THE EFFECTS OF A CONCUSSION ON DYNAMIC STABILITY AND COGNITIVE PERFORMANCE DURING SINGLE AND DUAL TASK TANDEM GAIT

By

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ABSTRACT

THE EFFECTS OF A CONCUSSION ON DYNAMIC STABILITY AND COGNITIVE PERFORMANCE DURING SINGLE AND DUAL TASK TANDEM GAIT

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PURPOSE: It is estimated that between 1.6 and 3.8 million concussions occur in the United States every year during competitive sports. To limit the risk of returning an athlete to play too soon a sensitive and reliable assessment is needed. Static balance assessments that are used currently only detect very short term balance deficits (1-3 days). The purpose of this study is to examine the effects of a concussion on dynamic stability and more specifically if those effects are seen to a greater degree with the addition of a secondary cognitive task. **METHODS:** This study used 18 Humboldt State University athletes, 9 athletes diagnosed with a concussion through the school's sports medicine protocol, and 9 healthy athletes to serve as a control group. We will examine the difference in walking kinematics between acutely concussed (within 48 hours of injury) and healthy individuals during a tandem gait walking test and tandem gait with a simultaneous secondary counting task. **RESULTS:** Several aspects of dynamic stability during tandem gait were compromised with the addition of a secondary task for both the concussion and healthy groups. Subjects walked slower, shortened step length, increased double support time and single support time and a decrease in swing time. However, no difference in dynamic stability or secondary task performance was found between concussed and healthy subjects. **DISCUSSION:** The results from this show that there is no difference in dynamic stability or cognitive function during single and dual task tandem gait tests between healthy and concussed college athletes. However, both concussed and healthy individuals did exhibit deficits in gait when faced with a secondary cognitive task.

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INTRODUCTION

Sport-related concussions have previously been trivialized and categorized as a measure of an athlete's toughness, rather than an injury (De Beaumont, Henry, & Gosselin, 2012). However, in recent years, as researchers and medical professionals gain a better understanding of the short and long term effects of a concussion on the brain, this image has started to change (Broglio, Eckner, Paulson, & Kutcher, 2012a). It is estimated that between 1.6 and 3.8 million concussions occur in the United States every year during competitive sports (Basford et al., 2003; Broglio et al., 2012a; Davis, Iverson, Guskiewicz, Ptito, & Johnston, 2009). Concussions are a prevalent injury in today's sports world, and those who are diagnosed with one often increase their risk of experiencing another (Broglio et al., 2014; Broglio, Eckner, Paulson, & Kutcher, 2012b). As more research is done on concussions it is becoming more clear that long term effects, not recognized in the past, show the real potential danger of concussions as well as a need for greater knowledge in their management.

Injury to the brain can affect an athlete physically, cognitively, and emotionally. To account for this, several tests have been constructed to focus on each of the different affected functions (Broglio et al., 2012b). It is suggested that a combination of these tests be used for evaluation to cover all areas, specifically a symptom checklist, balance assessment, and a computerized neurocognitive test (Broglio, Macciocchi, & Ferrara, 2007; Covassin, Elbin, Harris, Parker, & Kontos, 2012). The most common tests used are ImPACT (Immediate Post-Concussion Assessment and Cognitive Testing), BESS

(Balance Error Scoring System), SAC (Standardized Assessment of Concussion) and the SCAT-3 (Sport ConcussionAssessment Tool-3rd Edition).

What is a Concussion?

A concussion is a type of mild traumatic brain injury characterized by immediate and transient impairment of neural functions due to a mechanical force such as a bump, blow, or jolt to the head or body (McCrory et al., 2009; Meaney & Smith, 2011). Brain injuries can be categorized as either focal or diffuse. A focal brain injury refers to a more serious injury that includes subdural hematomas, epidural hematomas, cerebral contusions, and intracerebral hemorrhages. This type of injury is not commonly seen in sports but is a potential danger medical professionals should know how to identify. A concussion, on the other hand, is classified as a diffuse brain injury, caused by an acceleration-deceleration motion in either a linear or rotational direction (Congress of Neurosurgery, 1966).

The brain, because it is mostly composed of water, is resistant against changing shape when subjected to slow or transient pressures, however, when a shearing force is applied brain tissue deforms much easier (Meaney & Smith, 2011). More specifically, this shearing force creates damage in the white matter of the brain by stretching and tearing axons. Alterations to the cytoskeleton and axons from this force initiates the neurometabolic cascade causing an ionic flux and a quick, uncontrolled release of glutamate, a neurotransmitter responsible for brain functions such as cognition, memory, and learning. In order to restore cellular homeostasis adenosine triphosphate (ATP) dependent pumps work overtime causing hyperglycoloysis and depletion of intracellular energy. This shock of energy deficiency resulting from impaired metabolism of glucose leaves the brain in a state of hypometabolism (Giza & Hovda, 2014; Kontos & Ortega, 2011). Neurocognitive and neurophysiological changes are experienced during the acute phase of a concussion which can last up to three months post-injury (Henry et al., 2011). Though typically full recovery is achieved within that time frame, that is not always the case. If symptoms remain longer than three months the injury has become a chronic concussion (Henry et al., 2011).

Athletes who experience multiple concussions or an excessive amount of subconcussive blows run the risk of developing chronic traumatic encephalopathy (CTE) later in life. CTE is a progressive degenerative disease of the brain that has been known to affect boxers since the 1920's and is now being detected in retired football players as well. Degeneration of brain tissue can begin months or years after a brain injury or after an athlete becomes inactive in their sport (Henry, Tremblay, Boulanger, Ellemberg, & Lassonde, 2010). CTE is associated with a number of changes in the brain such as memory loss, impaired judgment, aggression, confusion, depression, and potentially progressive dementia (McKee et al., 2009). Researchers have recognized a cognitive decline in longtime professional football players and now neurologists have been able to conduct autopsies on brains donated from deceased NFL players that show heightened levels of tau protein, which is indicative of CTE (DeKosky, Ikonomovic, & Gandy, 2010).

Concussions, both acute and chronic, have many recognized signs and symptoms, this study will be focusing on those associated with the acute phase. The neurological effects of an acute concussion can be seen and measured through cognitive function as well as stability.

Concussion and Cognitive Function

Brain impairment from a concussion can be assessed through reported symptoms along with performance on neurocognitive tests. Some of the common cognitive effects include difficulty concentrating and remembering, confusion, mental fogginess, as well as slowed processing and reaction time. The ImPACT test was created to test all of these areas and easily determine an individual's cognitive function post-concussion compared to their baseline.

The computer-based ImPACT test is a tool used to evaluate cognitive function by testing verbal and visual short and long term memory, processing speed, and reaction time. It consists of six neuropsychological tests targeted to each of these areas and a 21-symptom checklist that records the severity of each individual symptom. The ImPACT test grades performance on each of the six categories separately to provide insight on which specific brain functions are suffering. Any category with a score that falls below the test taker's normal range, compared to their baseline score, will be flagged for further evaluation. When all areas of the test are back to baseline or better, and no symptoms are reported the athlete may be cleared to begin a graded return to play.

To determine the accuracy of the ImPACT test and its ability to detect a concussion 138 high school athletes, 72 of which had been diagnosed with a concussion and 66 healthy individuals took the test for experimental use (Schatz, Pardini, Lovell, Collins, & Podell, 2006). They found that among these 138 athletes the ImPACT test correctly diagnosed those with a concussion 85% of the time, proving it to be both a sensitive and specific tool in assessing and diagnosing neurocognitive function (Schatz et al., 2006). A similar study tested both high school and college athletes and the use of symptom scores, neurocognitive scores, and the combination of the two that are reported through ImPACT (Van Kampen, Lovell, Pardini, Collins, & Fu, 2006). A total of 192 athletes were used in this study, 122 of which were diagnosed with a concussion and 70 healthy controls. When looking at only self-reported symptoms 64% of the concussed group showed an increase, however, the neurocognitive test portion of the ImPACT test detected at least one abnormal score among 83% of the athletes diagnosed with a concussion through sideline assessments.

Though studies have shown the ImPACT test to be reliable and accurate, it provides strictly neurocognitive results, and is therefore limited. An alternative to cognitive tests such as ImPACT are tests of motor control, specifically standing and walking balance tests; both of which are postural control tests. These tests help clinicians understand the effect of concussion on the integration of sensory information and the ability of the motor cortex to control balance. Some research suggest that when these postural control tests are conducted simultaneously with a cognitive task, the negative effect of a concussion on postural control is amplified. Moreover, the combination of a postural control task such as walking with a secondary cognitive task can be more relatable to the demands that will be placed on an athlete's brain during sport activity (Parker et al., 2005).

Postural Control

Postural control can be broken down into two main functions: postural orientation and postural stability. Postural orientation refers to the body's ability to maintain a stationary position by actively controlling body alignment against gravity and in respect to the environment. This is what we would generally refer to as "balance". Postural stability on the other hand involves the ability to maintain the same control over the body but during a self-initiated or external disturbance (Kontos & Ortega, 2011). For example, postural orientation would be demonstrated by a soccer player preparing to take a penalty kick, and postural stability would be seen in a basketball player holding off a defender to take a shot. These two components of posture require interpreting and integrating sensory information between the vestibular, visual, and somatosensory systems. These three systems work together to maintain the eyes fixed and focused on stationary targets during movement as well as transmitting signals of movement to the lower extremities in order to make adjustments and maintain posture.

Gait and Dynamic Stability

While postural stability is important, more relevant to athletes is dynamic stability (Parker et al., 2005): the ability to balance while in motion, or more specifically, maintain steady posture during walking or running while withstanding external forces (Giza & Hovda, 2014). Walking, often referred to as gait, consists of continuous gait cycles, with a single cycle measured as one full stride completed by each foot; e.g. the period of time from a heel strike on the right foot to the next time the right heel strikes the ground.

Dynamic stability can be assessed through gait performance using a number of measurements including preferred walking speed (the time it takes to complete one gait cycle), stride length (the distance between consecutive ipsilateral foot strikes), and stride width (the lateral distance between placement of the two feet). The variability in both stride length and width can also be assessed by looking at the amount to which strides vary from each other, determining the consistency of gait.

Effects of Concussion on Postural and Dynamic Stability

A healthy brain integrates the use of the visual, vestibular, and somatosensory systems to balance (Riemann & Guskiewicz, 2000). Information from these combined sources produces an afferent signal sent to the central nervous system (CNS) to be received by the basal ganglia. A new signal is created by the basal ganglia, based on its perception of the current position of the extremities in space, which is then integrated with motor impulses coming from the motor cortex in the cerebellum. This generates a final efferent signal through the brainstem that is carried out to alpha motor neurons innervating the skeletal muscle in order to maintain postural equilibrium (Broglio, Tomporowski, & Ferrara, 2005). If one input system is deficient or altered the others will compensate, under normal circumstances. Mild traumatic brain injuries, such as a concussion, disrupt this process making the individual unable to compensate for altered sensory information which results in improper motor responses. This deficit is theorized to stem from two possible mechanisms: peripheral receptors responsible for sensing motion could be damaged from the impact and therefore providing inaccurate information to the brain, or the impairment of brain centers responsible for integrating senses from the vestibular, visual and somatosensory systems is transmitting misinformation (Riemann & Guskiewicz, 2000).

A study was conducted to evaluate the differences between concussed and healthy individuals during postural stability tests (Riemann & Guskiewicz, 2000). Each participant was instructed to perform the BESS test which consists of three stances (double, single, and tandem) on both a firm surface and a medium-density foam pad. Concussed subjects performed all six of these stances at four separate visits on day 1, 3, 5, and 10 post-injury. Results showed a significant difference between injured and control subjects only on day one post-injury on the firm surfaces and up to three days post-injury on the foam surface. More specifically, differences between injured and control subjects were observed for the double ($p=.01$), and single ($p=.01$) stance trials and with the greatest concussion related difference observed in the tandem stances ($p < .01$). The results from this study suggest that a static balance test might not be sensitive enough to detect longer term stability deficits in concussed individuals. The foam surface raised the difficulty slightly and the tandem stance proved to be the most sensitive but was still not able to detect a difference longer than 3 days.

Another study focused on balance differences between concussed and healthy individuals while using dynamic stability tests, instead of static, and during a single and dual-task walking situation (Parker, Osternig, P, & Chou, 2006). Thirty collegiate athletes participated, 15 of which were concussed and 15 healthy matched controls. All subjects performed walking trails within 48 hours of injury (day 2) and then again on day 5, 14, and 28. Results showed that gait velocity was significantly slower in the concussed group during the single walking task for the first 48 hours but became consistent with the healthy controls by day 5. Stride length was found to be significantly longer among the healthy controls up until day 14, showing that this might be a more sensitive measurement. When looking at COM/COP separation a significant difference between the two groups during single-task was seen only on day 2 whereas the dual-task found significant differences all the way through day 28. Comparing mediolateral displacement during the two tasks found no task differences for the control subjects, but detected significantly greater sway during dual-task until day 28 for the concussion group. The results from this study suggest that a single walking task is not sensitive enough and that a simple mental task may be needed in order to produce a test capable of detecting dynamic postural motor control differences in concussed individuals.

Effects of Concussion on Balance with a Secondary Cognitive Task

Current postural stability assessments, such as the BESS test, have been able to identify a concussed individual only one to three days post injury (Covassin et al., 2012). Cognitive symptoms measured through neuropsychological tests are often only detected up to 14 days post-injury. However, assessments using a dual task situation consisting of a cognitive task performed during gait have reported a decrease in dynamic stability in concussed individuals lasting up to a month post-injury (Catena, van Donkelaar, & Chou, 2009; Parker, Osternig, Van Donkelaar, & Chou, 2006). Previous research shows that performance deficits seen in undivided attention dynamic stability tests are exacerbated when a simple mental task, such as serial 7's (subtracting three-digit numbers by sevens), reciting the order of the months backwards, or spelling a five letter word backwards is added(Catena, van Donkelaar, & Chou, 2011; Parker, Osternig, Lee, Donkelaar, & Chou, 2005). These task deficits are measured by looking at differences in stride length, stride width, walking speed, velocity in anterior-posterior and medial-lateral directions, center of pressure (CoP), and center of mass (CoM) trajectory through gait. Center of pressure and center of mass are said to relate the closest to how the body moves through space and during locomotion (Catena, van Donkelaar, & Chou, 2007; Catena et al., 2009). Previous studies have shown that measuring gait by CoM motion is more sensitive in identifying conservative gait adaptations (Catena et al., 2007; Parker et al., 2005) (Chou et al., 2004).

This dual task situation creates a more sport-like condition in which athletes must focus on multiple things at once. By creating a divided attention situation the effects of a concussion become more evident. Individuals may test as functioning normal or back to their baselines with a singular task, but by giving them a higher capacity test and increasing the demand on the brain the deficits to brain function are noticeable for a longer period of time (Parker et al., 2005). When preparing an athlete for return to play, a test that closely mimics the stress a sport situation will place on their brain could provide medical professionals with a more accurate diagnosis of their readiness in a controlled environment.

Concussed athletes, when compared to healthy controls, showed an impaired walking performance when paired with a simple mental task (Catena et al., 2011; Parker et al., 2005). This was determined due to finding a slower walking speed, shorter stride lengths, and greater sway in the concussed individuals.

A study testing 10 concussed college-aged individuals against 10 healthy controls on reaction time during an undivided attention Stroop test while seated as well as Stroop test while walking (Catena et al., 2011). There were no significant differences in reaction time on the Stroop test during seated or walking trials. However, when looking at center of mass (CoM) measurements during walking there was a significant difference found in both peak anterior velocity ($p=0.004$) and range of motion in the sagittal plane ($p=0.015$) among the concussed group during dual-task walking. All individuals, both healthy and concussed, showed slower peak velocities and less sagittal plane motion during single task walking when compared to the dual task. However, the control individuals did not demonstrate a correlation between their range of motion along the sagittal plane and Stroop performance, whereas the concussed group did. A moderate significant correlation was found between sagittal plane CoM/CoP separation and Stroop performance ($p=0.046$), though only within 48 hours of injury (Catena et al., 2011).

Another study was conducted to investigate performance differences on single and dual-task walking among concussed and healthy college-aged individuals (Parker et al., 2005). The purpose of this study was to determine if adding a secondary cognitive task to the walking task would create a more sensitive test in identifying a concussion within the first 48 hours of injury. Subjects completing level walking with undivided attention as well as level walking while simultaneously performing a simple cognitive task. In this case the cognitive task was either spelling a 5 letter word, counting backwards by sevens, or reciting the months in reverse order. Both groups showed significantly slower gait velocity, stride length and stride time ($p<0.001$, $p<0.001$, and $p=0.001$, respectively) during dual-task when compared to single-task. When comparing the two groups the concussion group demonstrated a significantly shorter stride length ($p=0.042$) and slower gait velocity, though not a significant amount.

The 2005 study by Parker focused only on differences among concussed individuals seen within the first 2 days post-injury. A follow up study, *Gait Stability following Concussion (2006)*, was then conducted over a span of 28 days post-injury to investigate how long decreased dynamic stability was detected. Previously, the minimal differences between healthy and concussed individuals during single-task walking conditions from this study were discussed, however, when comparing dual-task walking performance, concussed individuals exhibited several characteristics of reduced stability. During single-task walking CoM/CoP separation was able to detect a difference between the two groups only on day 2 post-injury and mediolateral displacement measurements showed no significant difference. However, with the addition of a secondary task mediolateral and CoM/CoP separation revealed a significant difference between the concussed and healthy groups through day 28 post-injury (Parker, Osternig, Van

Donkelaar, et al., 2006).

Tandem Gait vs. Preferred Walking

Existing literature on the assessment of concussion has focused on the use of static balance tests or gait during preferred walking. Preferred walking can be simply explained as the speed at which individuals choose to walk, or what feels comfortable and natural. Tandem gait, on the other hand, requires walking along a designated line. Just as a tandem stance is more sensitive on the BESS test we predict that a tandem gait test will be more sensitive than preferred gait in the detection of dynamic stability deficits.

The Sport Concussion Assessment Tool (SCAT3) is the newest of the sideline assessments combining tests covering symptoms, cognitive function, balance and coordination. A tandem gait test (TG) was introduced by the SCAT3 and requires the evaluated athlete to walk heel to toe along a 3 m long and 38 mm wide piece of tape, turn 180 degrees, and repeat back to the start line as quickly and as accurately as possibly. This tandem gait test is used to measure dynamic balance, speed and coordination. Though there is still little research on this specific test, and on tandem gait in general, a study was done to investigate the consistency of the SCAT3 Tandem Gait test, more specifically to determine intra-rater reliability (A. G. Schneiders, Sullivan, Gray, Hammond-Tooke, & McCrory, 2009). A sample size of 172 healthy subjects between the ages of 18 and 40 were tested on the initial examination day, 40 of which volunteered to repeat the test one week later. On both visits each individual performed three trails of three tests taken from the SCAT3 (Tandem Gait (TG), Finger-to-Nose (FTN), and Single Leg-Stance (SLS) instructed and scored by the same evaluator. Results showed that FTN and TG were the most robust measures when looking at repeat testing. A. G. Schneiders, Sulliva, Gray, Hammond-Tooke, & McCrory (2009) concluded that the Tandem Gait test was precise and reliable when administered by the same evaluator and is therefore a dependable measurement of lower limb dynamic balance. The reliability of this test on healthy individuals suggests that it has potential for use as an assessment tool for sport-related concussion (Schneiders, Sullivan, Gray, Hammond-Tooke, & McCrory, 2009).

Following the previous study of the Tandem Gait test on healthy subjects Schneiders, Sullivan, Lee, & McCrory (2013) investigated the test's potential to identify a concussed athlete. A total of 18 concussed athletes were instructed to perform the Tandem Gait test (same procedure as explained in the previous paragraph) within 3 hours of injury. The test completion times of the concussed group was compared to 18 matched controls. The results showed significantly slower completion times in the concussed group ($p=0.009$) (Schneiders, Sullivan, Lee, & McCrory, 2013).

Thesis Statement

The primary purpose of this study is to examine the effects of a concussion on dynamic stability during single and dual task tandem gait walking. More specifically, this study will examine the difference in walking kinematics between acutely concussed (up to 48 hours post-injury) and healthy individuals during a tandem gait test and a tandem gait test performed simultaneously with a secondary counting task. We hypothesize that individuals diagnosed with an acute concussion will have a greater deficit in dynamic stability during tandem gait while performing a secondary cognitive task when compared to healthy controls. We hope that results from this study will provide more information on the effects of concussion leading to a better understanding and improved assessment tools.

METHODS

Participants

Participants for this study included a total of 18 college athletes ranging from 18 to 24 years of age split into two groups, experimental (n=9) and control (n=9). The experimental group consisted of concussed athletes referred to the study within 48 hours of injury diagnosis. Healthy athletes who volunteered for participation in the study were used as the control group.

Inclusion Criteria

- Age: 18-24 years
- Collegiate varsity athlete
- Experimental Group only: Sustained a diagnosed concussion within last 48 hours

Exclusion Criteria

- Current musculoskeletal injury
- History of mental illness, neurological disease or traumatic brain injury
- Visual impairment not correctable by lenses
- Control Group only: Diagnosed concussion within the last year

Procedures

All subjects participated in one experimental session. In this session subjects were oriented to the study, performed a neurocognitive test (ImPACT), and several over ground walking trials.

Initially, participants were oriented with the study and provided written informed consent with the knowledge of confidentiality and the risks and benefits of this study. In addition, participants were required to complete a health screening questionnaire. Subjects then completed the ImPACT test (ImPACT Applications Inc., Pittsburgh, PA), a computerized neurocognitive test that is approximately 30 minutes long. As part of the HSU sports medicine protocol all participants in the concussion group had baseline neurocognitive scores from the ImPACT test. This data was accessed and compared to scores on the ImPACT test taken during the experimental session conducted on day 2 post-injury. Participants in the control group were required to take the ImPACT test as a "post-injury" neurocognitive assessment during their visit as well.

Following the neruocogntive test, several anthropometric measurements were taken: height, weight, leg length, knee width, ankle width, shoulder offset, elbow width, wrist width, and hand thickness. Retroreflective markers were then placed on 35 different anatomical landmarks that were used for calculating stride kinematics. Subjects performed a minimum of six preferred speed tandem gait walking trails along a 20 meter walkway. Specifically, subjects were instructed to stay on the line but may use preferred speed and step length (not required to walk heel to toe). Subjects performed, in a counterbalance random order, three trials of tandem gait walking with no task and three trials of tandem gait walking with a simultaneous secondary cognitive task. The cognitive task required that the subject count backwards by 3's with an error recorded each time a number was said out of order (subtracted incorrectly).

Measures

During the trials both cognitive function and dynamic stability were measured. Dynamic stability was measured through the use of force plates and digital motion capture, to be discussed in greater detail below.

Neurocognitive Testing

As part of the HSU sports medicine protocol all participants in the concussion group had baseline neurocognitive scores from the ImPACT test. This data was accessed and compared to scores on the ImPACT test taken on the day of the experimental session (~48 hours post-injury) in order to verify a concussion injury was present. Participants in the control group were also required to take the ImPACT test on the day of the experimental session.

Kinematics

Stride kinematics were measured through the use of 35 retro-reflective marker balls placed on bony landmarks. Following anthropometric measurements adhesive reflective marker balls were placed bilaterally on the participant's' foot, ankle, lower leg, thigh, ASIS, PSIS, front and back of head, shoulder, elbow, medial and lateral wrist, and hand as well as on the sternum, clavicle, C7, T10, and right scapula, using a modified Helen Hayes model. Trajectory of these marker balls was recorded using an eight-camera Vicon digital motion capture system with a capturing frequency of 100 Hz. Trails were then digitized with Vicon Nexus 2.2.3 Motion Capture Software using a fourth-order zero-lag low pass Butterworth filter and a cutoff frequency of 6 Hz. Using Visual 3D software (Version 5.0, Qualisys Motion Capture Systems, Gothenburg Sweden) virtual marker positions were then estimated to represent internal segment endpoints from the external retro-reflective marker balls. These external markers, along with estimated joint centers, were used to calculate three-dimensional motion for each subject and each of their 13 body segments (head-neck, trunk, pelvis, upper and lower arms, upper and lower legs, feet). Stride kinematic data will be used to calculate preferred gait velocity, total lean and trunk lean. Each of these measurements will be used collectively to determine the subject's dynamic stability.

Force Plate

Ground reaction force data was collected using three six-channel force plates (Advanced Mechanical Technology Inc., Watertown, MA, USA) positioned in a series along the gait path, sampled at a frequency of 1000 Hz. Force plate motion data was analyzed through at least one complete gait cycle. This data was used to calculate temporal-distance parameters including walking speed, double support time, single support time, swing time, step length, and stride and step length relative to height. Variability of both stride length and stride width were calculated as the standard deviation in stride length and width, respectively, across all strides of each condition.

Cognitive Performance During Tandem Gait

Cognitive function during each of the tandem gait trials was measured by counting the total numbers recited and the number of errors made during the task. The secondary task required subjects to count backwards by 3's starting with a three digit number, with an error counted for each incorrectly subtracted number. Subjects were not told to focus on one task or the other, therefore we do not know which task the subject's gave primary attention to.

Statistical Analyses

We used a Two-Way Repeated Measures Analysis of variance (ANOVA) to determine statistical differences in dynamic stability in concussed and healthy athletes during two conditions (single and dual task tandem gait). The ANOVA was run with a Bonferroni adjustment and a significance level of $p<.05$ to determine a statistical significant difference between the two groups and tasks of each dependent variable. Sphericity was also checked using Mauchly's test, the assumption of equal variance of difference between within-subject conditions was met. In addition, a planned comparisons Independent Samples t-test on each of the dependent variables between healthy and concussed subject performance during dual task gait. All statistical analyses were performed using SPSS 23.0 (SPSS, Inc.) software.

Assumptions

In this study it was assumed that (a) subjects met the following inclusion criteria, (b) have a full understanding and have the ability to perform tasks, (c) perform the tasks to the best of their ability, (d) results from this study will be generalizable to concussed individuals outside this study.

Limitations

The limitations of this study included (a) subjects honesty on questionnaires and report of symptoms, (b) time of day subjects were tested, (c) differences in subject's dynamic stability ability, (d) differences in subject's ability on the cognitive task.

Delimitations

This study was delimited to (a) Humboldt State University varsity athletes, (b) between the ages of 18 to 24 years old, (c) sustained a concussion within the last 48 hours (experimental group), (d) have no recent history of concussion (control group), (e) no current neurological or orthopedic injury.

RESULTS

For this study, we tested 9 concussed collegiate athletes and 9 control athletes with similar body masses and heights (Table 1). All concussed athletes were tested within 48 hours following their injury

The purpose of this study was to determine if changes in gait stability, typically resulting from the addition of a secondary cognitive task to walking ("dual task"), are amplified by an acute concussive injury. The results of our investigation suggest that in contrast to our hypothesis, walking kinematics and kinetics change in a similar way as a result of performing dual tasks for healthy and concussed individuals ($p<.0001$; Table 2). Specifically, we found that between single task and dual task, walking speed decreased among subjects in both groups with control subjects walking 9% slower and concussed subjects walking 12.8% slower during the dual task condition ($p<.0001$). Both groups also displayed a decrease in step length with a decrease of 5.1% among the control group and 5.4% in the concussed group ($p<.0001$). Similar to the absolute measures, when step and stride length were quantified relative to body height both groups exhibited changes to their walking kinematics ($p<.0001$). Specifically, both the control and concussed groups showed 5.1-5.4% decrease in relative stride length. We also found that double support time increased by 5.6% for the control group and 10.5% for the concussed group during the dual-task condition ($p=.003$). Single support time increased as well for both groups, with the control group increasing by 0.8% and the concussed group by 2.2% ($p=.006$). In the gait cycle, swing time opposes single support time; therefore we saw an equal decrease in swing time as single support time increased within both groups; specifically a decrease of 1.2% in the control group and 3.4% in the concussed group was seen during the dual task condition (p=.006). Lastly, when compared to single task tandem gait walking, the within stride anterior-posterior velocity decreased by 4% and 7.7% for the control group and concussed group, respectively, during dual task tandem gait (p<.0001).

These results show that the addition of a cognitive task to tandem gait during the "dual task" walking did produce a measurable effect, both concussed and control groups showed a significant difference in their walking performance when comparing single and dual task trials. However, when looking at the difference between the two groups on the two tasks no significant difference was found, only a moderate difference was seen in the variability of stride width. This tells us that though the dual task condition was able to provide significant differences it did so for both groups similarly (shown in greater detail below in Table 2). To investigate further into the comparison of performance during dual-task gait between the two groups we ran a planned comparison t-test as a follow up test. From this test we found a significant difference in two of the variables, step length was 2.4% larger in control subjects, and variability of stride width was 49.7% more variable among controls. Though we did not find significant differences between the two groups on their performance on the two tasks we did notice that the concussed group had a larger standard deviation on a few of the kinematic measurements; meaning that though the averages were in the same range as the healthy control group, that their performance may have a greater variability. To investigate further in order to determine if this between subject variability could also be found within in subjects we ran a post-hoc test on four kinematic variables: total lean, swing time, double support time, and stride length. More specifically, we ran an ANOVA, as well as an independent samples t-test, on the dual task data alone, to determine if the concussed subjects showed more variability in their dynamic stability throughout their walking trials. We found no significant differences in the standard deviation of these measurements across the trials between the two groups.

Along with kinematic measurements we also looked into the secondary cognitive task performed while walking. Performance on the cognitive task was assessed by recording the total amount of numbers the subject counted during the trial and how many errors were made while counting backwards. Although no significant difference was found from our independent t-test, healthy subjects did tend to count more numbers and make fewer errors than the concussed subjects (Table 3).

DISCUSSION

In this study, we examined the effects of a concussion on dynamic stability and cognitive function during single and dual task tandem gait. We hypothesized that individuals diagnosed with an acute concussion (up to 48 hours post-injury) would have a greater deficit in dynamic stability during tandem gait while performing a secondary cognitive task, when compared to healthy controls. Our findings did not support this hypothesis, we found no difference in dynamic stability between the two groups. Although both groups showed deficits in dynamic stability with the addition of a cognitive task, the concussed group did not exhibit any greater deficits than the control group.

Given that we know there to be a measurable difference among the concussed subjects from the ImPACT test, yet their dynamic stability during gait were comparable to that of healthy subjects, there must be contributing factors that led to this finding. One factor may be that the cognitive task performed was not challenging enough to elicit differences. The use of continuous question and answer tasks were used as a secondary cognitive task in (Parker et al., 2005; Parker, Osternig, Van Donkelaar, et al., 2006; Catena, Van Donkelaar, & Chou, 2007; Howell, Osternig, Koester, & Chou, 2014). In these studies the term Q&A was used in reference to three cognitive tasks: spelling a five-letter word backwards, subtracting by a given number, and reciting the months of the year in reverse order. In each of these studies all subjects performed walking trials using all of these tasks. Catena, Van Donkelaar, & Chou (2007) and Howell, Osternig, Koester,

& Chou (2014) also compared secondary task difficulty by using a simpler task along with the Q&A task. A reaction time test was used by Catena, Van Donkelaar, & Chou (2007), which required subjects to press a handheld button as soon as they heard a specific noise, however, no difference in dynamic stability or cognition was found between concussed and control groups during these trials. Similar to this, Howell, Osternig, Koester, & Chou (2014) used two versions of an auditory stroop test. Subjects were instructed to listen for the word “high” or “low” to be said, in either a high or low pitch, and identify the pitch the word was said in. A single and multiple auditory stroop test, meaning that it occurred one or four times, respectively, throughout the walking trial. Some decrease in dynamic stability was found in concussed subjects during trials using the multiple auditory stroop test, however, not during the single stroop task. All of these studies found a decrease in dynamic stability among concussed subjects during Q&A dual task trials when compared to control subjects (Parker et al., 2005; Parker, Osternig, Van Donkelaar, et al., 2006; Catena, Van Donkelaar, & Chou, 2007; Howell, Osternig, Koester, & Chou, 2014). Though these secondary tasks were effective in creating a deficit in dynamic stability in the studies previously discussed, this study used one of Q&A tasks without any differences between the groups displayed. This could be because certain simple mental tasks come more easily to some than others and by testing three different cognitive tasks the other studies accounted for this. Another possible explanation is that the counting task is the easiest of the three and this was accounted for by having each subject also complete the other two tasks.

Another factor that could have played a role in the lack of difference in dynamic stability is the severity of the injury. It is possible that those who scored just slightly out of the healthy range on their ImPACT test and had mild concussions with fewer symptoms may have been more willing to participate in the study than those who suffered from more symptoms associated with a more severe injury. If this were to be true we would be evaluating the healthiest subjects of the injured population which would lead to less dramatic differences in balance and cognitive function.

The effect of concussion on gait kinematics varies tremendously across the literature. In the present study we observed that concussed individuals walked at a similar preferred walking speed and with similar stride lengths/frequencies. Unlike the studies of Parker et al. (2005), Catena, Van Donkelaar, & Chou (2007), Catena, Van Donkelaar, & Chou (2011), Howell, Osternig, Koester, & Chou (2014), we found that concussed and control subjects walked at a similar intermediate of 1.1 m/s, with a standard deviation of 0.17 during single task trials, and .96 m/s with a standard deviation of 0.17during dual task trials. Although a decrease in walking speed is more frequently observed in individuals with a concussion, post-injury changes in other stride kinematics such as stride length and stride frequency are less consistent. For example, while Parker et al. (2005) and Parker, Osternig, Van Donkelaar, et al. (2006) did find a difference in step length between concussed and health controls, our study and that of Howell, Osternig, & Chou (2013) found no difference due to concussion. It should also be noted that step width has also been shown to increase following a concussion injury (Catena, Van Donkelaar, & Chou, 2007), however, because our study had subjects walk along a line (i.e. tandem gait), there was no difference in step width. Though this might not be the only reason, the studies of Parker et al. (2005), Parker, Osternig, Van Donkelaar, et al. (2006), and Howell, Osternig, & Chou (2013) did not use tandem gait and still found no difference in step width.

Although not all of these studies are consistent in finding differences between groups they have been consistent in their findings between task differences, similar to the present study. In this study we found all subjects demonstrated a slower walking speed, shorter stride length, and a decrease in AP velocity during dual task walking when compared to single task. These results are consistent with those found by Parker et al. (2005), Parker, Osternig, Van Donkelaar, et al. (2006), Catena, Van Donkelaar, & Chou (2007), Howell, Osternig, Koester, & Chou (2014) who saw a slower walking speed during the dual task condition than the single task among both groups as well. Though we did not collect these measurements, increased APRoM and a longer time to complete strides during dual task walking has also been measured (Parker et al., 2005; Parker, Osternig, Van Donkelaar, et al., 2006; Catena, Van Donkelaar, & Chou, 2007).

The idea behind using a dual task test on concussed individuals to identify deficits comes from the theory of attention and capacity interference (Parker et al., 2005). This means that there is a limited capacity to the tasks our brain can put attention towards, and if this capacity is exceeded performance on one of the tasks will suffer (Ebersbach et al., 1995). Perhaps because walking is a habitual movement and was an easy dynamic stability test, differences would not be seen until brain attention capacity is exceeded and the two tasks used in this study did not reach that limit. Guskiewicz et al. (2001) also reports that there is no relationship between concussion symptoms, cognitive test performance, and static postural stability. Although these three measurements are used collectively to measure and diagnose a concussion injury they do not necessarily correlate with each other; measured cognitive deficits does not necessarily mean we will see deficits in dynamic stability.

Most comparable studies focused only on kinematic differences and did not report results from performance on the cognitive task, however, Catena, Van Donkelaar, & Chou (2007), did report seeing no significant difference in the scores of the cognitive secondary task which is consistent with this study.

This study had a few limitations, the first being a small sample size. We were limited by the concussed subject group because of its specific requirements that were out of our control. Athletes diagnosed with a concussion had to be referred to the study, choose to take part in it, and complete testing within 48 hours of their injury. Ideally this study would be conducted over a longer period of time in order to draw a larger experimental group. Another limitation to this study was the equipment used for data collection. Some of the subjects performed their trials with only seven of the eight cameras functioning, resulting in more gaps in the data collected. These gaps are filled either automatically or manually which can smooth out data, making it normalized to the rest of the trial. The large amount of gap filling could have averaged out large portions of data, meaning that we would not see the true instability and variability in the subject's movements. This problem did not occur on all trials or equally for concussed and control subjects, but was an issue that affected almost all of the concussed trials and only a couple of the healthy subject's trials. Another limitation was the size of the area captured, allowing only one or two stride lengths to be analyzed. This leaves a very short period of time for subjects to display variability or dysfunction in balance. The BESS test requires individuals to stand for 30 seconds in each stance, whereas our trials lasted 5-10 seconds. The SCAT-3 uses a walkway similar in length and tandem walking, however, it requires the subject to turn and walk the line back to the starting point which increases the difficulty and doubles the time of the test. However, Catena, Van Donkelaar, & Chou's (2007) study did detect deficits in concussed individual's dynamic stability with walking trials that were on average 8 seconds, so this may not be the reason for our lack of difference. With room size restricting the area that can be captured by the cameras, a test that requires the subjects to walk the line turn around and walk back would be an improvement to this study that would allow a longer period of dynamic stability to be observed. Upgraded technology and the use of marker ball clusters could provide better data collection and more accurate movement overall. Another limitation of this study is that the cognitive task was not also performed as a single task so we do not have a comparison for subject's performance while not walking. It is possible that subject's would attempt to count fewer numbers and make more errors on the counting task in the dual task situation than if performed alone. Future studies could benefit from testing a dynamic stability and a cognitive task separately and then together and comparing single and dual task performance on both.

This data can be used to gain a greater understanding of how concussions affect gait and cognition and what kind of test is best for identifying an injury or monitoring recovery. We had predicted that we would see concussed subjects struggle with multitasking a dynamic balance and a cognitive task more so than healthy subjects. It was interesting to find how concussed and healthy control subjects used very similar gait patterns. This suggests that a more rigorous dynamic stability assessment is needed for use in concussion identification and diagnosis. In order to gain a better understanding of how a concussion affects dynamic stability and what an appropriate test would be, this study needs to be taken further. Future studies could benefit from simply a larger sample size and longer trials. More research on using different secondary cognitive tasks would be helpful as well in determining which one would be the most effective to pair with a gait task.

Conclusion

The results from this study show that there is no difference in dynamic stability or cognitive function during single and dual task gait tests between healthy and concussed college athletes when using a tandem gait test paired with a counting task. However, both concussed and healthy individuals did exhibit deficits in gait when faced with a secondary cognitive task. It is unclear if this lack of concussion related difference can be attributed to the small sample size, the type of cognitive task used, or the severity of concussion among the test subjects. Further research on the effect of concussion on dual task dynamic stability needs to be conducted in order to gain a more concrete understanding that can be used to create an accurate assessment tool for medical professionals.

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TABLES

Table 1. Subject characteristics - means ± standard deviation

	Subject Group		
Characteristic	Healthy	Concussed	P Value
Height (m)	1.76 ± .08	1.65 ± .12	.350
Weight (kg)	78.60 ± 11.74	73.01 ± 11.54	.734
Subject Number	9	9	

Table 2. Gait kinematic variables in concussed and control subjects during single and dual task tandem gait - *Significant difference between tasks (p<.05)

Variable	Single Task		Dual Task	
	Control	Concussion	Control	Concussion
Double Support Time (%)*	20.70 ± 1.02	22.26 ± 3.37	21.86 ± 1.21	24.60 ± 4.12
Single Support Time (%)*	60.33 ± 0.74	61.03 ± 1.70	60.82 ± 1.05	62.35 ± 1.97
Swing Time (%)*	39.67 ± 0.74	38.97 ± 1.70	39.18 ± 1.05	37.65 ± 1.97
Step Length (m)*	0.62 ± 0.05	0.61 ± 0.07	0.59 ± 0.04	0.58 ± 0.07
Step Length/Height*	0.35 ± 0.02	0.37 ± 0.04	0.34 ± 0.02	0.35 ± 0.04
Stride Length/Height*	0.71 ± 0.05	0.74 ± 0.08	0.67 ± 0.05	0.70 ± 0.08
Stride Length Coefficient of Variance	0.01 ± 0.01	0.01 ± 0.01	0.02 ± 0.01	0.01 ± 0.00
Stride Width Coefficient of Variance	0.11 ± 0.05	0.10 ± 0.03	0.19 ± 0.09	0.09 ± 0.05
Walking Speed (m/s)*	1.09 ± 0.13	1.06 ± 0.20	0.99 ± 0.12	0.92 ± 0.21
AP Velocity*	1.74 ± 0.13	1.78 ± 0.10	1.67 ± 0.12	1.64 ± 0.15
Total Lean	7.54 ± 1.35	7.62 ± 1.41	7.80 ± 1.86	7.86 ± 1.73
Trunk Lean	1.73 ± 0.20	1.13 ± 0.89	1.49 ± 0.43	1.02 ± 1.36

Table 3. Cognitive function variables in concussed and control subjects during dual task tandem gait - Data are means ± SD

	Healthy	Concussed	P Value
Numbers Counted	9.9 ± 3.5	8.9 ± 3.1	0.711
Counting Errors	0.4 ± 0.4	0.7 ± .5	0.485