EFFECTS OF A DUAL-TASK PARADIGM ON TANDEM GAIT PERFORMANCE

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ABSTRACT

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In concussion management, a variety of cognitive and motor control tests, like the tandem gait, have been used for assessing the presence of a concussion injury at the sideline and through recovery. More recently, research suggests that introducing a secondary cognitive retention task during tandem gait (i.e., dual task) may provide a better assessment of concussion. The purpose of this study was to determine if a tandem gait test paired with a 6-digit retention is a valid and reliable tool. Participants completed three trials of both the single-task (ST) and dual-task (DT) tandem gait tests, and their average (MEAN) and fastest (BEST) completion times of both conditions were recorded. Seventy-five healthy collegiate athletes (age: 20.1 ± 1.8 years) performed the DT slower than the ST for both MEAN and BEST times ($p < .001$). Trial 3 was significantly faster than Trial 1 for both ST and DT ($p < .001$), but still showed high reliability across the three trials. Concussion history did not have a significant effect on DT MEAN or BEST times, but gender had a moderate effect on DT BEST times. The DT was found to have low correlations to SWAY's balance and reaction time tests, and the Immediate Post-Concussion Assessment and Cognitive Testing visual motor composite. Preliminary data has shown that the DT may be a reliable and valid tool for assessing the interaction

between balance and cognition in uninjured athletes, however application for concussed individuals needs to be explored before full implementation into concussion management protocols.

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LITERATURE REVIEW

Prevalence of Concussion in Sport

Approximately 3.8 million cases of sports-related concussions (SRC) are reported each year (Langlois et al., 2006), with up to 1.9 million of those cases occurring in youth sports (Bryan et al., 2016). The incidence of SRC may be even higher because of underreporting from athletes, with reasons involving lack of knowledge and pressure to continue playing (Kerr et al., 2016; Kroshus et al., 2015). Sports, such as football, soccer, ice hockey, basketball, and lacrosse have the greatest risk of athletes sustaining a concussion (Kerr et al., 2017; Marshall et al., 2015), with almost 62% of cases occurring during competition play (Covassin et al., 2016). When compared to male athletes, female athletes have a greater incidence rate of a concussion and can experience longer recoveries, especially in basketball and soccer (Covassin et al., 2016). These differences have been previously attributed to biomechanical differences (Tierney et al., 2005), neuroanatomical differences (Cheng et al., 2009), and honesty during reporting (Dick, 2009).

Definition of Concussion

An SRC is defined as the somatic, cognitive, and emotional instabilities resulting from the direct, biomechanical forces that collide with an individual’s head or body (McCroy et al., 2017). It is considered a functional disturbance, rather than the structural injury of a traumatic brain injury (McCrory et al., 2017), because the disturbance refers to an imbalance of the energy supply-and-demand system which creates interruptions in the ionic, metabolic, and pathophysiological events in the brain, also known as the neurometabolic cascade (Giza & Hovda, 2014). After an impact, several processes occur; ionic fluxes in and out of the neuron cells cause an enhanced need for energy usage, and the structural integrity of the axons decrease, leading to altered neurotransmission ability (Giza & Hovda, 2014). This leads to some of the common signs and symptoms of a concussion, such as headaches, light sensitivity, and altered cognition (Giza & Hovda, 2014). Other known signs that occur include loss of consciousness, behavioral changes (e.g., increases in sadness and irritability), and balance instabilities (McCrory et al., 2017). Because of the subjective nature of SRCs, many tests have been developed to assess the injured individuals.

Diagnosis and Post-Injury Assessments

Healthcare professionals, e.g., certified athletic trainers, utilize a series of tests to help diagnose and assess recovery after an athlete receives a concussive blow. Many of these tests are outlined in the Sport Concussion Assessment Tool 5th Edition (SCAT5) evaluation tool: symptom checklists, neurocognitive tests (e.g., memory recall), and physiological examinations (e.g., gait assessment; Echemendia et al., 2017). It has become common practice in collegiate sports to administer the tests before an athlete begins competition (i.e., baseline), immediately after the athlete is injured (i.e., sideline), through recovery, and when they are cleared to return to play (National Collegiate Athletic Association, 2017).

Typically, during a baseline test, the athlete receives education of how to recognize, report, and recover from concussions and performs symptom checklists, cognitive evaluations, and balance assessments. The data collected is then used as a comparison in the event they sustain a concussion, either at the time of injury (sideline) or within 48 hours, and continually during recovery until they reach their baseline values and become asymptomatic, or symptom free. Once baseline values are reached, healthcare professionals can then decide their return-to-play protocol, which usually takes 1-week if symptoms do not return (Harmon et al., 2019). Because athletes are more at risk for a secondary injury during the first 10 days following the initial injury (Giza & Hovda, 2014), these steps are utilized to protect the athlete from further injury and prolonged functional deficits (McCrory et al., 2017).

Symptom Assessment

Symptoms are considered the subjective signs of a concussion, and fall into three categories (McCrory et al., 2017); somatic (e.g., headaches, nausea, and sensitivity to light and noise); cognitive (e.g., difficulty concentrating, feeling slowed down, and confusion); emotional (e.g., irritability, sadness, and anxiousness; Eckner & Kutcher, 2010). The most common evaluation tool is the Post-Concussion Symptom Scale (PCSS), a 22-item Likert scale (0–6), as applied in the SCAT5. Symptoms can occur immediately, within hours, or even days after an impact, and the intensity and number of symptoms differ between individuals and the mechanism of impacts. One individual can receive a small hit, but experience intense symptoms immediately, while another individual receives a forceful hit and loses consciousness but does not develop symptoms until 2 days later. Despite differing experiences, expected recovery for symptoms is 10-14 days; however, symptoms can persist depending on the individual's amount of rest and abstinence of physical activity and other negative stimuli (McCrory et al., 2017). An athlete is usually prevented from beginning any strenuous physical activity until they become asymptomatic or return to their baseline scores (McCrory et al., 2017). Symptom evaluations are subjective and require the athlete to be truthful about their state-of-being. However, athletes have been found to under-report or be dishonest about their symptoms because they are prevented from playing until their symptoms are gone or return to baseline (Kerr et al., 2016). Because of the inconsistent symptom self-reporting by the athlete, healthcare professionals also depend on other objective diagnostic tools to manage an athlete's recovery.

Neurocognitive Assessment

Neurocognitive processes like attention, memory, and reaction time become impaired after a concussive injury, and can take up to 21 days to return to normal cognitive functioning (Covassin et al., 2010; Harmon et al., 2019). The Standardized Assessment of Concussion (SAC) tests the athlete's immediate cognitive status in five areas: orientation, immediate memory, neurological screening, concentration, and delayed recall. When administered at sideline, this brief (5 minute) and easily accessible test can demonstrate an athlete's acute mental status and aid in the decision of whether they should be removed from competition (McCrea, 2001). While the SAC is an objective test, it does not account for an athlete's symptomatic state or prior history of concussion and medical disorders.

The Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) is a computerized neuropsychological test that combines relevant demographic data (e.g., history of learning/attention disorders and concussion history), symptoms, and neuropsychological tests (e.g., attention, memory, processing speed, and reaction time) to generate scores in four areas: verbal memory, visual memory, visual motor speed, and reaction time. The ImPACT generally takes 25-30 minutes, and is typically administered at baseline, within 48 hours after injury, and throughout recovery to monitor changes in cognitive functioning (Elbin et al., 2019). There are limitations to the ImPACT that include high cost, low accessibility, sensitivity to learning and attention disorders, and an increased risk of participant cheating during post-injury testing or purposeful poor performance during baseline testing (Erdal, 2012). as it cannot be administered for initial diagnostic purpose immediately following a suspected injury (i.e., sideline),

<u>Motor Control Assessment</u>

A third key component of most concussion assessment batteries is the motor control test, typically in the form of a balance test. Most motor control tests used in concussion assessment are balance tests that require the integration of visual, vestibular, and proprioceptive information to maintain postural equilibrium (Guskiewicz, 2011). After an impact, one or more of these systems can be disturbed, resulting in difficulty in maintaining the appropriate center of mass and base of support relationship (Murray et al., 2015). Traditionally, balance after a concussion was assessed through static balance tests, where the athlete tries to maintain an upright posture with minimal movement. However, researchers have demonstrated that the dynamic balance tests where the patient walks in a straight line may provide greater sensitivity to concussion injury and reveal prolonged motor control deficits following a concussion injury not observed in static balance tests (Murray et al., 2015).

Static Balance. To measure motor control deficiencies, various balance assessments have been developed that range from simple sideline tests to more advanced laboratory tests. The current standard in clinical testing is the Balance Error Scoring System (BESS; Bell et al., 2011). It requires the athlete to remain in a quiet, standing posture during three stances on two different surfaces. The stances include standing with both feet, single leg on their non-dominant foot, and in a tandem stance where their non-dominant foot is placed behind their other foot while balancing on a firm and foam surface. Trials last for 20 seconds and are assessed by observations of deviations from the starting position (e.g., hands on iliac crest, opening eyes, etc.). It is a cost-effective, non-laboratory assessment tool that can be administered in a clinical setting or on the sideline during a game (Guskiewicz, 2011). However, the BESS is subjectively scored, has low interrater reliability, and only detects large changes in balance (Bell et al., 2011). The Sensory Organization Test (SOT) provides a more challenging static balance assessment because it utilizes a moving force-sensing platform and harness cage to measure an individual’s postural sway (Guskiewicz et al., 2001). The SOT has three conditions (i.e., eyes open, eyes closed, and sway-reference) and two surfaces (i.e., firm and sway-referenced). The scores from the SOT are more objective than the BESS, and they both show improvement and return to baseline scores 3 to 5 days post-injury (Guskiewicz et al., 2001).

However, there are still limitations to both tests. The SOT is less accessible as it is limited to clinical laboratory settings and has low sensitivity; the ability of a test to correctly identify those with a concussion (Broglio et al., 2008). Both tests require the individual to maintain a quiet standing posture that does not emulate game-like behavior and only identify large changes in postural control (Murray et al., 2015). Due to these limitations, recent studies have developed more appropriate tests that measure the dynamic movements required in sports games.

Dynamic Balance. The energetic demands of gameplay are more prevalent during dynamic tests, like gait assessments. Traditionally, assessing gait involves having a participant walk with their normal speed and using digital motion capture to measure gait speed, center of mass (COM) displacement, and COM velocity. However, this method is time-consuming, costly, and requires extensive knowledge of equipment, despite the notion that measuring COM motion is a sensitive marker for measuring concussions (Parker et al., 2006). The tandem gait test (TG) is a neurophysiological test utilized in SCAT5 and is a feasible clinical test that requires more coordinated movement than static balance or normal gait assessments (Oldham et al., 2018), and can be administered outside of a laboratory. The TG requires the participant to walk heel-to-toe down a 3m long, 38mm wide line as quickly and as accurately as possible without stepping off the line, having large space between the feet, or grabbing an object or examiner.

The SCAT3 previously set the passing time for the TG as 14s and based on the best time over 4 trials, but the SCAT5 features the TG as a simple pass/fail option. (Echemendia et al., 2017). Current research that has been looking at efficacy levels (Oldham et al., 2018), normative data sets (Oldham et al., 2017), and reliability (Howell et al., 2019), have found that the TG is a reliable measure for concussion testing. However, subacute deficits may not be detected by the TG as a single-task (Oldham et al., 2018), but by increasing the attentional demand during the task, creating a dual-task paradigm, subtle impairments may be better detected when tested through recovery.

Dual-Task Paradigms

Dual-task paradigms involve combining two separate tasks to divide attentional demands and increase impaired performance (McDowell et al., 1997 & Yogev-Seligmann et al., 2008). Those attentional demands are regulated by the central executive function, which involves both cognitive and behavioral mechanisms assisting in controlling the purposeful, goal-directed behaviors (McDowell et al., 1997; Yogev-Seligmann et al., 2008). Those processes become disturbed after a concussive impact, and there have been several theories developed to explain how it affects attentional demand during dual-task assessments, such as the capacity-sharing theory and the bottleneck theory (Yogev-Seligmann et al., 2008). The capacity-sharing theory states that there is a limited amount of attentional capacity, increasing the time it takes to process the stimuli being presented. The bottleneck theory explains that if two tasks are managed by the same neural processor, then the first task presented must be processed before the second task can be processed. For example, when an individual is asked to complete a secondary cognitive task while performing a motor control test, it can be expected that the competition for attention can lead to impaired gait stability and decreases in performance.

Dual-Task and Gait Stability

The ability to maintain gait control is disrupted by concussion, and those changes in postural control, such as gait velocity and COM displacement, have been documented during dual-task gait tests. Concussed participants have been found to walk significantly slower during dual-task tests when compared to both control participants and when performing single-task tests (Berkner et al., 2017; Catena et al., 2007; Howell et al., 2013, 2014, 2018; Parker et al., 2008). Results for stride lengths and cadences are mixed; some studies found that there were significant decreases in stride length for concussed participants (Berkner et al., 2017; Catena et al., 2007; Parker et al., 2006) while others did not find differences (Howell et al., 2013).

Few studies looked at changes in dual-task gait performance over time. Berkner et al (2017) tested participants within 21 days of injury and at symptom resolution and found that the dual-task test showed gait impairments continued after symptom recovery, while Parker et al (2006) also found impairments up to 4 weeks. Similarly, Howell et al (2013) found that there were still similar gait deficits that lasted up to 2 months after the initial injury point. In another study, researchers examined the association between the DT and a neurocognitive assessment during the acute (within 72 hours) and long-term (2 months) time points after a concussion (Howell et al., 2018). They found that there was no relationship between the neurocognitive test and the dual-task gait.

Together, these studies demonstrate that under normal gait conditions, dual-task assessments reveal a decrease in performance after a concussion. However, these previous dual-task gait tests required expensive technology and the participants to walked at a self-selected speed with normal step width. It does not present as a great motor control challenge compared to the tandem gait.

Dual-Task and Tandem Gait

As discussed, the TG challenges the postural system more than a static standing test or normal gait test and can improve the sensitivity of balance testing. When it comes to the addition of a cognitive task, research is still limited. There has been one study that has explored normative data for the DT in healthy adults. Howell et al. (2019b) found that collegiate athletes averaged the ST in 10.5 (SD = 1.87) seconds and the DT in 12.9 (SD = 3.40) seconds. They also found that men completed both the ST and DT faster than women. In other studies, concussed participants took longer to complete the DT than both the ST and control participants (Howell et al., 2017, 2019a, 2019c; Oldham et al., 2020; Van Deventer et al., 2020). Howell et al. (2017) also looked at how the DT changed over a 2-month period, where they tested participants within 72 hours, at 1 week, 2 weeks, 1 month, and 2 months post-injury. They found significant differences between concussed and control subjects up to two weeks post-injury. After finding significant correlation in the COM medial-lateral displacement compared to the TG completion time, they concluded participants who had longer TG times had greater instability (Howell, et al., 2017). Oldham et al. (2020) tested participants at baseline and through their recovery, and found that when concussed participants no longer reported symptoms, they were still significantly slower than controls, but when they returned to play, there were no significant differences. Van Deventer et al. (2020) also found that cognitive accuracy was significantly decreased in concussed participants. However, these studies did not look at the association between the DT and other validated measures, such as ImPACT, nor did they look at the differences between the secondary cognitive tests.

There has been little research on what type of secondary cognitive task is best. In a study by Lomeli (2019), they compared different cognitive tasks to see if one had a greater effect on dual-task times. Those tasks included an Auditory Stroop, 5-digit retention, 6-digit retention (6D), months in reverse order (MO), and counting backwards by 3 (B3). These tasks have been used in studies prior due to their validity and reliability, as forms of them are used in the SCAT5. Concussed participants completed both conditions of the TG slower than healthy participants. Among these DT tasks, differences in completion time and cognitive errors between concussed and control subject was greatest during the six-digit retention protocol. While the DT with a secondary cognitive task such as 6-digit retention may very well prove to be a useful post-injury assessment tool, little is known about its reliability and validity.

Purpose

While the ST is currently used in the SCAT5 battery of test, recent evidence suggests that DT may be more sensitive to detecting concussion injury. However, there is no normative data for collegiate athlete population and the reliability/validity of this test has not been fully established. Before integration of the 6-digit DT into concussion management practices, it is critical to establish normative values and test the reliability and validly of this new dynamic motor control test. The purpose of this study was to examine the reliability and validity of the 6-digit DT in healthy collegiate athletes by providing a normative data set and exploring the relationship of the DT to ST and other valid and reliable concussion assessments. The researcher believes the following outcomes will occur: (a) three outcomes will t athletes will complete the 6-digit DT slower than the ST. (b) the 6-digit DT will have high reliability across the three trials that is similar to the ST. Additionally, we will explore the effect of concussion history and gender on DT performance as well as the relations between DT performance and the composite scores for Sway™ and ImPACT™.

METHODS

Participant Characteristics

Healthy adult participants between the ages of 18-35 years old were recruited from the National Collegiate Athletic Association Division II sports at Humboldt State University. Exclusion criteria for all participants included: (a) neuromuscular or musculoskeletal disorders which may affect the individual's ability to balance and walk, (b) current medications that may affect the individual's ability to balance and walk, (c) history of cognitive deficiencies (e.g., attention deficit disorders or learning disabilities), (d) head injury in the 6 months prior to data collection. Each subject's medical history and demographics were recorded to ensure inclusion and exclusion criteria are met. All participants will provide written informed consent prior to beginning of data collection (Appendix A).

Procedure

Approval was obtained through Humboldt State University's institutional review board (IRB#: 19-129). Informed consent, medical history, and demographic information were gathered before data collection (Appendix A & Appendix B). Participants completed six tandem gait trials: three trials as ST (i.e., TG by itself) and three trials as DT (TG with a secondary 6-digit retention cognitive task). A trained testing administrator provided verbal instruction and recorded the completion times for both conditions via a stopwatch and the responses to the cognitive task for the DT (Appendix C). The six trials were in randomized order for each testing session to reduce the risk of a practice effect. Participants also completed a self-reported symptom evaluation (PCSS) at the beginning of the session. In addition, we collected participant's data from the ImPACT and Sway tests through the North Coast Concussion Program.

Before the trial began, the participants stood with their feet together at the start of the line. Following detailed instruction and demonstration, the participants walked heel-to-toe along a 38-mm wide, 3-m long taped line as fast and as accurately as possible to the end of the line, turned 180 degrees and walked back to the start. Errors such as stepping off the line, separation between feet, and grabbing an examiner or object were recorded without the participant reattempting the trial. The completion times of all three trials, without reattempts, were recorded and used for statistical analysis.

The secondary cognitive task consisted of a six-digit retention (6D). The 6D is used as a component to the SAC and has been established as valid and reliable tool for concussion identification. A testing administrator read a string of six numbers as the participant stood at the start line and instructed them to repeat the six numbers in reverse order when they completed the TG. No two similar numbers were used in each sequence and no sequence repeated for a single participant. Responses were recorded, and the average percent correct was calculated.

The symptom evaluation sheet consisted of a Likert scale 22-symptom evaluation sheet that measured physical, cognitive, and emotional symptoms (e.g., headache, dizziness, sleep quality, and fatigue) on a scale from 0 to 6 (Appendix D). We collected the ImPACT composite scores for visual memory, verbal memory, visual motor speed, and reaction time, and Sway composite scores for the mBESS, memory, reaction time, and impulse control (Lovell, et al., 2005 & VanRavenhorst-Bell et al., 2021).

Assumptions & Delimitations

We assume that participants will 1) meet inclusion criteria, 2) be truthful on their medical history and symptom reporting, and 3) adhere to all instructions and give their best effort on each test during data collection. We have delimited our population to healthy college athletes between the ages of 18 and 35 years with no history of neurological, cardiovascular, and orthopedic disorders in the 6-months prior to testing. The purpose of these delimitations was to help the research in their effort to assess performance in healthy, athletic individuals. Nonetheless, the author acknowledges that these delimitations will likely reduce the external validity of the results.

Statistical Analysis

Average (MEAN) and fastest (BEST) time (seconds) of the 3 trials for both the ST and DT were calculated. For the DT trials, cognitive accuracy (CA) was recorded as percent correct, and a total symptom severity score was calculated by summing the score of all symptoms self-reported. The composite scores for Sway and ImPACT were used for correlations to MEAN and BEST DT performance times. Data normality was checked using the Shapiro-Wilk test; the assumption of normality was not met for all the variables, so appropriate correlations were ran for individual comparisons.

A paired samples t-test was performed to compare the MEAN trial times of the ST and DT conditions and the BEST trial times of both conditions. Cohen's d effect sizes were calculated for all significant post hoc tests, where 0.2 corresponds to a small effect size, 0.5 a medium effect size, and 0.8 a large effect size. To examine the effect of Trial (1-3) on performance of the ST, DT, and CA respectively, we used a one-way repeated-measures analyses of variance with simple contrast, treating trial 3 as the reference trial. Greenhouse-Geisser corrections were used in the case that sphericity was violated as assessed through Mauchly's test, and follow-up pairwise comparisons were adjusted with the Bonferroni correction.

To determine reliability across the three trials of the ST and DT, we first calculated the intraclass correlation coefficient (ICC). The ICC was calculated using a 2-way mixed effects model with consistency type of single-rater per measurement (ICC 3,1). To estimate SEM, the pooled standard deviation for all three trials and the test–retest reliability index was used. For ICC values, we used the following ranges to interpret the clinical value of our results: >0.9 as very high, 0.80 to 0.89 as high, 0.70 to 0.79 as adequate, 0.60 to 0.69 as marginal, and ≤0.59 as low. Standard error of the measurement (SEM) was calculated as (SD x $\sqrt{[1 - \text{ICC}]}$). The SEM value might be considered an estimation of the expected random variation in scores when no real change has taken place. The Minimum Detectable Change (MDC) of each tandem gait measure (ST time and DT time) were estimated to represent potential practice effects across the trials. The MDC value might be regarded as the minimum amount of change that needs to be observed, at either the group or individual level, for it to be considered a real change.

MDC was calculated for both ST and DT trials (MDC= SEM x 1.96 x $\sqrt{2}$). Test-retest reliability was operationally defined by the number of participants within the range for minimum detectable change over each of the three trials of the ST and DT tests.

Separate independent-samples t-tests were used to compare effects of gender (male/female) and concussion history (yes/no) on DT MEAN and BEST trial times. To evaluate the relationship between DT performances and the other variables, we used the bivariate Pearson Product (normally distributed) or Spearman's rho (non-normally distributed) correlation for each outcome measure as appropriate. The following values were used to interpret the correlations: <.39 as low, .40 to .59 as moderate, .60 to .79 as moderately high, and ≥.80 as high. Statistical significance was set at α <.05 for all analyses and the data was handled with SPSS (version 28.0; IBM Corp, Armonk, NY).

RESULTS

A total of 75 collegiate athletes between the ages of 18 and 26 years participated in the study. Fifty-two percent were female, and the sports included in this study were soccer, basketball, and volleyball (Table 1). Participants completed the DT significantly slower than the ST for both their MEAN and BEST trial times (Table 2). On average, participants completed the DT 6% slower than the ST for their MEAN trial times ($t[74] = 5.51$, $p < .001$), and 5% slower than the ST for their BEST trial times ($t[74] = 5.39$, $p < .001$).

Table 1

Participant Characteristics

Variable	Mean ± SD or n (%)	Range
Age (y)	20.1 ± 1.8	18–26
Female sex	39 (52%)	
Height (cm)	178.0 ± 10.5	160.0–210.8
Mass (kg)	73.6 ± 12.6	54.3–133.8
Prior history of concussion	20 (26.7%)	
No. of concussions	.48 ± .89	0-3
Sport type		
Men’s Basketball	14 (18.7%)	
Women’s Basketball	7 (9.3%)	
Men’s Soccer	22 (29.3%)	
Women’s Soccer	16 (21.3%)	
Women’s Volleyball	16 (21.3%)	

Table 2

Evaluation of Relationship between Single-Task and Dual-Task Tandem Gait MEAN and BEST Time (s) with Pearson's Correlation and Effect Size.

Variable	MEAN Completion Time (Mean ± SD)	BEST Completion Time (Mean ± SD)
Single-task tandem gait (s)	18.89 ± 5.07	17.66 ± 4.85
Dual-task tandem gait (s)	20.02 ± 5.19	18.50 ± 4.93
Pearson Correlation (*r*)	.94*	.96*
Cohen's *d*	.64*	.63*
95% Confidence interval	.72 – 1.54	.52 – 1.14

Note. Pearson's correlations and paired-sample t-tests were run for MEAN and BEST completion times both conditions.
**p* <.001(2-tailed).

There was a significant improvement effect for both average ST times ($F[1.43, 105.98] = 30.19$, $p < .001$, $\eta2 = .29$) and DT times ($F[1.73, 128.35] = 26.00$, $p < .001$, $\eta2 = .26$) across the 3 trials (Table 3). Pairwise-comparisons showed participants walked significantly faster in trial 3 as compared to trial 1 for both the ST and DT conditions (Table 3). Trial 3 was ~10% faster than trial 1 for both the ST ($p < .001$) and DT ($p < .001$). There was no significant change for cognitive accuracy percent across the three DT trials (Table 3).

Table 3

Individual Trial Time (s) for Single-Task and Dual-Task Tandem Gait Performance.

Variable	Trial 1 (Mean ± SD)	Trial 2 (Mean ± SD)	Trial 3 (Mean ± SD)	*P*-Value
Single-task tandem gait time (s)	20.0 ± 5.6	18.6 ± 5.2	18.1 ± 4.8	<.001[a]
Dual-task tandem gait time (s)	21.2 ± 5.8	19.8 ± 5.3	19.1 ± 5.2	<.001[a]
DT Cognitive accuracy (%)	65.3 ± 33.9	73.4 ± 29.3	71.2 ± 31.0	.098

[a] pairwise follow-up testing indicated a slower time for trial 1 compared with trial 3 (*P* <.001).

Estimated ICCs for the ST conditions, DT conditions, and cognitive accuracy are summarized in Table 4. Both ST and DT trial times had very high intra-rater reliability (p < .001), while cognitive accuracy had an adequate intra-rater reliability (p < .001). The MDC for ST was 2.60 seconds and the MDC for DT was 3.58 seconds. Both ST and DT tandem gait tests demonstrated good test-retest reliability with 72.0-77.3% of scores falling within MDC range (Table 4). The ST had the lowest rate of reliability between testing sessions (72.0%) whereas DT demonstrated the highest rate of reliability (77.3%).

Table 4

Absolute and Relative Intra-Rater Reliability Estimates for Outcome Measures Across Three Trials

Variable	Intraclass Correlation Coefficient (3,1)	95% Confidence Interval	SEM	MDC_{95}	Within MDC (n within MDC/total n)
Single-task tandem gait	.97*	.95, .98	.94	2.60	72.0% (54/75)
Dual-task tandem gait	.96*	.94, .97	1.29	3.58	77.3% (58/75)
Cognitive accuracy	.72*	.59, .81	16.70	46.28	73.3% (55/75)

Note. Single- and dual-task tandem gait and cognitive accuracy values were based on average of three trials. SEM = Standard error of the mean. MDC = Minimal Detectable Change.
**p* <.001

Previous history of concussion had no significant effect on either DT MEAN (p = .13) or BEST (p = .16) trial times (Table 5). However, male participants walked 12% faster than female participants (p = .04) during the DT BEST trial time, but there was no significant difference between genders for DT MEAN times (p = .11). There was a significantly high positive correlation between DT MEAN and ST MEAN times (p < .001), as well as DT BEST and ST BEST times (p < .001) (Table 6). Both DT BEST and DT MEAN had low negative correlations with the SWAY simple reaction time, but were still found to be significant (p = .02 and p = .04, respectively). Only DT BEST had a low negative correlation with SWAY mBESS (p = .03) and only DT MEAN had a low negative correlation with the ImPACT Visual Motor composite (p = .05). There was no correlation between DT MEAN or BEST for Sway impulse and inspection, nor ImPACT composites score for verbal memory, visual memory, or reaction time (Table 6).

Table 5

Effect sizes for Concussion History and Gender on Dual-Task Tandem Gait (DT) MEAN and BEST time.

Variable	DT MEAN (s)	DT BEST (s)
Concussion History		
Yes (n = 20)	18.52 ± 4.03	17.15 ± 3.84
No (n = 55)	20.57 ± 5.49	18.99 ± 5.21
Cohen's *d*	.38	.38
Gender		
Male (n = 36)	19.02 ± 4.88	17.26 ± 4.23
Female (n = 39)	20.95 ± 5.37	19.64 ± 5.30
Cohen's *d*	.38	.49*

Note. MEAN refers to participants overall average time, and BEST refers to participant's average fastest time.
**p* <.001 (2-tailed)

Table 6

Bivariate Correlations Between Dual-Task Tandem Gait (DT) Outcomes and Computerized Neurocognitive and Motor Control Measures (ImPACT and Sway).

Variable	DT MEAN	DT BEST
Single-task tandem gait MEAN[a]	.94**	-
Single-task tandem gait BEST[a]	-	.96**
DT Cognitive accuracy	-.18	-.18
Symptom Severity	-.01	-.04
Concussion History (# of concussions)	-.16	-.15
Sway mBESS	-.22	-.25*
Sway Simple Reaction Motion	-.28*	-.24*
Sway Impulse	.13	.16
Sway Inspection	.17	.18
Sway Memory	-.22	-.18
ImPACT Verbal Memory	-.03	.00
ImPACT Visual Memory[a]	-.08	-.04
ImPACT Visual Motor Speed[a]	-.23*	-.18
ImPACT Reaction Time	.08	.06

Note. MEAN refers to participants overall average time, and BEST refers to participant's average fastest time. ImPACT = Immediate Post-Concussion Assessment and Testing. mBESS = modified Balance Error Scoring System.
[a] Pearson's Product Correlations were ran for these tests
*$p < .05$ level (2-tailed)
**$p < .001$ level (2-tailed)

DISCUSSION

The purpose of this study was to examine the reliability and validity of the DT by providing a normative data set and exploring the relationship to ST and other reliable concussion assessments. In support of our first two hypotheses, this study demonstrated that healthy participants performed the DT slower than the ST, and intra-rater reliability was very high (>.90) for both conditions. Our results also indicated a learning effect, as participants walked about 2 seconds faster from trial 1 to trial 3 for both ST and DT conditions. Cognitive accuracy did not show improvements across the three DT trials ($p = .098$) but showed an adequate reliability score ($ICC = .79$, $p < .001$). Additionally, the relationship between DT performances to concussion history and gender and found that a previous history of concussion did not have an effect ($d = .38$, $p > .05$) on DT MEAN or BEST times, but gender had a moderate effect ($d = .49$, $p < .001$) on DT BEST times. There were no significant correlations between DT performance times and SWAY scores for impulse, inspection, and memory, but there was a weak but significant negative correlation of both DT MEAN and BEST times to simple reaction motion and only DT BEST to mBESS. When compared to ImPACT composite scores, DT MEAN performance had a negative correlation to visual motor speed, but no significant correlations to verbal memory, visual memory, reaction time, or impulse control.

Results from this study are consistent with other studies where researchers reported that participants completed the DT slower than the ST in control and concussed participants (Howell et al. 2017a; Howell et al. 2019a, 2019b, 2019c; & Van Deventer et al. 2021). The SCAT3 recommended a pass/fail time of 14 seconds or less for the ST, using the best time of four trials (McCroy et al., 2012). When using that criteria for our ST, only 19% of our participants had a "pass" time less than 14 seconds for their BEST time and 16% for their MEAN time. This significantly contrasts from other studies, where Hänninen et al. (2016) reported that 90% of their participants completed the ST in less than 12.8 seconds, and Oldahm et al. (2017) reported that the 75% completed the test in less than 12.65 seconds. Additionally, our averaged ST times (18.89 to 17.66 seconds) were slower than other studies that reported normative values between 10.3 seconds to 11.5 seconds (Schneiders et al., 2010; Hänninen et al. 2016; & Oldham et al., 2017). Moreover, when comparing the DT performances to the SCAT3 pass/fail time mentioned above, a lower percentage of participants passing the cutoff was observed. For example, 17% of our participants had times lower than 14 seconds for their BEST time and 7.5% passed with their MEAN scores. This trend of lower DT passing rates was also reported by Howell et al. (2019b) who reported 98% of participants had less than 14 seconds for their best ST trial, but only 71% had a passing time for their best DT trial. These lower percentages compared to the ST suggests that a new "pass" time may be needed for the DT. Furthermore, as there has been only one study examining normative data for the DT to compare performances of healthy subjects, generalizability of our results should be cautioned.

Despite these results, it is unknown why participants' completion times overall were slower than previously reported data, as both studies implemented similar instruction for completing the tandem gait, as well as similar populations. One potential difference may have been due to a presence of fatigue. It was noted during our data collection that many participants came either right after or during their sport practice, as scheduling conflicts was a major issue during data collection. Fatigue has been shown to influence postural control, where researchers reported increases in errors and sway for the BESS (Erkmen et al., 2009; Fox et al., 2008; Susco et al., 2004; & Wilkins et al., 2004;) and Schneiders et al. (2012) reported high-intensity exercise decreased ST times by 5.8%. However, the studies also reported that scores returned to normal up to 20 minutes after cessation of exercise (Fox et al., 2008 & Schneiders et al., 2012).

Similar to the results of several past studies there appears to be a learning effect across the three trials of each tandem gait test. Learning effects have been observed for other concussion assessments for healthy individuals. Valovich McLeod et al. (2004) tested participants five times over a 60-day period and reported total BESS error scores decreased and BESS tandem stance scores improved. Manaseer (2020) also reported participants had less errors on the BESS and reacted faster in the Clinical Reaction Time assessments from trial one to trial three and between the two testing days for both ST and DT conditions. By averaging all trials, it can produce a higher score compared to the individual's final trial due to the learning effect; however, by using the fastest time (i.e., BEST) for comparisons, it reduces that effect and allows for more appropriate measurement of the test (Oldham et al., 2016). Based on these results, the SCAT3 recommendation that the fastest time be used is representative of the results shown in our study and other literature (Hänninen et al. 2016; Howell et al., 2019b; Oldham et al. 2016; & Schneiders et al., 2010).

While the reliability of the ST has been previously reported for within-day trials (ICC > .90), very few studies have explored reliability scores of DT and none have looked at this for 6D DT (Schneiders et al. 2010 & Koyama et al., 2018). Our study's intra-rater reliability scores for both ST and DT (Table 4) were slightly higher compared to other studies where Manaseer et al. (2020) reported a low reliability score for ST tandem gait (ICC = 0.54) but found a high reliability for the DT (ICC = 0.94) in individuals between the ages of 13 to 24 years. In adolescent populations, Howell et al. (2019b) reported high intra-rater reliability estimates for ST (ICC = 0.86) and DT (ICC = 0.84) and Wingerson et al. (2020) reported ICC estimates for controls (ST ICC = 0.93, DT ICC = 0.92) and concussed individuals (ST ICC = 0.96, DT ICC = 0.94). In comparison, reliability scores for neurocognitive tests like ImPACT's composite scores range from 0.26 to 0.88 and other postural control assessments (i.e., BESS) had range of 0.50 to 0.88 (Resch et al. 2016; Finnoff et al., 2009). Nevertheless, our reliability scores are within the acceptable range for clinical practice (> 0.75; Koo & Li, 2016). Based on these findings, the DT may be considered a dependable measure of dynamic balance in healthy individuals, but further reliability of this test among concussed athletes needs to be explored, especially in broader adult athletic populations representing different sports.

Ages, different sample sizes, and the type of secondary cognitive task used may have attributed to the differences found between our study and others. Manaseer et al. (2020) had 24 participants spell a five-letter word backwards in adolescent and adult populations. Wingerson et al. (2020) had 117 participants and Howell et al. (2019c) had 32 participants, but both studies used one of three different cognitive tasks chosen randomly (i.e., spell 5 letter word backwards, serially subtract by 6 or 7, or recite months in backwards order) and tested adolescent populations. The studies discussed above had their participants complete the cognitive tasks simultaneously with the DT, but our study utilized a cognitive retention task where the participants had to remember a string of six numbers and recall them in a backwards order after they performed the TG. We found a moderate effect size for our cognitive accuracy, but it did not have a correlation to the DT times. Moreover, the studies that utilized more than one cognitive task did not compare the results of the individual tasks together, unlike Lomeli (2019). Lomeli compared performance of five different cognitive tasks: 1) 5-digit retention, 2) 6-digit retention, 3) months in reverse order, 4) counting backwards by 3, and 5) an auditory Stroop test (2019). They found that the 6-digit retention, months in reverse order, and counting backwards tasks caused concussed participants to walk slower than controls, and the 6-digit retention showed the greatest difference between both the control and concussed groups. While these individual tasks are consistent across research, future studies should more thoroughly investigate if there are differences between the cognitive tasks and whether performing the cognitive tasks during the tandem gait influences performance differently than a retention type task.

A history of concussion has been found to show inconsistent effects on cognitive and postural control deficits. Similar to our study, Oldham et al. (2017) and Hänninen et al., (2016) did not find effects of concussion history for the ST performance. However, conservative gait strategies (i.e., reduced step length and step velocity, and increased step width) and increased postural sway have been found in other balance and gait tests among individuals that experienced a concussion injury 6 months to 12 years prior to the study (Buckley et al., 2016; Martini et al., 2011; Sosnoff et al. 2011). In our study, the majority (96%) of those that self-reported a history of prior concussions experienced that concussion injury over a year prior to the study and 40% reported having only one prior concussion. Our study did not look at the effect of the number of concussions reported and DT performance, however Buckley et al. (2016) found that having one or more concussions resulted in conservative gait strategies. For other concussion assessments, Zimmer et al. (2015) did not find effects of concussion history on the SAC or BESS, and many studies found that previous history of concussion did not influence performance of ImPACT (Broglio et al., 2006; Brooks et al., 2013.; Iverson et. al, 2006; Solomon, Haase, & Kuhn, 2013).

There has been conflicting evidence of gender effects on the tandem gait and other concussion assessment outcomes. In this study, we found women to perform the DT significantly slower than men. In comparison, some studies had reported no associated effect of gender in adults (Schnieders et al. 2010, & Oldham et al., 2017) while one study showed adolescent girls to be slower than adolescent boys (Santo et al., 2017). In a dual-task gait study, researchers found no gender effects in healthy controls for gait speed but found concussed females significantly lower step frequency (# of steps per second) than males (Howell et al., 2017b). For other assessments, one study found that females showed greater severity and number of symptoms, but that there was no difference between genders for the King-Devick reading test, SAC cognitive test, or mBESS balance test (Benedict et al., 2015). Foot size has been considered a possible co-variate due to the nature of the tandem gait. Galea et al. (2019) found non-athletic individuals with foot size larger than 27 centimeters completed the ST and DT around 3 seconds faster, and Santo et al. (2017) found that taller individuals completed the ST faster. Foot size and body height have been found to be associated with men typically having larger sizes then women (Pawar & Pawar, 2012). Our study did not look at foot size nor did we factor body height into our analysis.

Correlating our results to other validated concussion assessments, such as SWAY and ImPACT, will assist in determining the validity of the DT. Reliability of the SWAY application (ICC > 0.70) and ImPACT (ICC < .90) have been reported, and SWAY Cognitive Assessments were found to have a positive correlation to the ImPACT visual motor speed ($r = 0.22$; Amick et al., 2015; Resch et al., 2013; & VanRavenhorst-Bell et al., 2021). In terms of cognitive aspects, our study found negative correlations between the DT performance, the SWAY simple reaction motion, and ImPACT visual motor speed composite scores. For postural control specifically, we found that the DT time also had a negative correlation to the SWAY mBESS balance score (Table 6). Reaction time refers to an individual's response rate to an observed stimulus (Woods et al., 2016), and SWAY measures reaction time as a combination of visual processing and neuromotor function by measuring how fast an individual can move the phone in response to the correct visual cue (VanRavenhorst-Bell et al., 2021). ImPACT visual motor speed composite is similar to SWAY's reaction time, where it measures the time elapsed between the stimulus being presented to their action and the rate of correct responses (Lovell, et al., 2005). Both tests demonstrate dual-task paradigms because they test the interaction between the cognitive and motor pathways in much the same way as the DT. For SWAY's mBESS measurement, it utilizes the mobile device's built-in tri-axial accelerometer to create an objective, unit-less score from 0-100, with 100 being best (Amick et al., 2015). While the correlation between the ST and BESS in general has not been well explored, Hänninen et al. (2016) had found no significant correlation between the ST and subjectively scored mBESS, but the BESS has been shown to have a strong negative correlation to SWAY's mBESS ($r = -0.54$; Hatoum et al., 2017).

Our study may have found significance due to the objectivity of SWAY's electronic mBESS as there would have been less rater error for scoring. Additionally, since the above computerized measurements use a scale where a lower score is associated with lower cognitive or motor control function, it is reasonable that the correlations between DT time and SWAY mBESS were negative because the lower the DT time, the faster (i.e., better) the individual performs. However, non-significant correlations to the other composite scores for SWAY and ImPACT may be due to the tasks only testing cognitive function and not interaction effects with other motor control processes. Additionally, the scores we used for statistical analysis for both SWAY and ImPACT were collected by other individuals and done remotely, thus introducing potential error to the validity of the scores.

Limitations and Future Directions

Despite the significance of this study, there were some limitations, and for the DT protocol to be considered for widespread use, future research will need to further explore the effects of key demographic variables including such factors as gender, age, concussion history, and sport participation on both baseline and post-injury six-digit DT tandem gait performance. This study had a moderate sample size; however, it may not have been representative enough of the athletic population, since athletes from only two contact sports and one non-contact sport were sampled. Furthermore, a comparison between sports is missing. Outliers were present in statistical analysis due to no attributable reason to exclude them, introducing variability to the dataset. Concussion history was self-reported, we did not compare effects of number of concussions individually, and we did not test for the acute effects of concussion on DT performance. While repeat administration of the test showed a learning effect through trials, this study did not test participants over time (e.g., days or months). Test-retest reliability needs to be established for the DT tandem gait so that post-injury testing can be validated. Due to fatigue having a potential effect on performance for our study, future research should also investigate fatigue as a co-variate, especially for sideline tests right after injury because the potential effect of playing in competition or practice can affect performance.

CONCLUSIONS

Motor control and balance testing is an important aspect of concussion management, and by adding a secondary cognitive task to postural control assessments, it can increase difficulty. Dual-task tests challenge more than one processing system and may provide practitioners with more insight about impairments after a concussion because it may show greater deficits in performance. The tandem gait test is a valid and reliable tool by itself, but in our study, participants completed the DT slower than the ST. This preliminary data has shown that the six-digit retention DT can be a reliable test for assessing the interaction effect of balance and cognition in uninjured athletes. However, the relationship to other confounding variables (i.e., age, gender, and fatigue) and the effects of concussion on performance need to be further explored before being fully implemented into concussion management protocols.

OPERATIONAL DEFINITIONS

1. **Baseline:** an initial assessment typically performed prior to the start of the athletic season that is used to compare scores to after a concussion injury.
2. **Cognitive accuracy**: the percentage of correct responses during the cognitive task.
3. **Concussion**: A clinically diagnosed injury that is a result of the direct, biomechanical forces that collide with an individual's head or body causing somatic, cognitive, and emotional instabilities.
4. **Dual-Task**: a participant performs two tests simultaneously, i.e., Tandem Gait and secondary cognitive task.
5. **ImPACT Test:** The Immediate Post-Concussion Assessment and Cognitive Test is a computerized neurocognitive test that examines an individual's attention, speed of processing information, verbal memory, visual memory, visual motor speed, and multi-tasking ability. It contains six individual tests where the scores are the generated into composite scores used for measuring an individual's mental status.
6. **Neurocognitive test:** a noninvasive assessment of an individual's cognitive abilities (e.g., reaction time, memory, processing speed, and attention). They can be pen-and-paper or computerized, and administered by themselves or within a dual-task procedure.

7. **Secondary Cognitive Task**: a task that assess a participant's cognitive function in conjunction with a primary task.
8. **Single-Task**: a participant only performs one test, i.e. Tandem Gait test.
9. **SWAY test:** a computerized test that can be completed on a mobile device. It consists of a balance test, cognitive tests, and symptom tracking. The balance test uses the motion sensors within the individual's phone to track their movements. The cognitive tests are similar to the ImPACT where thy assess the individual's reaction time, memory, and visual processing.
10. **Tandem Gait Test**: a dynamic stability test that measures a participant's balance during a heel-to-toe gait.
11. **6-digit retention test:** a cognitive test that requires the participant to remember a string of numbers and repeat the string in the reverse order.

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APPENDICES

Appendix A

Effects of a Dual-Task Paradigm on Tandem Gait Performance After Concussion

Principal Investigator: Courtney Perry, B.S.

(IRB Approval #19-129)

PARTICIPANT INFORMED CONSENT FORM

Please read the following material that explains this research study. Signing this form will indicate that you have been informed about the study and that you want to participate. We want you to understand what you are being asked to do and what risks and benefits are associated with the study. This should help you decide whether or not you want to participate in this study.

You are being asked to participate in a research project conducted by Courtney Perry under the supervision of Justus Ortega, Ph.D., Department of Kinesiology and Recreation Administration, 1 Harpst St., Arcata, CA, 95521. **Dr. Justus Ortega, may be reached at (707) 826-4274 or jdo1@humboldt.edu to answer any questions or concerns.**

Project Description:

The aims of this study are 1) to determine the effect of a secondary cognitive task on performance of the Tandem Gait in concussed and non-concussed individuals during a recovery period and 2) to determine the relation between Tandem Gait performance and performance on other concussion related assessments throughout recovery. You will be asked to complete a series of tests: 1) Tandem Gait 2) Tandem Gait with a secondary cognitive task 3) symptom assessment 4) neurocognitive assessment (ImPACT), 5) King-Devick reading test assessment, and 6) Visual-Ocular Motor Screening (VOMS). Potential findings from this study could be directly utilized to implement a dual-task protocol for more sensitive sideline assessments of concussion and allow for better return-to-play decisions.

Procedure:

If you agree to take part in this study, you will be asked to come to the laboratory for up to eight experimental sessions ranging from 10 minutes to 1-hour each, except for the consenting session which is an additional 15 minutes. You will be asked to come in for two baseline testing sessions. If injured with a concussion you will be asked to come in for 1-6 additional testing sessions. For each testing sessions, we will have you perform a variety of concussion assessments that may include a balance test (tandem gait), symptom evaluation, brain function test (SAC, ImPACT), reading test (King-Devick) and vision test (VOMS). *Concussed participants*: You will be asked to provide consent for all past and future concussion assessment data gathered from standard care procedures completed by the North Coast Concussion Program. There is no monetary compensation for participation in this study. The experimental sessions will take place in the Humboldt State University Biomechanics Lab.

Session 1 (Baseline #1): up to *45 minutes* (healthy)

- Consent, symptom evaluation, SAC, King-Devick, Tandem Gait tests

Session 2 (Baseline #1): up to *30 minutes* (healthy)

- Symptom evaluation, SAC, King-Devick, Tandem Gait tests

Session 3 (within 48 hours post injury): up to *1 hour (concussed)*

- Symptom evaluation, SAC, King-Devick, VOMS, ImPACT, and Tandem-Gait tests.

Session 4 (1 week post injury): up to *10 minutes (concussed)*

- Symptom evaluation, Tandem Gait tests

Session 5 (2 weeks post injury): up to *10 minutes (concussed)*

- Symptom evaluation, Tandem Gait tests

Session 6 (3 weeks post injury): up to *10 minutes (concussed)*

- Symptom evaluation, Tandem Gait tests

Session 7 (Asymptomatic post injury): up to *1 hour (concussed)*

- Symptom evaluation, SAC, King-Devick, VOMS, ImPACT, and Tandem-Gait tests

Session 8 (Return-to-play): up to *1 hour (concussed)*

- Symptom evaluation, SAC, King-Devick, VOMS, ImPACT, and Tandem-Gait tests

Informed Consent (*15 minutes*):

- We will explain the study and what we will ask you to do.
- You will read the informed consent.
- We will answer any questions you may have.
- You will sign the informed consent form, if you agree to participate in the study.
- You will complete a medical history/demographics questionnaire.

Procedure (Up to *1-hour*):

Primary Tests

- You will complete a symptom evaluation form that will measure symptoms on a scale from 0-6, including headache, dizziness, sleep quality, and concentration (*1-2 minutes*).
- You will complete the three trials each of the Tandem Gait and Tandem Gait with a secondary cognitive task (*5-10 minutes*)
    - Tandem Gait: You will walk heel-to-toe, down and back along a 3-m line while maintaining an up-right posture.
    - Secondary Cognitive Task: You will be asked to remember six digits, which then you will repeat in reverse order after completing the Tandem Gait.

Additional tests (if needed):

- You will complete the Standardized Assessment of Concussion (SAC) that will measure mental status, such as immediate memory, orientation, and concentration. *(5 minutes*)
- You will complete an online neurocognitive assessment (ImPACT) that will measure your memory, processing speed, and reaction time (*20-30 minutes*) through verbal/visual memory, symbol matching, color matching, and speed tasks.

- You will perform a rapid reading assessment (King-Devick) that will evaluate your eye movements, attention, and language function by reading aloud single-digit numbers with progressively difficult cards (*2-3 minutes*).
- You will perform a vision and ocular movement test (VOMS) where you will be asked to rate four symptoms (headache, dizziness, nausea, & fogginess; on a scale from 0-10) before and after performing 7 different conditions of eye and head movement (*3-5 minutes*).

A maximum of 200 participants will be invited to participate in this research study.

Risks and Discomforts:

There are minimal physical risks associated with participation in this study. All assessments used in the study are part of the normal battery of clinical tests used in the assessment of concussion injury. A risk associated with all these tests is an increase in symptoms. There is also a small risk of falling during the Tandem Gait trials; however, our exclusion criteria will help to ensure that participants are able to perform the Tandem Gait without falling. If at any point you feel too symptomatic, fatigued, or uncomfortable to continue with the protocol, you are allowed to discontinue trials/participation.

Benefits:

The investigators cannot promise any benefits to the participant for taking place in the research. However, for concussed participants, the assessment results may be used by participant and their health care provider to guide treatment and recovery.

Subject Payment:

You will not be paid for participation in this research study.

Injury and Compensation:

If you feel that you have been harmed while participating in this study, you should inform the faculty supervisor, Dr. Justus Ortega, (707) 826-4274 immediately. If you are injured, Humboldt State University will not be able to pay for your medical care. State law may limit Humboldt State University's legal responsibility if an injury happens because of this study.

Study Withdrawal:

You have the right to withdraw your consent or stop participating at any time. You have the right to refuse to answer any question(s) or participate in any procedure for any reason.

Confidentiality:

All information obtained in this study will be considered confidential and privileged. No information will be released outside of investigators in this study. From the beginning of your participation, you will be given a unique subject code. This code will be used instead of your name for all documentation of your participation. We will keep your individual data and results confidential including computer files, paper files, and any personal information. In written or oral presentations of the results of this research, your identity and individual information will be kept confidential. After the project is complete, the materials associated with the project, including computer files, paper files, digital video files, and personal information will be secured in a locked cabinet in a locked office under the supervision of Dr. Justus Ortega for 10 years in case there is a need for future verification or reanalysis of the data. Upon completion of this informed consent form, you will receive a signed copy of the consent form.

Other than the research team, only regulatory agencies, such as the Humboldt State University Committee for the Protection of Human Subjects in Research may see your individual data as a part of routine audits.

Invitation for Questions:

If you have questions about this study, you should ask the researcher before you sign this consent form. **You may also contact Courtney Perry, the Primary Investigator to answer any questions or concerns regarding the study.**

If you have any concerns with this study or questions about your rights as a participant, contact the Institutional Review Board for the Protection of Human Subjects at irb@humboldt.edu or (707) 826-5165.

Authorization:

I have read this paper about this study or it was read to me. I know the possible risks and benefits. I know that being in this study is voluntary. I know that I can withdrawal at any time. I have received, on the date signed, a copy of this document containing 4 pages. I understand that the researcher will answer any questions that I may have concerning the investigation or procedures at any time. I also understand that my participation in this study is entirely voluntary and that I may decline to enter this study or may withdraw from it at any time without any penalty. I understand that the investigator may terminate my participation in the study at any time.

Name of Participant (Printed) ____

Signature of Participant____________________________ Date____________

Appendix B

Medical History and Demographics

Demographics

Subject ID: ________________________

Biological Sex: M ☐ F ☐

Age: ______ Height: ________cm Mass: ________kg

Primary Language:

English ☐ Spanish ☐ Other ☐ ________________

Sport History

I am an Athlete at a College/University Yes ☐ No ☐

Sport: ______________________ Position: ______________________

Years played: _____

Concussion History

Have you ever had a concussion related to sport or other activities? ☐ Yes ☐ No

If yes, how many previous concussions have you had? __________

Have you had any concussions in the last 6 months ☐ Yes ☐ No

INJURY	DIAGNOSIS	APPROXIMATE DATE OF INJURY (mm/yy)
#1	☐ Diagnosed ☐ Undiagnosed	______/______
#2	☐ Diagnosed	

INJURY	DIAGNOSIS	APPROXIMATE DATE OF INJURY (mm/yy)
	☐ Undiagnosed	______/______
#3	☐ Diagnosed ☐ Undiagnosed	______/______
#4	☐ Diagnosed ☐ Undiagnosed	______/______
#5	☐ Diagnosed ☐ Undiagnosed	______/______

Current Injury **(Concussed subjects only)**

Date of Injury: ___________________ Time of Injury: ________________

Did you experience a loss of consciousness? ☐ Yes ☐ No

If so, how many minutes? _______

When did the injury occur? (Circle one) Practice/training Competition Neutral

What part of your body or head did the collision occur? __________________

Medical History

☐ Yes ☐ No Balance disorder

☐ Yes ☐ No Learning disorder

☐ Yes ☐ No Attention Deficit-Hyperactivity Disorder (ADD/ADHD)

☐ Yes ☐ No Brain Surgery

☐ Yes ☐ No Vision Problems (other than glasses/contacts)

☐ Yes ☐ No Hearing Problems

Medications

Are you currently taking prescription medications? ☐ Yes ☐ No

If yes, check all that apply:

☐ Antidepressants ☐ Anti-anxiety ☐ Antipsychotic

☐ Narcotic pain ☐ Non-narcotic pain ☐ Sleep aid/sedative

☐ Psychostimulant ☐ Birth Control ☐ Allergy

☐ Asthma ☐ Acid Reflux/Heartburn

☐ Other(s)____

If you answered yes to any of the above, please provide the name(s):

____

Additional Questions

☐ Yes ☐ No Do you have a neuromuscular or musculoskeletal disorder that affect your balance or ability to walk?

☐ Yes ☐ No Are you currently under care of a physician?

☐ Yes ☐ No Do you have any other illness, disease, or medical condition (beyond those already covered in this questionnaire)?

☐ Yes ☐ No Are you currently taking medications which affect your balance or ability to walk?

If you answered yes to any of these questions, please explain.

I certify that the information I have provided is complete and accurate to the best of my knowledge.

_________________________________ ____________
Signature of Subject Date

_________________________________ ____________
Signature of Test Administrator Date

Appendix C

Dual-Task Tandem Gait Score Card

Tandem Gait

☐ Socks ☐ No Socks

	Trial	Time	# of Errors
	1		
	2		
	3		

Errors:

Misstep and trip

Step off the line

Large separation between heel and toe

Grab examiner/object

Tandem Gait with 6-Digit Retention

	Trial	Time	# of Errors	6-Digit	6-Digits Repeated
	1				
	2				
	3				

Appendix D

SYMPTOM EVALUATION

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