and three months post concussion (3mos)(Time3) time points. Error bars represent standard error (*p<0.05).

Reaction time

When comparing baseline to return to play, we observed that Concussion group athletes had significantly slower reaction times ($t= -3.805$, $df = 5$, $p=0.013$) in the standard condition (Figure 8).

When comparing the Concussion group to the Control group, we observed a significant difference in reaction time ($\chi^2=6.585$, $p=0.010$) on the standard condition at time of return to play (Time2), with a mean rank score of 7.50 for the Control group, and 2.50 for the Concussion group (Figure 8).

No significant differences were found for the Concussion group, the Control group, or a comparison between the two for the non-standard condition. However, when comparing baseline to three months post, we observed that Concussion group athletes had a trend toward faster reaction times ($z= -1.753$, $p=0.08$) in the non-standard condition (Figure 8)

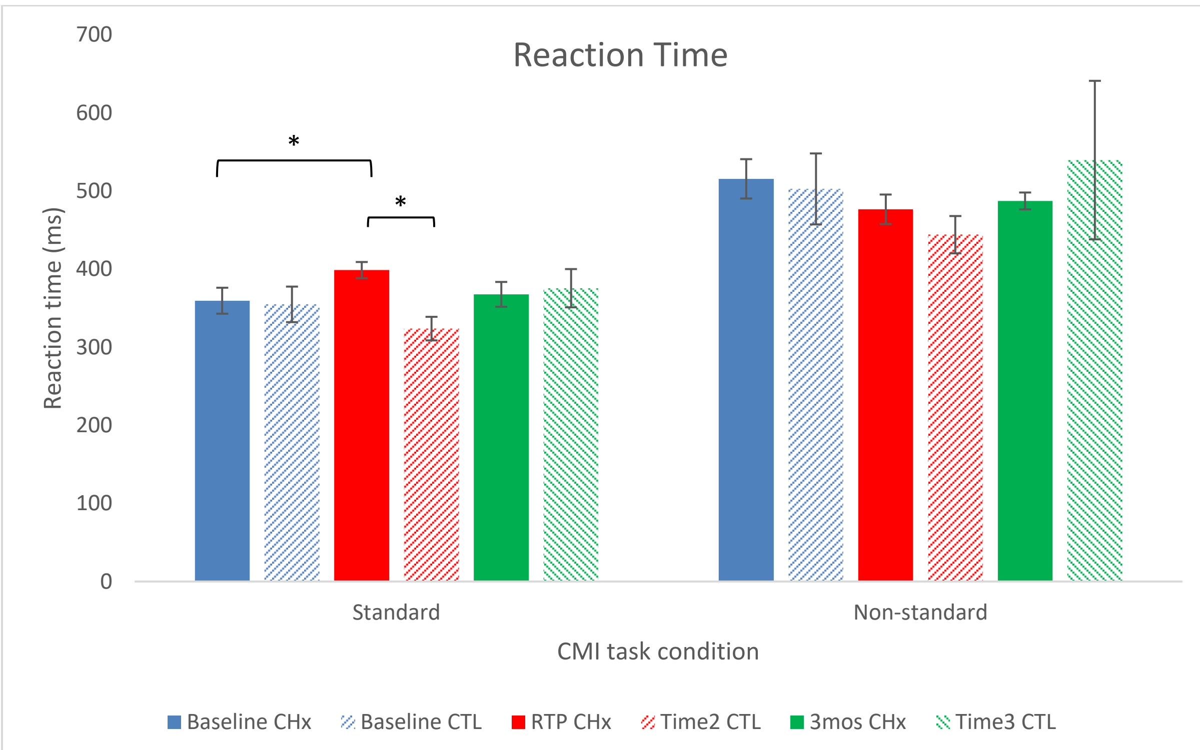

Figure 8. Histogram showing reaction time in milliseconds (ms) as a function of cognitive-motor integration (CMI) task condition (standard or non-standard) measured for concussion group (CHx) and control group (CTL) at baseline, return to play (RTP)(Time2) and three months post concussion (3mos)(Time3) time points. Error bars represent standard error (*$p<0.05$).

Full movement time

No significant differences were found on full movement time on any comparisons. See Figure 9.

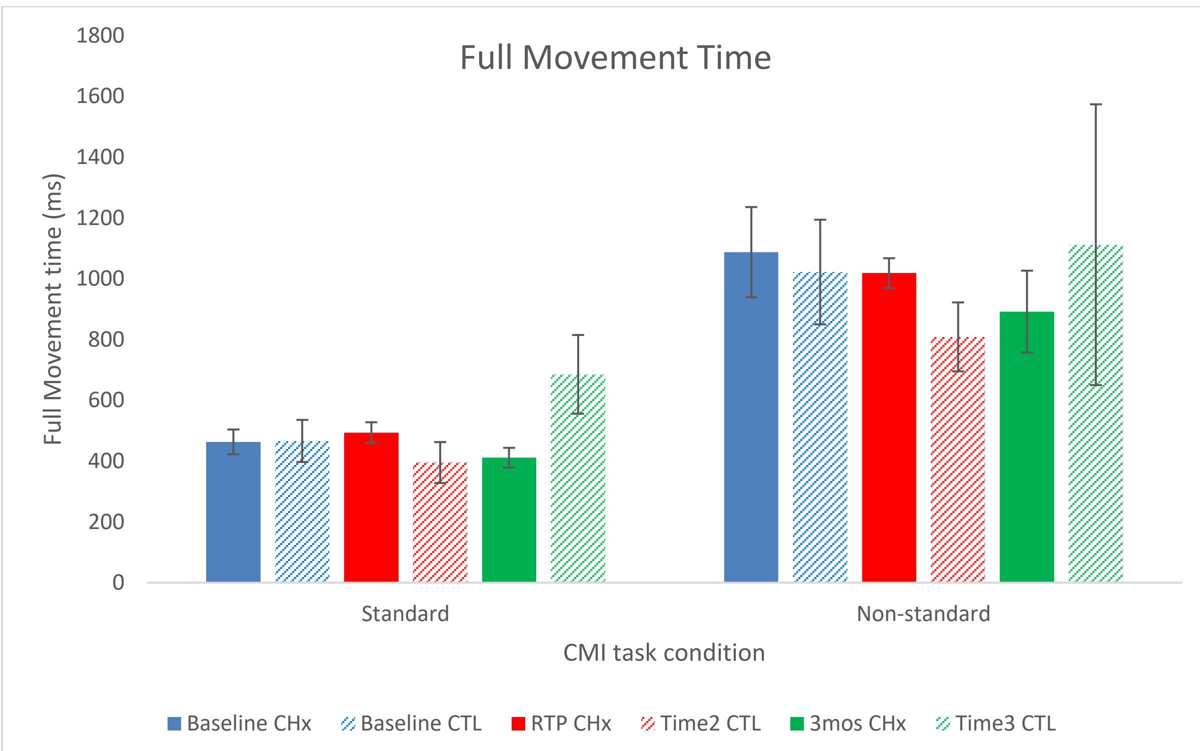

Figure 9. Histogram showing full movement time in milliseconds (ms) as a function of cognitive-motor integration (CMI) task condition (standard or non-standard) measured for concussion group (CHx) and control group (CTL) at baseline, return to play (RTP)(Time2) and three months post concussion (3mos)(Time3) time points. Error bars represent standard error (*p<0.05).

Absolute Error

When comparing baseline to Time 3, we observed a significant decrease in absolute error for the Control group athletes ($t=-39.957$, $df=1$, $p=0.016$) in the non-standard condition (Figure 10).

No significant differences were found for the Concussion group.

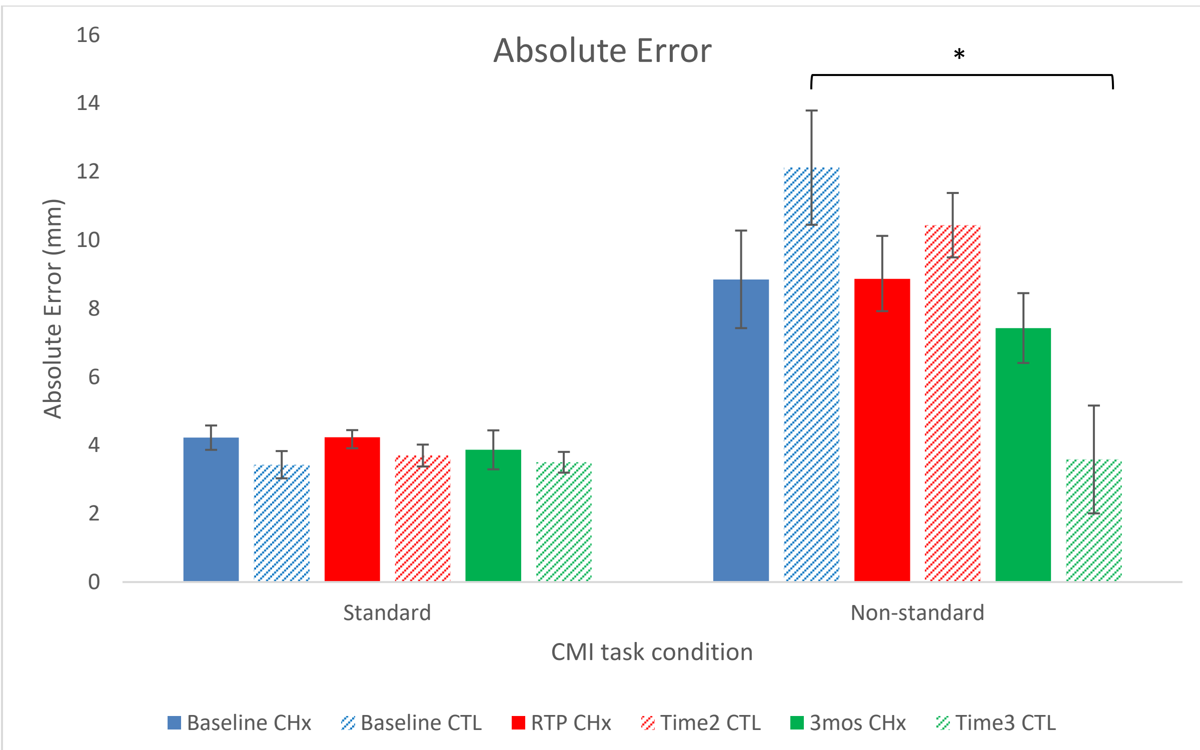

Figure 10. Histogram showing absolute error in millimeters (mm) as a function of cognitive-motor integration (CMI) task condition (standard or non-standard) measured for concussion group (CHx) and control group (CTL) at baseline, return to play (RTP)(Time2) and three months post concussion (3mos)(Time3) time points. Error bars represent standard error (*$p<0.05$).

Variable error

When comparing baseline to Time 2, we observed a significant increase in variable error for the Control group athletes (t=-3.210, df = 3, p=0.049) on the standard condition (Figure 11). This was unexpected given the learning effect of the task.

When comparing baseline to three months post concussion, we observed a significant decrease in variable error for the Concussion group athletes (z=-2.023, p=0.043) on the standard condition (Figure 11).

When comparing baseline to three months post concussion, we observed a trend towards decreased variable error for the Concussion group athletes (z= -1.753, p = 0.08) on the non-standard condition (Figure 11).

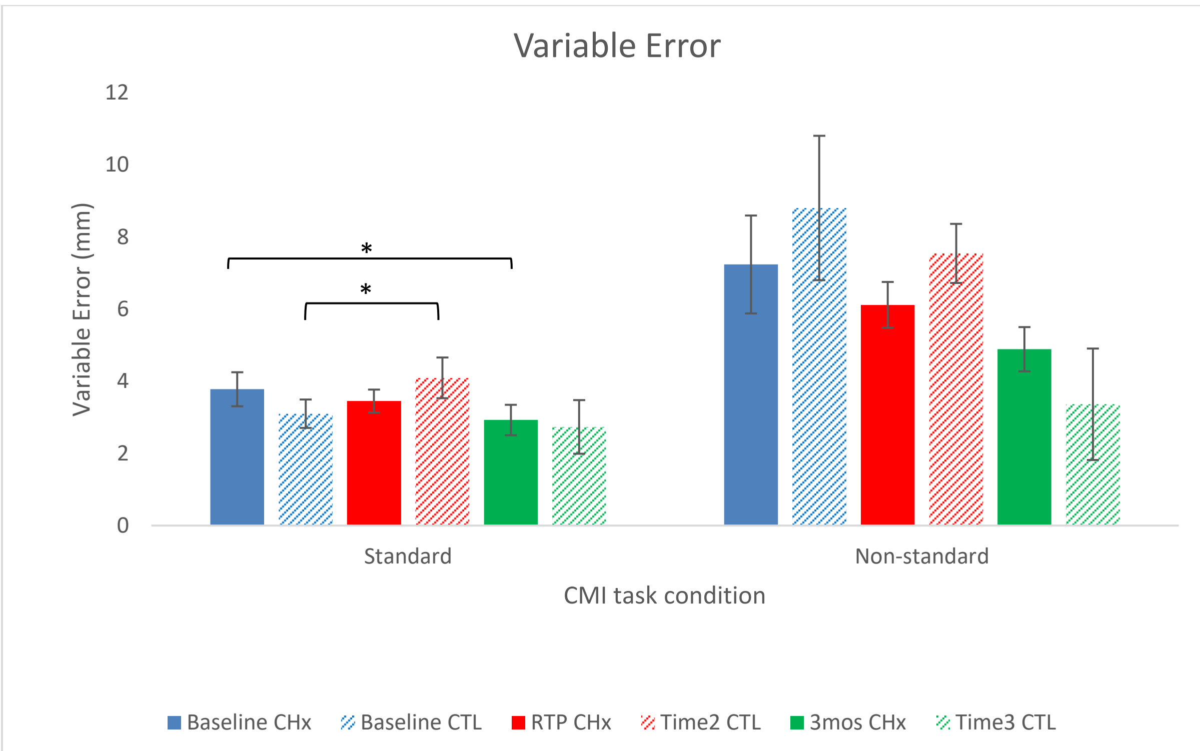

Figure 11. Histogram showing variable error in millimeters (mm) as a function of cognitive-motor integration (CMI) task condition (standard or non-standard) measured for Concussion group (CHx) and Control group (CTL) at baseline, return to play (RTP)(Time2) and three months post concussion (3mos)(Time3) time points. Error bars represent standard error (*p<0.05).

Normalized full path length

No significant differences were found on normalized full path length on any comparisons. See Figure 12.

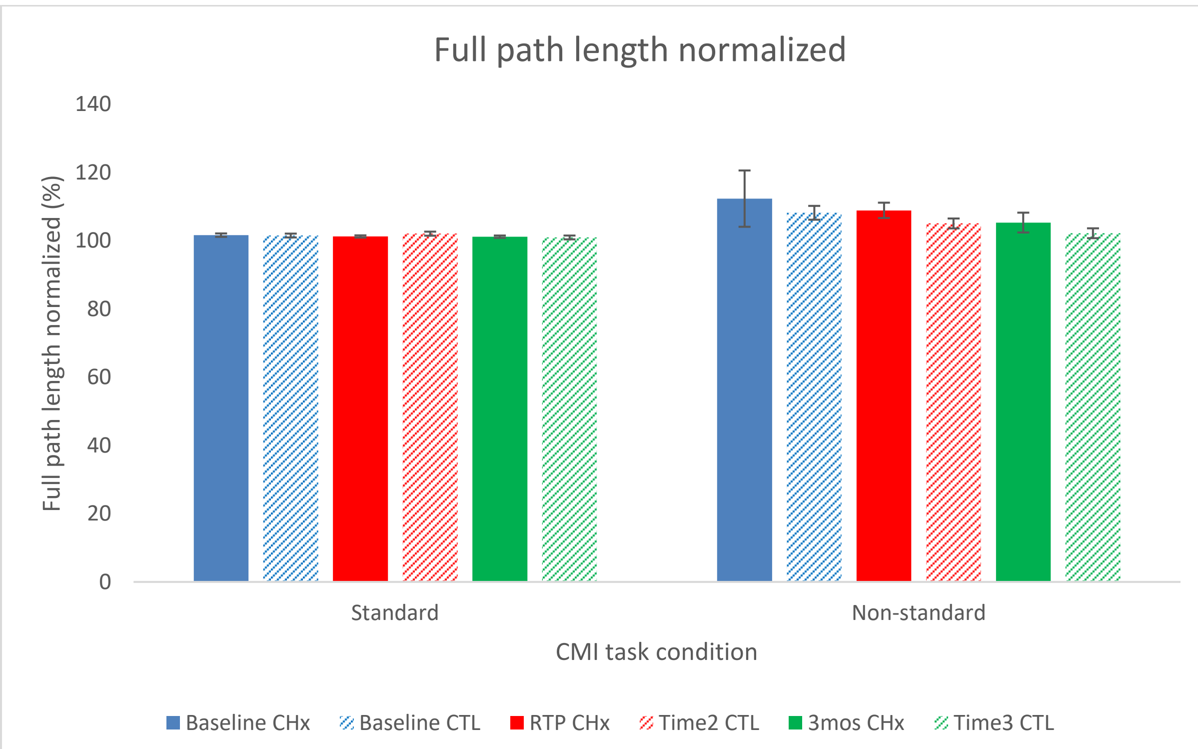

Figure 12. Histogram showing normalized full path length as a percentage of start point to end-point (%) as a function of cognitive-motor integration (CMI) task condition (standard or non-standard) measured for Concussion group (CHx) and Control group (CTL) at baseline, return to play (RTP)(Time2) and three months post concussion (3mos)(Time3) time points. Error bars represent standard error (*p<0.05).

Peak velocity

No significant differences were found on peak velocity on any comparisons. See Figure 13.

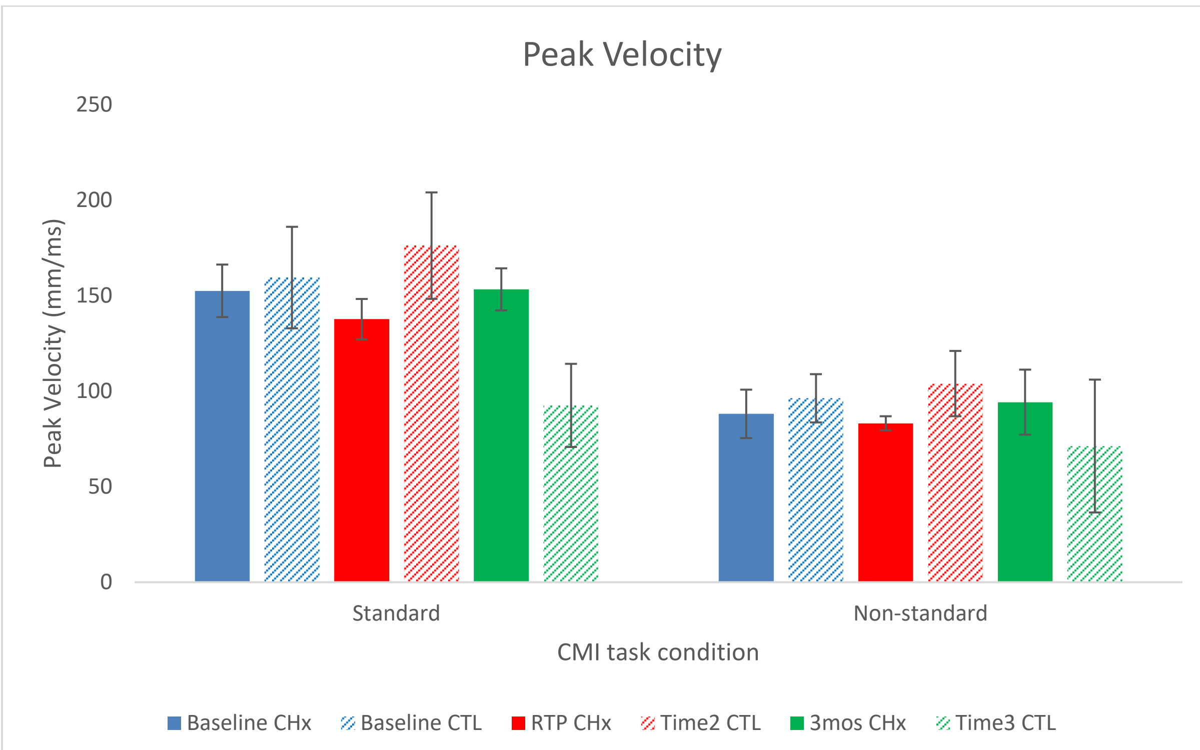

Figure 13. Histogram showing peak velocity measured as millimeters per millisecond (mm/ms) as a function of cognitive-motor integration (CMI) task condition (standard or non-standard) measured for Concussion group (CHx) and Control group (CTL) at baseline, return to play (RTP)(Time2) and three months post concussion (3mos)(Time3) time points. Error bars represent standard error (*$p<0.05$).

Wilcoxon Signed-ranks table

Due to the small sample size, a Wilcoxon signed-ranks test was used to observe the number of individual improvements and declines in each variable at each time point in order to quantify non-significant trends visible in the figures. Using the positive and negative ranks, tables were constructed indicating the number of participants who exhibited an improvement, decline, or no change, from their baseline scores. Results can be found below in Tables 2-9. These tests uncovered interesting patterns in the data, despite not reaching statistical significance.

Table 2. Wilcoxon signed-rank test results comparing return to play versus baseline measures on the standard task for the Concussion group. *indicates significance

Variable	Z	P-value	# improve	# decline	# no change
***%DR**	-2.000	0.046	4	0	2
***%Err**	-2.232	0.026	6	0	0
***RT**	-2.201	0.028	0	6	0
MTf	-0.734	0.463	2	4	0
AE	-0.734	0.463	2	4	0
VE	-1.153	0.249	5	1	0
PLfN	-1.363	0.173	5	1	0
PV	-1.363	0.173	1	5	0

Table 3. Wilcoxon signed-rank test results comparing Time 2 versus baseline measures on the standard task for the Control group. No significant differences.

Variable	Z	P-value	# improve	# decline	# no change
%DR	0.000	1	0	0	4
%Err	-0.447	0.655	1	1	2
RT	-0.365	0.715	3	1	0
MTf	-1.461	0.144	3	1	0
AE	-0.365	0.715	2	2	0
VE	-1.826	0.068	0	4	0
PLfN	-0.730	0.465	2	2	0
PV	-0.365	0.715	3	1	0

Table 4. Wilcoxon signed-rank test results comparing return to play versus baseline measures on the non-standard task for the Concussion group. ***indicates significance

Variable	Z	P-value	# improve	# decline	# no change
%DR	-0.315	0.752	3	3	0
***%Err**	-2.214	0.027	6	0	0
RT	-1.572	0.116	4	2	0
MTf	-0.105	0.917	2	4	0
AE	-0.105	0.917	4	2	0
VE	-1.153	0.249	5	1	0
PLfN	-0.524	0.600	3	3	0
PV	-0.943	0.345	3	3	0

Table 5. Wilcoxon signed-rank test results comparing Time 2 versus baseline measures on the non-standard task for the Control group. No significant differences.

Variable	Z	P-value	# improve	# decline	# no change
%DR	0.000	1.00	2	2	0
%Err	-1.095	0.273	3	1	0
RT	-0.730	0.465	2	2	0
MTf	-0.730	0.465	2	2	0
AE	-0.730	0.465	3	1	0
VE	-0.365	0.715	3	1	0
PLfN	-0.730	0.465	3	1	0
PV	0.000	1.00	2	2	0

Table 6. Wilcoxon signed-rank test results comparing three months post concussion versus baseline measures on the standard task for the Concussion group. No significant differences.

Variable	Z	P-value	# improve	# decline	# no change
%DR	-0.378	0.705	3	1	1
%Err	-1.490	0.136	4	1	0
RT	-0.944	0.345	1	4	0
MTf	-1.214	0.225	4	1	0
AE	-0.674	0.500	3	2	0
VE	-1.753	0.08	4	1	0
PLfN	-1.483	0.138	4	1	0
PV	-0.674	0.500	4	1	0

Table 7. Wilcoxon signed-rank test results comparing Time 3 versus baseline measures on the standard task for the Control group. No significant differences.

Variable	Z	P-value	# improve	# decline	# no change
%DR	0.000	1	0	0	2
%Err	0.000	1	0	0	2
RT	-1.342	0.180	2	0	0
MTf	-0.447	0.655	1	1	0
AE	-1.342	0.180	2	0	0
VE	-0.447	0.655	1	1	0
PLfN	-0.447	0.655	1	1	0
PV	-0.447	0.655	1	1	0

Table 8. Wilcoxon signed-rank test results comparing three months post concussion versus baseline measures on the non-standard task for the Concussion group. *indicates significance

Variable	Z	P-value	# improve	# decline	# no change
%DR	-0.677	0.498	3	2	0
%Err	-1.214	0.225	4	1	0
RT	-1.753	0.080	4	1	0
MTf	-1.214	0.225	3	2	0
AE	-1.483	0.138	4	1	0
***VE**	-2.023	0.043	5	0	0
PLfN	-1.214	0.225	4	1	0
PV	-0.405	0.686	3	2	0

Table 9. Wilcoxon signed-rank test results comparing Time 3 versus baseline measures on the non-standard task for the Control group. No significant differences

Variable	Z	P-value	# improve	# decline	# no change
%DR	-1.342	0.180	2	0	0
%Err	-1.342	0.180	2	0	0
RT	-0.447	0.655	1	1	0
MTf	-1.342	0.180	2	0	0
AE	-1.342	0.180	2	0	0
VE	-1.342	0.180	2	0	0
PLfN	-1.342	0.180	2	0	0
PV	-0.447	0.655	1	1	0

Further Analysis

Z-Scores of change(Δ)

Given the number of kinematic variables measured on our tasks, z-scores were calculated to compare individual scores at RTP (time 2) and 3 months post concussion (time 3) to the mean of each group at baseline. These calculations were used to create overall scores for Trajectory, Movement timing, and Success. Trajectory consisted of variable error, absolute error, and full path length; Movement timing consisted of reaction time, and movement time; and Success consisted of percentage direction reversal and percentage error. Scores on Trajectory, Movement timing, and Success for each participant can be found below in Table 10,11, and 12, respectively; (Concussion group) and Table 13, 14, and 15 (Control Group), respectively. Overall, these tables show that on average, both concussed athletes, and non-concussed control athletes are performing better than the respective group baselines at both return to play (Time 2) and three months post concussion (Time 3). However, when Concussion group participants are compared to control group participants, we see that non-concussed controls are showing improved performance to a higher degree than concussed athletes, as indicated by the percentage of athletes from each group who are performing better than baseline levels (Table 16).

Concussion group

Table 10. Trajectory Score created using z-scores for return to play (RTP) and three months post concussion (3 mos. post) on both the standard and non-standard condition for all participants within the Concussion group; (negative = better)

	RTP		**3 mos. post**	
Participant	**Standard**	**Non-standard**	**Standard**	**Non-standard**
1	-1.211	-0.501	--	--
2	0.248	2.029	-0.979	-0.028
3	-0.474	-0.124	-0.077	-2.224
4	0.658	-0.946	1.468	-0.302
5	-2.556	-2.267	--	--
6	-0.157	-1.170	-4.416	-2.843
7	--	--	-3.546	-1.874

Table 11. Movement timing Score created using z-scores for return to play (RTP) and three months post concussion (3 mos. post) on both the standard and non-standard condition for all participants within the Concussion group; (negative = better)

	RTP		**3 mos. post**	
Participant	**Standard**	**Non-standard**	**Standard**	**Non-standard**
1	2.441	-0.678	--	--
2	1.435	-0.852	-0.744	-1.721
3	1.860	0.878	0.973	0.037
4	0.441	-1.711	-0.663	-0.377
5	1.024	-1.939	--	--
6	0.419	-0.603	0.824	-0.759
7	--	--	-1.999	-2.146

Table 12. Success Score created using z-scores for return to play (RTP) and three months post concussion (3 mos. post) on both the standard and non-standard condition for all participants within the Concussion group; (positive = better)

	RTP		**3 mos. post**	
Participant	**Standard**	**Non-standard**	**Standard**	**Non-Standard**
1	1.118	-1.20	--	--
2	1.118	-0.09	-0.111	-0.588
3	1.118	-0.22	1.118	-0.22
4	0.503	1.30	1.118	0.86
5	1.118	2.16	--	--
6	1.118	1.75	0.503	1.699
7	--	--	-3.02	1.297

Control group

Table 13. Trajectory Score created using z-scores for Time 2 and Time 3on both the standard and non-standard condition for all participants within the Control group; (negative = better)

	RTP		3 mos. post	
Participant	**Standard**	**Non-standard**	**Standard**	**Non-standard**
1	4.298	-1.927	--	--
2	3.614	-1.556	--	--
3	-1.212	-0.783	0.846	-3.73
4	0.773	-1.418	--	--
5	--	--	-2.408	-5.909

Table 14. Movement timing Score created using z-scores for Time 2 and Time 3 on both the standard and non-standard condition for all participants within the Control group; (negative = better)

	RTP		3 mos. post	
Participant	**Standard**	**Non-standard**	**Standard**	**Non-standard**
1	-1.157	-0.517	--	--
2	-2.363	-2.512	--	--
3	0.664	-0.357	0.504	-1.60
4	-1.422	-1.136	--	--
5	--	--	3.138	2.796

Table 15. Success Score created using z-scores for Time 2 and Time 3 on both the standard and non-standard condition for all participants within the Control group; (positive = better)

	RTP		3 mos. post	
Participant	**Standard**	**Non-standard**	**Standard**	**Non-standard**
1	-0.679	-1.677	--	--
2	0.957	0.53	--	--
3	1.844	1.26	1.844	2.530
4	1.43	0.782	--	--
5	--	--	1.844	2.530

Table 16. Percentage of athletes from both the Concussion group (CHx), and Control group (CTL), who had z-scores indicating improved performance on Trajectory, Movement timing, and Success on the non-standard condition.

Time point	Trajectory		Movement Timing		Success	
	CHx	**CTL**	**CHx**	**CTL**	**CHx**	**CTL**
Return to Play	83%	100%	83%	100%	50%	75%
3 mos. post	100%	100%	80%	50%	60%	100%

Correlational analyses

Based on the speed-accuracy trade-off hypothesis, a pearson's correlation was calculated between reaction time and percentage error, and full movement time and percentage of error, at baseline, return to play, and three months post concussion time points for the Concussion group and baseline, Time 2, and Time 3 for the Control group. The results can be found below in Table17 (Concussion group) and Table 18 (Control group). These tables indicate a strong, positive correlation ($r=0.814$, $p=0.049$) between reaction time and percentage of error trials for the Concussion group athletes on the non-standard condition, at the time of return to play. No other statistically significant correlation patterns were found between reaction time and percentage of error trials, or full movment time and percentage of errors on either the standard or non-standard condition for the Concussion group or the Control Group.

Table 17. Results of Pearson's correlation to compare reaction time (RT) and percentage of error (%Err), and full movement time (MTf) and percentage of error at baseline, return to play (RTP) and three months post concussion (3 mos post) time points on both the standard and non-standard task, for the Concussion Group

Time point	**RT vs. %Err Standard**	**RT vs. %Err Non-standard**	**MTf vs. %Err Standard**	**MTf vs. %Err Non- standard**
	r-value (p-value)	**r-value (p-value)**	**r-value (p-value)**	**r-value (p-value)**
Baseline	0.111 (0.575)	0.006 (0.977)	-0.335ǂ (0.081)	0.86 (0.665)
RTP	-0.574 (0.234)	0.814* (0.049)	-0.059 (0.912)	0.448 (0.372)
3 mos post	0.347 (0.567)	0.547 (0.340)	-0.302 (0.621)	0.477 (0.417)

*($p<0.05$)

ǂ trend towards statistical significance

Table 18. Results of Pearson's correlation to compare reaction time (RT) and percentage of error (%Err), and full movement time (MTf) and percentage of error at baseline,Time 2, and Time 3 time points on both the standard and non-standard task, for the Control Group

Time point	**RT vs. %Err Standard**	**RT vs. %Err Non-standard**	**MTf vs. %Err Standard**	**MTf vs. %Err Non- standard**
	r-value (p-value)	**r-value (p-value)**	**r-value (p-value)**	**r-value (p-value)**
Baseline	-0.827ǂ (0.084)	-0.619 (0.265)	-0.857ǂ (0.064)	-0.704 (0.184)
Time 2	0.179 (0.821)	-0.538 (0.462)	-0.647 (0.353)	-0.934ǂ (0.066)
Time 3	/	/	/	/

/ - no errors were made

ǂ trend towards statistical significance

Discussion

The aim of this study was to determine whether athletes cleared by current return to sport protocols had lingering functional deficits making it unsafe for them to be returned to play. As well, this study looked at whether a computer-based congnitive-motor integration (CMI) task could be used to evaluate athlete's recovery from concussion in a more sensitive and objective way than current protocol measures.

Results of this preliminary study demonstrate that concussed individuals are able to improve upon certain aspects of the CMI task; however, other aspects of the performance suffer. As well, concussed athletes may not be improving on the task at the same rate as non-concussed control athletes. Our hypothesis that athletes have lingering deficits despite being cleared by current return to sport protocols is partially supported, but requires further research. When compared to baseline measures, Concussion group athletes exhibited improved performance by reducing the percentage of error trials, but with this there appeared to be an effect on reaction time and full movement time. As well, Concussion group athletes continued to show direction reversal errors, and overall errors on the task even at 3 months post concussion, while control athletes were able to perform all BrDI™ trials successfully by this time. In using histograms, supported by data from Wilcoxon signed-ranks test, interesting tendencies were observed when comparing Concussion group patterns to Control group patterns, and Concussion group performance at the different time points, despite the current lack of statistical significance. However, due to the small sample size measured in this study, we believe certain results not statistically significant at this time may show significance with a greater sample size.

Concussion and learning a novel cognitive-motor integration task

Recent studies have found both cognitive and motor alterations in those with a history of concussion[27,28,29,62,63] For example, De Beaumont et al. (2012) found that GABA-mediated intracortical inhibition in the primary motor cortex (M1) as caused by concussion was associated with reduced motor learning ability in these participants[63]. As well, Collins, Grindel, and Lovell (1999)[64] used a large sample of 393 university football athletes to assess the relationship between concussion history and cognitive performance. They found that a history of concussion was associated with reduced cognitive performance on neuropsychological tests. Importantly, the BrDI™ task used in this study has detected lingering deficits following concussion in a wide variety of athletes.[27,28,29] Therefore, based on previous research and the use of an already validated task, we would expect to see a significant decline in Concussion group athletes on the performance of the non-standard condition at the time of return to play, and possibly even at three months post concussion.

Interestingly, no significant differences are seen in the non-standard condition at return to play, other than a significant improvement in the number of error trials within the Concussion group. While this may seem like an indication that the Concussion group is performing well, it is important to note that this variable takes into account all errors. Therefore, an improvement on this variable may indicate a better understanding of the execution of the task, but not necessarily a better overall performance. While not statistically significant, full movement time shows a pattern of decline by certain participants in this condition.Therefore, while participants are able to improve on one variable, it may be at the expense of performance on another, which indicates that participants may still be having difficulties with the overall performance of the task.

The only statistically significant difference in the concussion group at the three month post concussion time point is an improvement in variable error. This measures the accuracy of the participant's initial movement toward the target. Improvement in this variable may be indicative of an improvement on the task. Therefore, it is important to then use the control group as a comparison of what level of improvement should be expected. Due to our small sample size there is a lack of statistical significance in the control group. However, an underlying trend is still evident. In Figure 11, it is evident that both groups show a decrease in variable error on the non-standard condition at what looks like the same rate. This may indicate that Concussion group athletes are able to successfully improve upon variable error, despite a lack of improvement in other measures.

When looking at Figure 11, 12, and 13 respectively, we see a pattern of improvement in variable error and normalized full path length, but a non-significant decline in peak velocity for the Concussion group on the standard condition when comparing baseline levels to time of RTP. When observing the same group on the non-standard condition we see a pattern of improvement only in variable error. Comparing these results to controls, in Figure 8, 9 and 13 respectively, we see a pattern of improvement in reaction time, full movement time, and peak velocity on the standard condition; and in Figure 7, 10, 11, and 12 respectively, we see a pattern of improvement in percentage of error trials, absolute error, variable error, and normalized full path length on the non-standard condition. This may be an indication of a learning effect of the task, which the concussion group athletes are clearly not exhibiting. Halstead et al., (2013)[65] deem it common for children to experience difficulties learning new tasks and remembering previously learned material following concussion. Therefore, although the concussion group is not exhibiting lingering behavioural deficits per se, the data may indicate that deficits still remain within the connectivity of the brains and therefore, motor learning abilities of these participants.

Additionally, by using z-scores to create overall scores in Trajectory, Movement timing, and Success, comparison between Concussion group performance to Control group performance becomes slightly easier. When observing Trajectory, Movement timing, and Success scored at RTP, the concussed group shows 83% 83% and 50% improvement, respectively. In comparison, the control group shows 100% 100% and 75% improvement, respectively. When observing Trajectory, Movement timing, and Success at three months post concussion the concussed group shows 80%,100%,and 60%improvement, respectively. In comparison, the control group shows, 50%, 100% and 100% improvement, respectively. Even with these pilot control results, the Control group appears to be performing better than the Concussion group on all three of the measures at time of RTP and two of the three measures at three months post concussion. However, given the size of the Control group, a group comparison is not ideal. Therefore, it is interesting to compare the individuals within the concussed group to their age and sex matched controls. For example, Concussion group participant 2 was age and sex matched with Control group participant 3. When looking at the z-scores for each participant, Control group participant 3 performs better at all time points and conditions on both timing and success. A better performance by individuals in the Control group when age and sex matched with the Concussion group is seen in four out of the six comparisons. Therefore, while the data may suggest that athletes are technically performing back at baseline levels at time of return to play and three months post concussion, they should actually be improving their performance on the task as seen with the Control group. This provides support to our hypothesis that athletes are still exhibiting impairments when compared to non-concussed controls. As well, it provides some evidence that the effects of concussion may still be impacting athletes performance at time of return to play and even three months later.

Concussion and alteration of motor planning

Motor planning is essential to properly execute a goal directed reach. It has been suggested that integrated position estimates are required at two stages of motor planning when planning goal-directed reaches; the desired movement vector must first be determined, and then the vector must be transformed into a joint-based motor command[66]. Sober and Sabes (2003)[66] sought to determine if different combinations of sensory input are weighted differently depending on the stage of motor planning for a reach. By displacing visual feedback from the arm prior to movement onset, they used the resulting movement errors to suggest that the position estimate for movement vector planning uses mostly visual input, whereas the estimate for the joint-based motor command uses mostly proprioceptive signals. These results suggest that the brain selects different combinations of sensory input when estimating the position of the arm depending on how the resulting estimate will be used. As mentioned previously, visuomotor integration tasks require the combination of both intrinsic and extrinsic information to create an appropriate motor plan.[47-50] Additionally, the frontoparietal network has been established as crucial for the visuomotor integration required for reaching.[50, 52] Specifically, changes within the dorsal premotor cortex (PMd)[54] and superior parietal lobule(SPL)[42] have been noted during a non-standard mapping visuomotor task. This, in combination with the suggestion that the transformation of signals into different coordinate frames create errors through possible additional noise from computation, or imperfections in their mappings,[66] suggests that damage to those areas responsible for the transformations would make successfully completing the goal-directed reach very difficult. Specifically, previous studies have found impairment in movement planning in concussion, and those at risk for Alzheimer's and dementia.[67] Further, lesions to the deep nuclei of the spinocerebellum result in disrupted accuracy, hand path, and timing errors in reaching movements; while lesions to the deep cerebellar nucleus of the cerebrocerebellum result in delays in initiating movements and irregularities in movement timing.[51] Issues with these areas have been suggested to be common with those who have experienced concussion.

As previously noted, those with mild cognitive impairment have shown impaired reaction time and movement time on a task with more than one level of decoupling.[58] In this study, we saw similar results in that the Concussion group athletes seem to be exhibiting issues with both reaction time and movement time; whereby, when reaction time appears to improve, movement time appears to decline on the non-standard condition at both time points. However, in the standard condition we do not see this relationship. This supports the idea that the two levels of decoupling are more sensitive to these impairments than the basic motor task alone. Additionally, in this study we noted irregularities in variables associated with movement timing such as reaction time(Figure 8) full movement time (Figure9) and peak velocity (Figure 13) throughout the standard and non-standard tasks at all time points for the Concussion group athletes. This suggests that something about the concussive head injury is affecting the abilities of these participants. However, further research is needed in order to determine the underlying cause of these patterns.

Interestingly, the Control group exhibits a moderate to strong negative correlation between movement time and percentage of error trials in the standard condition at baseline (r=-0.857, p=0.064) , and the non-standard condition at both baseline (r=-0.704, p=0.184) and return to play (r=-0.934, p=0.066). Conversely, the Concussion group exhibits a negative (albeit, weak) correlation in the standard condition at both time points (r=-0.335, p-0.081) (r=-0.059, p=0.912), and a positive correlation in the non-standard condition at both time points (r=0.860, p-

0.665)(r=0.448, p=0.372). It is interesting to note that the Concussion group athletes are exhibiting a positive correlation on the non-standard task while the Control group athletes are exhibiting a negative one. As well, it is interesting that the strength of the correlation in the Concussion group athletes decreases from baseline to RTP, while the correlation in the Control group increases. These results together may indicate that the athletes of each group initially applied a different strategy, or perhaps a different combination of sensory input, in the cognitive-motor integration task. However, it is then important to note that the Concussion group strategy does not stay the same, or possibly does not work as well, following a concussion. The decrease in strength of correlation between movement time and percentage of errors at time of return to play when compared to baseline in the Concussion group suggests a possible change in which aspects of performance are being focused on and successfully executed. For example, Sober and Sabes (2005)[68] suggest that an increased focused on proprioceptive signals may create faster reaction times but lower accuracy. While we are not seeing this exact change, a change in the relationship between two initially strongly correlated variables may point towards a change in weighting of available information. As previously mentioned, the processing in the frontoparietal network consists of extensive reciprocal corticocortical projections and changes in the pattern of activity have been noted during cognitive-motor integration.[42,54] Therefore, these changes may be due to damage, as a result of concussion, in communication between the frontoparietal network required to coordinate the compensatory trade-off strategy, which is still evidently intact in controls. Importantly, this provides some evidence to the hypothesis that athletes have not returned to baseline levels of performance as it implies that concussed athletes are having difficulty successfully employing the same strategy they used at baseline.

Concussion and immeasurable changes

While currently not fully quantified, another difference in performance is noticeable when visually comparing trajectories, as demonstrated in Figures 4 and 5. From these trajectories, it is suggestive of the fact that the concussed group individual has not returned to their baseline performance ability, while the control participant is performing relatively similar at all time points. In the sample control participant we see smoother finger trajectories, less variable starting positions, less variable final positions, and a higher number of successful trials (indicated by the number of green lines per target). As well, we see that their performance at time 3 looks relatively the same as their performance at time one. In the sample Concussion group participant we see more erratic finger trajectories, variability in both starting and ending positions, and a lack of improvement from baseline to three months post concussion. Studies show that humans' hands prefer to travel in a relatively straight path from initiation to target location.[69] This type of path requires increased coordination between muscle activations and joint maniuplations; therefore, increasing the need for the central nervous system to act on more complex factors.[70] While not statistically significant at a group level, it is evident from the green trajectory lines shown in Figure 5 that some Concussion group participants are having difficulty controlling their path in situations requiring increased cognitive control. For this reason, it is important to also compare concussed individuals to themselves, as well as normative data. While, as a group, the concussed individuals did not show an abundance of statistically significant changes, it is well known that concussions present themselves and resolve very differently in different individuals.[71] Recently, assessment tools for concussion are increasingly trying to make measures more objective in order to allow for more sentive diagnostic measures. However, it is important to take into account the individual nature of these injuries, and to remain vigilant when assessing an individual especially if they are showing possible signs of difficulties but are able to pass objective tests such as SCAT and ImPACT.

While an objective measure is the ideal standard in order to ensure interrater reliability, it is unwise to ignore the capability of assessments potentially subjective in nature as an addition to those objective in nature. For example, one of the symptoms listed on the SCAT5 symptom checklist reads "just don't feel right". This may seem unuseful to those individuals who have never experienced concussion, but it may be an indication of underlying deficits. Concussion literature is not at the stage yet where all signs and symptoms have been linked to their underlying causes, and given the nature of the injury, there is a possibility it never will be. As shown in this study, we note changes in performance on kinematic variables but are still speculating as to the underlying causes. Therefore, it is important to include comprehensive and sensitive objective measures, as well as supporting subjective components to ensure all bases are covered and no athletes are cleared before it is safe to do so. If an individual happens to remain below the threshold of statistical significance on a cognitive-motor integration task, but is still exhibiting trajectories as those seen in Figure 5, an underlying deficit may still be at play, and to avoid further injury it would be wise to favour the subjective measure in this case. Additionally, when observing Figure 7, 8, and 13, a pattern is noticeable amongst the Concussion group athletes which is not only different from the Control group athletes, but may also be indicative of some sort of change in performance at time of RTP when compared to baseline, and a trend towards return to baseline levels at three months post concussion. While we are yet unable to pin point the nature of this change, or perhaps the best measure with which to quantify it, we suggest this pattern is indicative of a lingering change in brain function not being detected by current Return-to-sport protocols.

The goal of concussion assessments should be to not allow a single individual to return to an unsafe environment if they are not fully recovered. The data from this study suggests that these assessments should be updated to include improved objective measures, and subjective sub-components.

Conclusion

While concussion is a very difficult topic of study given its heterogeneity, and overall smaller available sample sizes, it is important to continue improving our current standards of assessments for the safety of those obtaining this type of injury. Given what appears to be the impariment of learning on this novel visuomotor transformation task, and the suspected change in strategy by concussed athletes after concussion, it is assumed that our task is tapping into diverse brain networks which appear to be affected by concussion. Therefore, it is important to integrate these types of cognitive-motor integration tasks into current Return-to-sport protocols in order to have a better overall indication of neural healing following concussion.

As well, it appears that the Concussion group athletes are able to show improvements on some variables, but this comes with declines on other variables, lasting as long as three months post concussion. These athletes are unable to effortlessly execute a visuomotor reaching task, in a controlled environment, with just their finger, but current standards are deeming them fit to return to a much more complicated environment. Therefore, it is recommended that more detailed, and also continued monitoring of those diagnosed with concussion through tasks such as BrDI™ which incorporate more difficult cognitive and motor standards combined, be integrated into current standards.

Lastly, while some behaviours may not be statistically significant, observable changes in behaviours are, at the very least, a good place to start. While concussion group athletes were able to successfully pass current protocols and complete some cognitive-motor integration trials, the visual trajectories for many of them were very qualitatively different from their baselines. The measurements may not be perfect yet, but it is important to explore all possible indications of deficits – such as objective performance on kinematic variables, and subjective performance on visually observable behavioural changes - in order to appropriately diagnose and return athletes to play.

In the end, it is evident that behavioural differences exist between those with a history of concussion and those without, and that Concussion damage may still be present and affecting ones' abilities even after passing current recovery measurement standards. However, the potential factors leading to these discrepancies must be investigated further.

Study Limitations

One major limitation of this study is the small sample size in both groups. As concussion symptoms and recoveries are already extremely heterogeneous, a larger sample size is recommended in order to potentially uncover performance improvement and decline trends. As well, a larger control sample size is recommended in order to better represent the athletic population, consisting of more individuals of both sexes from a wider variety of sports. Not only would this assist in the comparison to concussed athletes, but it may also uncover interesting trends between types of sport and cognitive-motor integration abilities.

Secondly, some studies have found a correlation between number of previous concussions and performance on cognitive and motor tasks. [62,63,72] The controls used in this study are deemed controls based on a self-report of their concussion history. It is possible that these controls may have experienced a concussion in the past without being diagnosed properly. This may effect the trends of the data seen when comparing concussed athletes to controls. Similarly, Concussion group athletes were asked about number of *diagnosed* concussions at baseline testing. Therefore, it is also possible that performance on the BrDI™ task and variability within the Concussion group could be affected due to previously undiagnosed concussions.

Additionally, theses data may reflect a sample bias. Specifically, those players with greater motor skill ability are more likely to have an increased playing time, and in conjuction may be more likely to obtain a concussion.[71] This may affect the results of the kinematic variables given that Concussion group athletes may be more skilled than Control group athletes.

Hence, for future research, it is recommended that a larger sample size be recruited for both groups, and a detailed investigation into realistic concussion history of controls, and concussion history of the concussion group be completed.

Glossary of Terms

%DR – Percentage of Direction Reversals

%Err – Percentage of Error Trials

ADD – Attention Deficit Disorder

ADHD – Attention Deficit Hyperactivity Disorder

AE – Absolute Error

BrDI™ - Brain Dysfunction Indicator

CDC – Centers for Disease Control and Prevention

CISG – Concussion in Sport Group

CMI – Cognitive-motor integration

CST – Corticospinal tract

DTI – Diffusion tensor imaging

M1 – Primary motor cortex

MCI – Mild cognitive impairment

MOI – Mechanism of Injury

MTf – Full Movement Time

NPLf – Normalized Full Path Length

PCS – Post-concussion syndrome

PMC – premotor cortex

- SMA - Supplementary motor area
- CMA – cingulate motor area
- PMd – lateral dorsal premotor area
- PMv – lateral ventral premotor areas

PO – Parieto-occipital extrastriate cortex

PPC – Posterior parietal cortex

SPL – Superior parietal lobule

MDP – Median dorsal parietal area

IPS – Intraparietal sulcus

MIP – Medial intraparietal sulcus

LIP – Lateral intraparietal sulcus

VIP – Ventral intraparietal sulcus

PV – Peak Velocity

RT – Reaction time

RTP – Return to Play

RTS – Return to Sport

SCAT3 – Sport Concussion Assessment Tool

SLF – Superior longitudinal fasiculus

V1 – Primary Visual Cortex

VE – Variable Error

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Appendix A

I. Full list of concussion symptoms divided by categorical classification

Symptom Category	**Symptoms**	
Physical	Headache Nausea/Vomiting Balance Problems Numbness/Tingling	Sensitivity to light/noise Visual Problems Dizziness Dazed/Stunned
Emotional	Irritable Sadness	More emotional Nervousness
Cognitive	Feeling mentally foggy Difficulty Concentrating Difficulty Remembering Repeat Questions	Feeling mentally slowed down Forgetful of recent information Confused about recent events
Sleep Disturbances	Drowsiness Sleeping less than usual	Sleeping more than usual Trouble falling asleep

II. Graduated return to play protocol. Obtained from McCrory et al. (2017)[3]

Rehabilitation Stage	**Functional exercise at each stage of rehabilitation**	**Objective of each stage**
1) Symptom-limited activity	Every day activities which do not cause exacerbation of symptoms	Recovery
2) Light Aerobic Exercise	Walking, swimming or stationary cycling keeping intensity <70% maximum permitted heart rate No resistance training	Increase HR
3) Sport-specific exercise	Skating drills in ice hockey, running drills in soccer No head impact activities	Add movement
4) Non-contact training drills	Progression to more complex training drills E.g. Passing drills in football and ice hockey May start progressive resistance training	Exercise, coordination, and cognitive load
5) Full-contact practice	Following medical clearance participate in normal training activities	Restore confidence and assess functional skills by coaching staff
6) Return to sport	Normal game sport	

III. Distribution of normally and non-normally distributed variables for both Concussion and Control group

	Concussion Group	**Control Group**
Normally Distributed	Reaction Time Absolute Error	Absolute Error Variable Error Normalize full Path Length Peak Velocity
Non-normally Distributed	% Direction Reversals % Errors Full Movement Time Normalized full Path Length Peak Velocity Variable Error	% Direction Reversals % Errors Full Movement Time Reaction Time

IV. Average percentage of deleted trials (for a variety of reasons) per condition at each time point for both Concussion group and Control group

	Concussion Group		**Control Group**	
	Condition 1	**Condition 8**	**Condition 1**	**Condition 8**
Baseline	9.82	7.53	8.75	6.25
Return to Play (Time 2)	4.17	9.04	12.5	7.8
3 mos post (Time 3)	8.75	9.42	9.38	12.5

Appendix B

Questionnaire

Date: _______________

Name: ______________________________ Age: _________

Dominant Hand: _____________________ Sex: Male or Female

Team/League: ___________________________ Position: __________________________

What age did you start playing your sport? ____________

1. Do you currently have a concussion? YES or NO

If YES,
a) Approximate date of concussion: ___________________________

b) Did you lose consciousness? _____________________ If so, for how long? ___________

c) Please list any current signs and symptoms:

____

____

____

2. Have you previously had any concussions? YES or NO

If YES,
a) How many? _________

b) Did you lose consciousness? _____________________ If so, for how long? ___________

c) Dates(s) and time out before returning to play / regular activity:

____

____

3. Do you currently have a non-head related injury? YES or NO

If YES,
a) Please describe the nature of the injury:

____

b) Has it kept you from play for longer than 48 hours? YES or NO

c) Has it kept you from play for longer than 3 weeks? YES or NO

4. Have you been diagnosed with any neurological disorders? YES or NO

If so, please describe the disorder:

____

5. Do you play video games? YES or NO
If YES,
a) What kind of video games do you play most often? (i.e. Fast-paced action games, or Puzzle/strategy games, or both?) Please list some example games.

____

____

b) How would you rate your skill at video games compared to your peers?

(low skill) 1 2 3 4 5 6 7 8 9 10 (high skill)

7. To your knowledge, does anyone in your immediate or close family (parent, sibling, aunt, uncle,
cousin, grandparent) have any form of dementia? YES or NO

If YES,
a) What is their relationship to you (e.g., Maternal aunt, father, paternal uncle, cousin on mother's side, etc.)? Please list all if there is more than one relative.

____

____

____

This page is for the researchers to complete only.

BrDI

File Name(s): ____

Hand used: Right   or   Left

Order of conditions and comments:

____ Direct: ____

____ Direct Rotated: ____

____ Plane Change: ____

____ Plane Change Rotated: ____

Tester: ______________________________________

Modified Tinetti

File Name(s): ____

Comments:

____

____

____

____

Appendix C

SCAT3™

Sport Concussion Assessment Tool – 3rd Edition

For use by medical professionals only

Name

Date/Time of Injury:
Date of Assessment:

Examiner:

What is the SCAT3?[1]

The SCAT3 is a standardized tool for evaluating injured athletes for concussion and can be used in athletes aged from 13 years and older. It supersedes the original SCAT and the SCAT2 published in 2005 and 2009, respectively[2]. For younger persons, ages 12 and under, please use the Child SCAT3. The SCAT3 is designed for use by medical professionals. If you are not qualified, please use the Sport Concussion Recognition Tool[1]. Preseason baseline testing with the SCAT3 can be helpful for interpreting post-injury test scores.

Specific instructions for use of the SCAT3 are provided on page 3. If you are not familiar with the SCAT3, please read through these instructions carefully. This tool may be freely copied in its current form for distribution to individuals, teams, groups and organizations. Any revision or any reproduction in a digital form requires approval by the Concussion in Sport Group.

NOTE: The diagnosis of a concussion is a clinical judgment, ideally made by a medical professional. The SCAT3 should not be used solely to make, or exclude, the diagnosis of concussion in the absence of clinical judgement. An athlete may have a concussion even if their SCAT3 is "normal".

What is a concussion?

A concussion is a disturbance in brain function caused by a direct or indirect force to the head. It results in a variety of non-specific signs and/or symptoms (some examples listed below) and most often does not involve loss of consciousness. Concussion should be suspected in the presence of **any one or more** of the following:

- Symptoms (e.g., headache), or
- Physical signs (e.g., unsteadiness), or
- Impaired brain function (e.g. confusion) or
- Abnormal behaviour (e.g., change in personality).

SIDELINE ASSESSMENT

Indications for Emergency Management

NOTE: A hit to the head can sometimes be associated with a more serious brain injury. Any of the following warrants consideration of activating emergency procedures and urgent transportation to the nearest hospital:

- Glasgow Coma score less than 15
- Deteriorating mental status
- Potential spinal injury
- Progressive, worsening symptoms or new neurologic signs

Potential signs of concussion?

If any of the following signs are observed after a direct or indirect blow to the head, the athlete should stop participation, be evaluated by a medical professional and **should not be permitted to return to sport the same day** if a concussion is suspected.

Any loss of consciousness?	Y	N
"If so, how long?" ______		
Balance or motor incoordination (stumbles, slow/laboured movements, etc.)?	Y	N
Disorientation or confusion (inability to respond appropriately to questions)?	Y	N
Loss of memory:	Y	N
"If so, how long?" ______		
"Before or after the injury?" ______		
Blank or vacant look:	Y	N
Visible facial injury in combination with any of the above:	Y	N

1 Glasgow coma scale (GCS)

Best eye response (E)	
No eye opening	1
Eye opening in response to pain	2
Eye opening to speech	3
Eyes opening spontaneously	4
Best verbal response (V)	
No verbal response	1
Incomprehensible sounds	2
Inappropriate words	3
Confused	4
Oriented	5
Best motor response (M)	
No motor response	1
Extension to pain	2
Abnormal flexion to pain	3
Flexion/Withdrawal to pain	4
Localizes to pain	5
Obeys commands	6
Glasgow Coma score (E + V + M)	of 15

GCS should be recorded for all athletes in case of subsequent deterioration.

2 Maddocks Score[3]

"I am going to ask you a few questions, please listen carefully and give your best effort."

Modified Maddocks questions (1 point for each correct answer)

What venue are we at today?	0	1
Which half is it now?	0	1
Who scored last in this match?	0	1
What team did you play last week/game?	0	1
Did your team win the last game?	0	1
Maddocks score		of 5

Maddocks score is validated for sideline diagnosis of concussion only and is not used for serial testing.

Notes: Mechanism of Injury ("tell me what happened"?):

Any athlete with a suspected concussion should be REMOVED FROM PLAY, medically assessed, monitored for deterioration (i.e., should not be left alone) and should not drive a motor vehicle until cleared to do so by a medical professional. No athlete diagnosed with concussion should be returned to sports participation on the day of injury.

BACKGROUND

Name: ____________ Date: ____________

Examiner: ____________

Sport/team/school: ____________ Date/time of injury: ____________

Age: ____________ Gender: ☐ M ☐ F

Years of education completed: ____________

Dominant hand: ☐ right ☐ left ☐ neither

How many concussions do you think you have had in the past? ____________

When was the most recent concussion? ____________

How long was your recovery from the most recent concussion? ____________

Have you ever been hospitalized or had medical imaging done for a head injury? ☐ Y ☐ N

Have you ever been diagnosed with headaches or migraines? ☐ Y ☐ N

Do you have a learning disability, dyslexia, ADD/ADHD? ☐ Y ☐ N

Have you ever been diagnosed with depression, anxiety or other psychiatric disorder? ☐ Y ☐ N

Has anyone in your family ever been diagnosed with any of these problems? ☐ Y ☐ N

Are you on any medications? If yes, please list: ☐ Y ☐ N

SCAT3 to be done in resting state. Best done 10 or more minutes post excercise.

SYMPTOM EVALUATION

3 How do you feel?

"You should score yourself on the following symptoms, based on how you feel now".

	none	mild		moderate		severe	
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Trouble falling asleep	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6

Total number of symptoms (Maximum possible 22) ____

Symptom severity score (Maximum possible 132) ____

Do the symptoms get worse with physical activity? ☐ Y ☐ N

Do the symptoms get worse with mental activity? ☐ Y ☐ N

☐ self rated ☐ self rated and clinician monitored

☐ clinician interview ☐ self rated with parent input

Overall rating: If you know the athlete well prior to the injury, how different is the athlete acting compared to his/her usual self?

Please circle one response:

no different	very different	unsure	N/A

Scoring on the SCAT3 should not be used as a stand-alone method to diagnose concussion, measure recovery or make decisions about an athlete's readiness to return to competition after concussion. Since signs and symptoms may evolve over time, it is important to consider repeat evaluation in the acute assessment of concussion.

COGNITIVE & PHYSICAL EVALUATION

4 Cognitive assessment

Standardized Assessment of Concussion (SAC)[4]

Orientation (1 point for each correct answer)

What month is it?	0	1
What is the date today?	0	1
What is the day of the week?	0	1
What year is it?	0	1
What time is it right now? (within 1 hour)	0	1
Orientation score		of 5

Immediate memory

List	Trial 1		Trial 2		Trial 3		Alternative word list		
elbow	0	1	0	1	0	1	candle	baby	finger
apple	0	1	0	1	0	1	paper	monkey	penny
carpet	0	1	0	1	0	1	sugar	perfume	blanket
saddle	0	1	0	1	0	1	sandwich	sunset	lemon
bubble	0	1	0	1	0	1	wagon	iron	insect
Total									

Immediate memory score total ____ of 15

Concentration: Digits Backward

List	Trial 1		Alternative digit list		
4-9-3	0	1	6-2-9	5-2-6	4-1-5
3-8-1-4	0	1	3-2-7-9	1-7-9-5	4-9-6-8
6-2-9-7-1	0	1	1-5-2-8-6	3-8-5-2-7	6-1-8-4-3
7-1-8-4-6-2	0	1	5-3-9-1-4-8	8-3-1-9-6-4	7-2-4-8-5-6
Total of 4					

Concentration: Month in Reverse Order (1 pt. for entire sequence correct)

Dec-Nov-Oct-Sept-Aug-Jul-Jun-May-Apr-Mar-Feb-Jan	0	1
Concentration score		of 5

5 Neck Examination:

Range of motion Tenderness Upper and lower limb sensation & strength

Findings: ____________

6 Balance examination

Do one or both of the following tests.

Footwear (shoes, barefoot, braces, tape, etc.) ____________

Modified Balance Error Scoring System (BESS) testing[5]

Which foot was tested (i.e. which is the **non-dominant** foot) ☐ Left ☐ Right

Testing surface (hard floor, field, etc.) ____________

Condition

Double leg stance: ____ Errors

Single leg stance (non-dominant foot): ____ Errors

Tandem stance (non-dominant foot at back): ____ Errors

And/Or

Tandem gait[6,7]

Time (best of 4 trials): ______ seconds

7 Coordination examination

Upper limb coordination

Which arm was tested: ☐ Left ☐ Right

Coordination score ____ of 1

8 SAC Delayed Recall[4]

Delayed recall score ____ of 5

INSTRUCTIONS

Words in *italics* throughout the SCAT3 are the instructions given to the athlete by the tester.

Symptom Scale

"You should score yourself on the following symptoms, based on how you feel now".

To be completed by the athlete. In situations where the symptom scale is being completed after exercise, it should still be done in a resting state, at least 10 minutes post exercise.

For total number of symptoms, maximum possible is 22.

For Symptom severity score, add all scores in table, maximum possible is 22 x 6 = 132.

SAC[4]

Immediate Memory

"I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order."

Trials 2 & 3:

"I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before."

Complete all 3 trials regardless of score on trial 1 & 2. Read the words at a rate of one per second. **Score 1 pt. for each correct response.** Total score equals sum across all 3 trials. Do not inform the athlete that delayed recall will be tested.

Concentration

Digits backward

"I am going to read you a string of numbers and when I am done, you repeat them back to me backwards, in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7."

If correct, go to next string length. If incorrect, read trial 2. **One point possible for each string length.** Stop after incorrect on both trials. The digits should be read at the rate of one per second.

Months in reverse order

"Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November ... Go ahead"

1 pt. for entire sequence correct

Delayed Recall

The delayed recall should be performed after completion of the Balance and Coordination Examination.

"Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order."

Score 1 pt. for each correct response

Balance Examination

Modified Balance Error Scoring System (BESS) testing[5]

This balance testing is based on a modified version of the Balance Error Scoring System (BESS)[5]. A stopwatch or watch with a second hand is required for this testing.

"I am now going to test your balance. Please take your shoes off, roll up your pant legs above ankle (if applicable), and remove any ankle taping (if applicable). This test will consist of three twenty second tests with different stances."

(a) Double leg stance:

"The first stance is standing with your feet together with your hands on your hips and with your eyes closed. You should try to maintain stability in that position for 20 seconds. I will be counting the number of times you move out of this position. I will start timing when you are set and have closed your eyes."

(b) Single leg stance:

"If you were to kick a ball, which foot would you use? [This will be the dominant foot] Now stand on your non-dominant foot. The dominant leg should be held in approximately 30 degrees of hip flexion and 45 degrees of knee flexion. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."

(c) Tandem stance:

"Now stand heel-to-toe with your non-dominant foot in back. Your weight should be evenly distributed across both feet. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."

Balance testing – types of errors

1. Hands lifted off iliac crest
2. Opening eyes
3. Step, stumble, or fall
4. Moving hip into > 30 degrees abduction
5. Lifting forefoot or heel
6. Remaining out of test position > 5 sec

Each of the 20-second trials is scored by counting the errors, or deviations from the proper stance, accumulated by the athlete. The examiner will begin counting errors only after the individual has assumed the proper start position. **The modified BESS is calculated by adding one error point for each error during the three 20-second tests. The maximum total number of errors for any single condition is 10.** If a athlete commits multiple errors simultaneously, only one error is recorded but the athlete should quickly return to the testing position, and counting should resume once subject is set. Subjects that are unable to maintain the testing procedure for a minimum of **five seconds** at the start are assigned the highest possible score, ten, for that testing condition.

OPTION: For further assessment, the same 3 stances can be performed on a surface of medium density foam (e.g., approximately 50 cm x 40 cm x 6 cm).

Tandem Gait[6,7]

Participants are instructed to stand with their feet together behind a starting line (the test is best done with footwear removed). Then, they walk in a forward direction as quickly and as accurately as possible along a 38mm wide (sports tape), 3 meter line with an alternate foot heel-to-toe gait ensuring that they approximate their heel and toe on each step. Once they cross the end of the 3m line, they turn 180 degrees and return to the starting point using the same gait. A total of 4 trials are done and the best time is retained. Athletes should complete the test in 14 seconds. Athletes fail the test if they step off the line, have a separation between their heel and toe, or if they touch or grab the examiner or an object. In this case, the time is not recorded and the trial repeated, if appropriate.

Coordination Examination

Upper limb coordination

Finger-to-nose (FTN) task:

"I am going to test your coordination now. Please sit comfortably on the chair with your eyes open and your arm (either right or left) outstretched (shoulder flexed to 90 degrees and elbow and fingers extended), pointing in front of you. When I give a start signal, I would like you to perform five successive finger to nose repetitions using your index finger to touch the tip of the nose, and then return to the starting position, as quickly and as accurately as possible."

Scoring: 5 correct repetitions in < 4 seconds = 1

Note for testers: Athletes fail the test if they do not touch their nose, do not fully extend their elbow or do not perform five repetitions. **Failure should be scored as 0.**

References & Footnotes

1. This tool has been developed by a group of international experts at the 4th International Consensus meeting on Concussion in Sport held in Zurich, Switzerland in November 2012. The full details of the conference outcomes and the authors of the tool are published in The BJSM Injury Prevention and Health Protection, 2013, Volume 47, Issue 5. The outcome paper will also be simultaneously co-published in other leading biomedical journals with the copyright held by the Concussion in Sport Group, to allow unrestricted distribution, providing no alterations are made.

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ATHLETE INFORMATION

Any athlete suspected of having a concussion should be removed from play, and then seek medical evaluation.

Signs to watch for

Problems could arise over the first 24–48 hours. The athlete should not be left alone and must go to a hospital at once if they:

- Have a headache that gets worse
- Are very drowsy or can't be awakened
- Can't recognize people or places
- Have repeated vomiting
- Behave unusually or seem confused; are very irritable
- Have seizures (arms and legs jerk uncontrollably)
- Have weak or numb arms or legs
- Are unsteady on their feet; have slurred speech

Remember, it is better to be safe.
Consult your doctor after a suspected concussion.

Return to play

Athletes should not be returned to play the same day of injury.
When returning athletes to play, they should be **medically cleared and then follow a stepwise supervised program,** with stages of progression.

For example:

Rehabilitation stage	Functional exercise at each stage of rehabilitation	Objective of each stage
No activity	Physical and cognitive rest	Recovery
Light aerobic exercise	Walking, swimming or stationary cycling keeping intensity, 70 % maximum predicted heart rate. No resistance training	Increase heart rate
Sport-specific exercise	Skating drills in ice hockey, running drills in soccer. No head impact activities	Add movement
Non-contact training drills	Progression to more complex training drills, eg passing drills in football and ice hockey. May start progressive resistance training	Exercise, coordination, and cognitive load
Full contact practice	Following medical clearance participate in normal training activities	Restore confidence and assess functional skills by coaching staff
Return to play	Normal game play	

There should be at least 24 hours (or longer) for each stage and if symptoms recur the athlete should rest until they resolve once again and then resume the program at the previous asymptomatic stage. Resistance training should only be added in the later stages.

If the athlete is symptomatic for more than 10 days, then consultation by a medical practitioner who is expert in the management of concussion, is recommended.

Medical clearance should be given before return to play.

Scoring Summary:

Test Domain	Score		
	Date: ______	Date: ______	Date: ______
Number of Symptoms of 22			
Symptom Severity Score of 132			
Orientation of 5			
Immediate Memory of 15			
Concentration of 5			
Delayed Recall of 5			
SAC Total			
BESS (total errors)			
Tandem Gait (seconds)			
Coordination of 1			

Notes:

CONCUSSION INJURY ADVICE

(To be given to the **person monitoring** the concussed athlete)

This patient has received an injury to the head. A careful medical examination has been carried out and no sign of any serious complications has been found. Recovery time is variable across individuals and the patient will need monitoring for a further period by a responsible adult. Your treating physician will provide guidance as to this timeframe.

If you notice any change in behaviour, vomiting, dizziness, worsening headache, double vision or excessive drowsiness, please contact your doctor or the nearest hospital emergency department immediately.

Other important points:

- Rest (physically and mentally), including training or playing sports until symptoms resolve and you are medically cleared
- No alcohol
- No prescription or non-prescription drugs without medical supervision. Specifically:
  - No sleeping tablets
  - Do not use aspirin, anti-inflammatory medication or sedating pain killers
- Do not drive until medically cleared
- Do not train or play sport until medically cleared

Clinic phone number

Patient's name ____________________

Date/time of injury ____________________

Date/time of medical review ____________________

Treating physician ____________________

Contact details or stamp

BJSM Online First, published on April 26, 2017 as 10.1136/bjsports-2017-097506SCAT5
To download a clean version of the SCAT tools please visit the journal online (http://dx.doi.org/10.1136/bjsports-2017-097506SCAT5)

SCAT5©

SPORT CONCUSSION ASSESSMENT TOOL — 5TH EDITION

DEVELOPED BY THE CONCUSSION IN SPORT GROUP

FOR USE BY MEDICAL PROFESSIONALS ONLY

supported by

Patient details

Name: ______________________________

DOB: ______________________________

Address: ______________________________

ID number: ______________________________

Examiner: ______________________________

Date of Injury: ______________ Time: ______________

WHAT IS THE SCAT5?

The SCAT5 is a standardized tool for evaluating concussions designed for use by physicians and licensed healthcare professionals[1]. The SCAT5 cannot be performed correctly in less than 10 minutes.

If you are not a physician or licensed healthcare professional, please use the Concussion Recognition Tool 5 (CRT5). The SCAT5 is to be used for evaluating athletes aged 13 years and older. For children aged 12 years or younger, please use the Child SCAT5.

Preseason SCAT5 baseline testing can be useful for interpreting post-injury test scores, but is not required for that purpose.Detailed instructions for use of the SCAT5 are provided on page 7. Please read through these instructions carefully before testing the athlete. Brief verbal instructions for each test are given in italics. The only equipment required for the tester is a watch or timer.

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Recognise and Remove

A head impact by either a direct blow or indirect transmission of force can be associated with a serious and potentially fatal brain injury. If there are significant concerns, including any of the red flags listed in Box 1, then activation of emergency procedures and urgent transport to the nearest hospital should be arranged.

Key points

- Any athlete with suspected concussion should be REMOVED FROM PLAY, medically assessed and monitored for deterioration. No athlete diagnosed with concussion should be returned to play on the day of injury.
- If an athlete is suspected of having a concussion and medical personnel are not immediately available, the athlete should be referred to a medical facility for urgent assessment.
- Athletes with suspected concussion should not drink alcohol, use recreational drugs and should not drive a motor vehicle until cleared to do so by a medical professional.
- Concussion signs and symptoms evolve over time and it is important to consider repeat evaluation in the assessment of concussion.
- The diagnosis of a concussion is a clinical judgment, made by a medical professional. The SCAT5 should NOT be used by itself to make, or exclude, the diagnosis of concussion. An athlete may have a concussion even if their SCAT5 is "normal".

Remember:

- The basic principles of first aid (danger, response, airway, breathing, circulation) should be followed.
- Do not attempt to move the athlete (other than that required for airway management) unless trained to do so.
- Assessment for a spinal cord injury is a critical part of the initial on-field assessment.
- Do not remove a helmet or any other equipment unless trained to do so safely.

1

IMMEDIATE OR ON-FIELD ASSESSMENT

The following elements should be assessed for all athletes who are suspected of having a concussion prior to proceeding to the neurocognitive assessment and ideally should be done on-field after the first first aid / emergency care priorities are completed.

If any of the "Red Flags" or observable signs are noted after a direct or indirect blow to the head, the athlete should be immediately and safely removed from participation and evaluated by a physician or licensed healthcare professional.

Consideration of transportation to a medical facility should be at the discretion of the physician or licensed healthcare professional.

The GCS is important as a standard measure for all patients and can be done serially if necessary in the event of deterioration in conscious state. The Maddocks questions and cervical spine exam are critical steps of the immediate assessment; however, these do not need to be done serially.

STEP 1: RED FLAGS

RED FLAGS:

- **Neck pain or tenderness**
- **Double vision**
- **Weakness or tingling/ burning in arms or legs**
- **Severe or increasing headache**
- **Seizure or convulsion**
- **Loss of consciousness**
- **Deteriorating conscious state**
- **Vomiting**
- **Increasingly restless, agitated or combative**

STEP 2: OBSERVABLE SIGNS

Witnessed ☐ Observed on Video ☐

Lying motionless on the playing surface	Y	N
Balance / gait difficulties / motor incoordination: stumbling, slow / laboured movements	Y	N
Disorientation or confusion, or an inability to respond appropriately to questions	Y	N
Blank or vacant look	Y	N
Facial injury after head trauma	Y	N

STEP 3: MEMORY ASSESSMENT MADDOCKS QUESTIONS[2]

"I am going to ask you a few questions, please listen carefully and give your best effort. First, tell me what happened?"

Mark Y for correct answer / N for incorrect

What venue are we at today?	Y	N
Which half is it now?	Y	N
Who scored last in this match?	Y	N
What team did you play last week / game?	Y	N
Did your team win the last game?	Y	N

Note: Appropriate sport-specific questions may be substituted.

Name: __________

DOB: __________

Address: __________

ID number: __________

Examiner: __________

Date: __________

STEP 4: EXAMINATION GLASGOW COMA SCALE (GCS)[3]

Time of assessment			
Date of assessment			
Best eye response (E)			
No eye opening	1	1	1
Eye opening in response to pain	2	2	2
Eye opening to speech	3	3	3
Eyes opening spontaneously	4	4	4
Best verbal response (V)			
No verbal response	1	1	1
Incomprehensible sounds	2	2	2
Inappropriate words	3	3	3
Confused	4	4	4
Oriented	5	5	5
Best motor response (M)			
No motor response	1	1	1
Extension to pain	2	2	2
Abnormal flexion to pain	3	3	3
Flexion / Withdrawal to pain	4	4	4
Localizes to pain	5	5	5
Obeys commands	6	6	6
Glasgow Coma score (E + V + M)			

CERVICAL SPINE ASSESSMENT

Does the athlete report that their neck is pain free at rest?	Y	N
If there is NO neck pain at rest, does the athlete have a full range of ACTIVE pain free movement?	Y	N
Is the limb strength and sensation normal?	Y	N

In a patient who is not lucid or fully conscious, a cervical spine injury should be assumed until proven otherwise.

Davis GA, *et al. Br J Sports Med* 2017;**0**:1–8. doi:10.1136/bjsports-2017-097506SCAT5

OFFICE OR OFF-FIELD ASSESSMENT

Please note that the neurocognitive assessment should be done in a distraction-free environment with the athlete in a resting state.

STEP 1: ATHLETE BACKGROUND

Sport / team / school: ____________________

Date / time of injury: ____________________

Years of education completed: ____________________

Age: ____________________

Gender: M / F / Other

Dominant hand: left / neither / right

How many diagnosed concussions has the athlete had in the past?: ____________________

When was the most recent concussion?: ____________________

How long was the recovery (time to being cleared to play) from the most recent concussion?: ____________________ (days)

Has the athlete ever been:

Hospitalized for a head injury?	Yes	No
Diagnosed / treated for headache disorder or migraines?	Yes	No
Diagnosed with a learning disability / dyslexia?	Yes	No
Diagnosed with ADD / ADHD?	Yes	No
Diagnosed with depression, anxiety or other psychiatric disorder?	Yes	No

Current medications? If yes, please list:

____

____

____

____

____

____

Name: ____________________

DOB: ____________________

Address: ____________________

ID number: ____________________

Examiner: ____________________

Date: ____________________

2

STEP 2: SYMPTOM EVALUATION

The athlete should be given the symptom form and asked to read this instruction paragraph out loud then complete the symptom scale. For the baseline assessment, the athlete should rate his/her symptoms based on how he/she typically feels and for the post injury assessment the athlete should rate their symptoms at this point in time.

Please Check: ☐ **Baseline** ☐ **Post-Injury**

Please hand the form to the athlete

	none	mild		moderate		severe	
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6
Trouble falling asleep (if applicable)	0	1	2	3	4	5	6

Total number of symptoms:	of 22
Symptom severity score:	of 132
Do your symptoms get worse with physical activity?	Y N
Do your symptoms get worse with mental activity?	Y N
If 100% is feeling perfectly normal, what percent of normal do you feel?	

If not 100%, why?

____

____

____

Please hand form back to examiner

3

STEP 3: COGNITIVE SCREENING

Standardised Assessment of Concussion (SAC)[4]

ORIENTATION

What month is it?	0	1
What is the date today?	0	1
What is the day of the week?	0	1
What year is it?	0	1
What time is it right now? (within 1 hour)	0	1
Orientation score		of 5

IMMEDIATE MEMORY

The Immediate Memory component can be completed using the traditional 5-word per trial list or optionally using 10-words per trial to minimise any ceiling effect. All 3 trials must be administered irrespective of the number correct on the first trial. Administer at the rate of one word per second.

Please choose EITHER the 5 or 10 word list groups and circle the specific word list chosen for this test.

I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order. For Trials 2 & 3: I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before.

List	Alternate 5 word lists					Score (of 5) Trial 1	Trial 2	Trial 3
A	Finger	Penny	Blanket	Lemon	Insect			
B	Candle	Paper	Sugar	Sandwich	Wagon			
C	Baby	Monkey	Perfume	Sunset	Iron			
D	Elbow	Apple	Carpet	Saddle	Bubble			
E	Jacket	Arrow	Pepper	Cotton	Movie			
F	Dollar	Honey	Mirror	Saddle	Anchor			
					Immediate Memory Score			of 15
					Time that last trial was completed			

List	Alternate 10 word lists					Score (of 10) Trial 1	Trial 2	Trial 3
G	Finger	Penny	Blanket	Lemon	Insect			
	Candle	Paper	Sugar	Sandwich	Wagon			
H	Baby	Monkey	Perfume	Sunset	Iron			
	Elbow	Apple	Carpet	Saddle	Bubble			
I	Jacket	Arrow	Pepper	Cotton	Movie			
	Dollar	Honey	Mirror	Saddle	Anchor			
					Immediate Memory Score			of 30
					Time that last trial was completed			

Name: __________
DOB: __________
Address: __________
ID number: __________
Examiner: __________
Date: __________

CONCENTRATION

DIGITS BACKWARDS

Please circle the Digit list chosen (A, B, C, D, E, F). Administer at the rate of one digit per second reading DOWN the selected column.

I am going to read a string of numbers and when I am done, you repeat them back to me in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7.

Concentration Number Lists (circle one)					
List A	List B	List C			
4-9-3	5-2-6	1-4-2	Y	N	0
6-2-9	4-1-5	6-5-8	Y	N	1
3-8-1-4	1-7-9-5	6-8-3-1	Y	N	0
3-2-7-9	4-9-6-8	3-4-8-1	Y	N	1
6-2-9-7-1	4-8-5-2-7	4-9-1-5-3	Y	N	0
1-5-2-8-6	6-1-8-4-3	6-8-2-5-1	Y	N	1
7-1-8-4-6-2	8-3-1-9-6-4	3-7-6-5-1-9	Y	N	0
5-3-9-1-4-8	7-2-4-8-5-6	9-2-6-5-1-4	Y	N	1
List D	List E	List F			
7-8-2	3-8-2	2-7-1	Y	N	0
9-2-6	5-1-8	4-7-9	Y	N	1
4-1-8-3	2-7-9-3	1-6-8-3	Y	N	0
9-7-2-3	2-1-6-9	3-9-2-4	Y	N	1
1-7-9-2-6	4-1-8-6-9	2-4-7-5-8	Y	N	0
4-1-7-5-2	9-4-1-7-5	8-3-9-6-4	Y	N	1
2-6-4-8-1-7	6-9-7-3-8-2	5-8-6-2-4-9	Y	N	0
8-4-1-9-3-5	4-2-7-9-3-8	3-1-7-8-2-6	Y	N	1
		Digits Score:			of 4

MONTHS IN REVERSE ORDER

Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November. Go ahead.

Dec - Nov - Oct - Sept - Aug - Jul - Jun - May - Apr - Mar - Feb - Jan	0 1
Months Score	of 1
Concentration Total Score (Digits + Months)	of 5

Davis GA, *et al. Br J Sports Med* 2017;**0**:1–8. doi:10.1136/bjsports-2017-097506SCAT5

Name:
DOB:
Address:
ID number:
Examiner:
Date:

4

STEP 4: NEUROLOGICAL SCREEN

See the instruction sheet (page 7) for details of test administration and scoring of the tests.

Can the patient read aloud (e.g. symptom check-list) and follow instructions without difficulty?	Y	N
Does the patient have a full range of pain-free PASSIVE cervical spine movement?	Y	N
Without moving their head or neck, can the patient look side-to-side and up-and-down without double vision?	Y	N
Can the patient perform the finger nose coordination test normally?	Y	N
Can the patient perform tandem gait normally?	Y	N

BALANCE EXAMINATION

Modified Balance Error Scoring System (mBESS) testing[5]

Which foot was tested (i.e. which is the non-dominant foot) ☐ Left ☐ Right

Testing surface (hard floor, field, etc.) __________

Footwear (shoes, barefoot, braces, tape, etc.) __________

Condition	Errors
Double leg stance	of 10
Single leg stance (non-dominant foot)	of 10
Tandem stance (non-dominant foot at the back)	of 10
Total Errors	of 30

5

STEP 5: DELAYED RECALL:

The delayed recall should be performed after 5 minutes have elapsed since the end of the Immediate Recall section. Score 1 pt. for each correct response.

Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order.

Time Started

Please record each word correctly recalled. Total score equals number of words recalled.

____

____

____

Total number of words recalled accurately: of 5 or of 10

6

STEP 6: DECISION

Domain	Date & time of assessment:		
Symptom number (of 22)			
Symptom severity score (of 132)			
Orientation (of 5)			
Immediate memory	of 15 of 30	of 15 of 30	of 15 of 30
Concentration (of 5)			
Neuro exam	Normal Abnormal	Normal Abnormal	Normal Abnormal
Balance errors (of 30)			
Delayed Recall	of 5 of 10	of 5 of 10	of 5 of 10

Date and time of injury: __________

If the athlete is known to you prior to their injury, are they different from their usual self?
☐ **Yes** ☐ **No** ☐ **Unsure** ☐ **Not Applicable**
(If different, describe why in the clinical notes section)

Concussion Diagnosed?
☐ **Yes** ☐ **No** ☐ **Unsure** ☐ **Not Applicable**

If re-testing, has the athlete improved?
☐ **Yes** ☐ **No** ☐ **Unsure** ☐ **Not Applicable**

I am a physician or licensed healthcare professional and I have personally administered or supervised the administration of this SCAT5.

Signature: __________

Name: __________

Title: __________

Registration number (if applicable): __________

Date: __________

SCORING ON THE SCAT5 SHOULD NOT BE USED AS A STAND-ALONE METHOD TO DIAGNOSE CONCUSSION, MEASURE RECOVERY OR MAKE DECISIONS ABOUT AN ATHLETE'S READINESS TO RETURN TO COMPETITION AFTER CONCUSSION.

CLINICAL NOTES:

Name:
DOB:
Address:
ID number:
Examiner:
Date:

CONCUSSION INJURY ADVICE

(To be given to the person monitoring the concussed athlete)

This patient has received an injury to the head. A careful medical examination has been carried out and no sign of any serious complications has been found. Recovery time is variable across individuals and the patient will need monitoring for a further period by a responsible adult. Your treating physician will provide guidance as to this timeframe.

If you notice any change in behaviour, vomiting, worsening headache, double vision or excessive drowsiness, please telephone your doctor or the nearest hospital emergency department immediately.

Other important points:

Initial rest: Limit physical activity to routine daily activities (avoid exercise, training, sports) and limit activities such as school, work, and screen time to a level that does not worsen symptoms.

1) Avoid alcohol

2) Avoid prescription or non-prescription drugs without medical supervision. Specifically:

   a) Avoid sleeping tablets

   b) Do not use aspirin, anti-inflammatory medication or stronger pain medications such as narcotics

3) Do not drive until cleared by a healthcare professional.

4) Return to play/sport requires clearance by a healthcare professional.

Clinic phone number:

Patient's name:

Date / time of injury:

Date / time of medical review:

Healthcare Provider:

Contact details or stamp

INSTRUCTIONS

Words in *Italics* throughout the SCAT5 are the instructions given to the athlete by the clinician

Symptom Scale

The time frame for symptoms should be based on the type of test being administered. At baseline it is advantageous to assess how an athlete "typically" feels whereas during the acute/post-acute stage it is best to ask how the athlete feels at the time of testing.

The symptom scale should be completed by the athlete, not by the examiner. In situations where the symptom scale is being completed after exercise, it should be done in a resting state, generally by approximating his/her resting heart rate.

For total number of symptoms, maximum possible is 22 except immediately post injury, if sleep item is omitted, which then creates a maximum of 21.

For Symptom severity score, add all scores in table, maximum possible is 22 x 6 = 132, except immediately post injury if sleep item is omitted, which then creates a maximum of 21x6=126.

Immediate Memory

The Immediate Memory component can be completed using the traditional 5-word per trial list or, optionally, using 10-words per trial. The literature suggests that the Immediate Memory has a notable ceiling effect when a 5-word list is used. In settings where this ceiling is prominent, the examiner may wish to make the task more difficult by incorporating two 5–word groups for a total of 10 words per trial. In this case, the maximum score per trial is 10 with a total trial maximum of 30.

Choose one of the word lists (either 5 or 10). Then perform 3 trials of immediate memory using this list.

Complete all 3 trials regardless of score on previous trials.

"I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order." The words must be read at a rate of one word per second.

Trials 2 & 3 MUST be completed regardless of score on trial 1 & 2.

Trials 2 & 3:

"I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before."

Score 1 pt. for each correct response. Total score equals sum across all 3 trials. Do NOT inform the athlete that delayed recall will be tested.

Concentration

Digits backward

Choose one column of digits from lists A, B, C, D, E or F and administer those digits as follows:

Say: *"I am going to read a string of numbers and when I am done, you repeat them back to me in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7."*

Begin with first 3 digit string.

If correct, circle "Y" for correct and go to next string length. If incorrect, circle "N" for the first string length and read trial 2 in the same string length. One point possible for each string length. Stop after incorrect on both trials (2 N's) in a string length. The digits should be read at the rate of one per second.

Months in reverse order

"Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November ... Go ahead"

1 pt. for entire sequence correct

Delayed Recall

The delayed recall should be performed after 5 minutes have elapsed since the end of the Immediate Recall section.

"Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order."

Score 1 pt. for each correct response

Modified Balance Error Scoring System (mBESS)[5] testing

This balance testing is based on a modified version of the Balance Error Scoring System (BESS)[5]. A timing device is required for this testing.

Each of 20-second trial/stance is scored by counting the number of errors. The examiner will begin counting errors only after the athlete has assumed the proper start position. The modified BESS is calculated by adding one error point for each error during the three 20-second tests. The maximum number of errors for any single condition is 10. If the athlete commits multiple errors simultaneously, only one error is recorded but the athlete should quickly return to the testing position, and counting should resume once the athlete is set. Athletes that are unable to maintain the testing procedure for a minimum of five seconds at the start are assigned the highest possible score, ten, for that testing condition.

OPTION: For further assessment, the same 3 stances can be performed on a surface of medium density foam (e.g., approximately 50cm x 40cm x 6cm).

Balance testing – types of errors

1. Hands lifted off iliac crest
2. Opening eyes
3. Step, stumble, or fall
4. Moving hip into > 30 degrees abduction
5. Lifting forefoot or heel
6. Remaining out of test position > 5 sec

"I am now going to test your balance. Please take your shoes off (if applicable), roll up your pant legs above ankle (if applicable), and remove any ankle taping (if applicable). This test will consist of three twenty second tests with different stances."

(a) Double leg stance:

"The first stance is standing with your feet together with your hands on your hips and with your eyes closed. You should try to maintain stability in that position for 20 seconds. I will be counting the number of times you move out of this position. I will start timing when you are set and have closed your eyes."

(b) Single leg stance:

"If you were to kick a ball, which foot would you use? [This will be the dominant foot] *Now stand on your non-dominant foot. The dominant leg should be held in approximately 30 degrees of hip flexion and 45 degrees of knee flexion. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."*

(c) Tandem stance:

"Now stand heel-to-toe with your non-dominant foot in back. Your weight should be evenly distributed across both feet. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."

Tandem Gait

Participants are instructed to stand with their feet together behind a starting line (the test is best done with footwear removed). Then, they walk in a forward direction as quickly and as accurately as possible along a 38mm wide (sports tape), 3 metre line with an alternate foot heel-to-toe gait ensuring that they approximate their heel and toe on each step. Once they cross the end of the 3m line, they turn 180 degrees and return to the starting point using the same gait. Athletes fail the test if they step off the line, have a separation between their heel and toe, or if they touch or grab the examiner or an object.

Finger to Nose

"I am going to test your coordination now. Please sit comfortably on the chair with your eyes open and your arm (either right or left) outstretched (shoulder flexed to 90 degrees and elbow and fingers extended), pointing in front of you. When I give a start signal, I would like you to perform five successive finger to nose repetitions using your index finger to touch the tip of the nose, and then return to the starting position, as quickly and as accurately as possible."

References

1. McCrory et al. Consensus Statement On Concussion In Sport – The 5th International Conference On Concussion In Sport Held In Berlin, October 2016. British Journal of Sports Medicine 2017 (available at www.bjsm.bmj.com)
2. Maddocks, DL; Dicker, GD; Saling, MM. The assessment of orientation following concussion in athletes. Clinical Journal of Sport Medicine 1995; 5: 32-33
3. Jennett, B., Bond, M. Assessment of outcome after severe brain damage: a practical scale. Lancet 1975; i: 480-484
4. McCrea M. Standardized mental status testing of acute concussion. Clinical Journal of Sport Medicine. 2001; 11: 176-181
5. Guskiewicz KM. Assessment of postural stability following sport-related concussion. Current Sports Medicine Reports. 2003; 2: 24-30

CONCUSSION INFORMATION

Any athlete suspected of having a concussion should be removed from play and seek medical evaluation.

Signs to watch for

Problems could arise over the first 24-48 hours. The athlete should not be left alone and must go to a hospital at once if they experience:

- Worsening headache
- Drowsiness or inability to be awakened
- Inability to recognize people or places
- Repeated vomiting
- Unusual behaviour or confusion or irritable
- Seizures (arms and legs jerk uncontrollably)
- Weakness or numbness in arms or legs
- Unsteadiness on their feet.
- Slurred speech

Consult your physician or licensed healthcare professional after a suspected concussion. Remember, it is better to be safe.

Rest & Rehabilitation

After a concussion, the athlete should have physical rest and relative cognitive rest for a few days to allow their symptoms to improve. In most cases, after no more than a few days of rest, the athlete should gradually increase their daily activity level as long as their symptoms do not worsen. Once the athlete is able to complete their usual daily activities without concussion-related symptoms, the second step of the return to play/sport progression can be started. The athlete should not return to play/sport until their concussion-related symptoms have resolved and the athlete has successfully returned to full school/learning activities.

When returning to play/sport, the athlete should follow a stepwise, **medically managed exercise progression, with increasing amounts of exercise.** For example:

Graduated Return to Sport Strategy

Exercise step	Functional exercise at each step	Goal of each step
1. Symptom-limited activity	Daily activities that do not provoke symptoms.	Gradual reintroduction of work/school activities.
2. Light aerobic exercise	Walking or stationary cycling at slow to medium pace. No resistance training.	Increase heart rate.
3. Sport-specific exercise	Running or skating drills. No head impact activities.	Add movement.
4. Non-contact training drills	Harder training drills, e.g., passing drills. May start progressive resistance training.	Exercise, coordination, and increased thinking.
5. Full contact practice	Following medical clearance, participate in normal training activities.	Restore confidence and assess functional skills by coaching staff.
6. Return to play/sport	Normal game play.	

In this example, it would be typical to have 24 hours (or longer) for each step of the progression. If any symptoms worsen while exercising, the athlete should go back to the previous step. Resistance training should be added only in the later stages (Stage 3 or 4 at the earliest).

Written clearance should be provided by a healthcare professional before return to play/sport as directed by local laws and regulations.

Graduated Return to School Strategy

Concussion may affect the ability to learn at school. The athlete may need to miss a few days of school after a concussion. When going back to school, some athletes may need to go back gradually and may need to have some changes made to their schedule so that concussion symptoms do not get worse. If a particular activity makes symptoms worse, then the athlete should stop that activity and rest until symptoms get better. To make sure that the athlete can get back to school without problems, it is important that the healthcare provider, parents, caregivers and teachers talk to each other so that everyone knows what the plan is for the athlete to go back to school.

Note: If mental activity does not cause any symptoms, the athlete may be able to skip step 2 and return to school part-time before doing school activities at home first.

Mental Activity	Activity at each step	Goal of each step
1. Daily activities that do not give the athlete symptoms	Typical activities that the athlete does during the day as long as they do not increase symptoms (e.g. reading, texting, screen time). Start with 5-15 minutes at a time and gradually build up.	Gradual return to typical activities.
2. School activities	Homework, reading or other cognitive activities outside of the classroom.	Increase tolerance to cognitive work.
3. Return to school part-time	Gradual introduction of school-work. May need to start with a partial school day or with increased breaks during the day.	Increase academic activities.
4. Return to school full-time	Gradually progress school activities until a full day can be tolerated.	Return to full academic activities and catch up on missed work.

If the athlete continues to have symptoms with mental activity, some other accomodations that can help with return to school may include:

- Starting school later, only going for half days, or going only to certain classes
- More time to finish assignments/tests
- Quiet room to finish assignments/tests
- Not going to noisy areas like the cafeteria, assembly halls, sporting events, music class, shop class, etc.
- Taking lots of breaks during class, homework, tests
- No more than one exam/day
- Shorter assignments
- Repetition/memory cues
- Use of a student helper/tutor
- Reassurance from teachers that the child will be supported while getting better

The athlete should not go back to sports until they are back to school/learning, without symptoms getting significantly worse and no longer needing any changes to their schedule.

Davis GA, *et al. Br J Sports Med* 2017;**0**:1–8. doi:10.1136/bjsports-2017-097506SCAT5