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The Influence of the Initiation of a Graded Exercise Protocol on Dynamic Postural Stability Following a Concussion

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THE INFLUENCE OF THE INITIATION OF A GRADED EXERCISE PROTOCOL ON
DYNAMIC POSTURAL STABILITY FOLLOWING A CONCUSSION

by

LAURYN HUNTER

(Under the Direction of Thomas Buckley)

ABSTRACT

Context: Current post-concussion assessment tools may lack sensitivity in identifying recovery. Athletes demonstrating decreased postural control may have an increased likelihood of suffering sports-related injury. Exercise has been shown to briefly alter static postural control and the visual contribution to static postural stability deteriorates with moderate intensity exercise. Gait variability, defined as the fluctuation in gait characteristic between steps, is a sensitive measure of postural stability in populations with higher level gait disorders. **Objective:** The purpose of this study was to examine the influence of a progressive exertional return-to-play program on dynamic postural stability following a concussion. **Design:** Prospective longitudinal. **Setting:** Biomechanics laboratory. **Participants:** Nine participants (Height: 173.6 ± 9.3 , Weight: 85.7 ± 24.7 , Age: 19.4 ± 1.3) who suffered sports-related concussions during intercollegiate athletic participation and nine physically active control participants (Height: 161.7 ± 12.98 , Weight: 77.3 ± 19.98 , Age: 22.8 ± 1.99). **Interventions:** Both groups performed 10 trials of self-selected paced normal and fast gait along a 7.9m instrumented walkway. The concussion participants baseline testing was performed during pre-participation physicals prior to intercollegiate athletic participation. The second session was within 24 hours of suffering a concussion, the third session was the day before the exercise protocol began, and the remaining sessions were after the

participant completed day one (stationary bike) and day two (elliptical) of the exercise protocol.

Main Outcome Measures: Dependent variables of interest included step length variability, step width variability and step time variability. These values were expressed using a coefficient of variation [(standard deviation/mean)*100]. Dependent variables were compared with six 2x5 (group x day) repeated measures ANOVAs with a 0.01 adjusted alpha. **Results:** For normal speed, there was no group by time interaction (p=.526, p=.562, p=.271) or main effects for time (p=.925, p=.669, p=.808) for step length, step time, or step width variability across the testing days. A significant difference was found between the groups (p=.007) for normal speed step length variability (Concussion 3.26±0.93, Controls 2.48±0.37), but not for step time or step width (p=.027, p=.071). For fast speed, there was no group by time interaction (p=.518, p=.866, p=.780) or main effects for time (p=.087, p=.884, p=.033) for step length, step time, or step width variability across the testing days. No significant differences were found between the two groups (p=.384, p=.072, p=.597) for fast speed variability measures. **Conclusions:** The results of this study suggest that athletes suffering from sports-related concussion do not display altered gait variability compared to healthy controls, potentially indicating that otherwise healthy post-concussion student-athletes have sufficient compensatory mechanisms and/or strategies to reduce gait variability upon initiating exercise. This finding is surprising as previous studies have identified dynamic postural stability insufficiencies post-concussion, suggesting a conservative gait strategy has been adopted.

INDEX WORDS: Concussion, Postural Stability, Exercise, Gait variability, Return-to-play

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CHAPTER 1

INTRODUCTION

An estimated 1.6 to 3.8 million concussions occur annually in the United States.¹ A history of concussion may be associated with an increased risk of future concussive injuries, a slower rate of recovery in neurological function following subsequent concussions, as well as an increased risk of developing chronic conditions such as clinically diagnosed depression, earlier onset of Alzheimer's disease, and chronic traumatic encephalopathy.²⁻⁹ Returning to play prematurely following a concussion increases the risk of sustaining second impact syndrome, a rare but potentially fatal condition which may occur when an individual suffers a second concussive impact before recovering from the initial impact.¹⁰ Athletes may also become vulnerable to other injuries resulting from both decreased reaction time and processing speed characteristically observed in concussed patients via neuropsychological testing.¹¹ Postural instability is a cardinal post-concussion symptom, and the assessment tool currently used is only moderately reliable at best.¹²⁻¹⁷ If post-concussion signs and symptoms can be better detected, symptom resolution and recovery may be better identified. This may subsequently reduce the risk of recurrent concussion and associated sequelae by allowing adequate recovery before returning to participation in sport.¹⁸

The current cornerstone of concussion management involves both physical and cognitive rest until symptoms subside, followed by a progressive exertional program prior to medical clearance and full return to participation.¹⁹ This progressive exertional

program includes light aerobic exercise, sport-specific exercise, non-contact drills, and concluding with full-contact practice, requiring the athlete to maximally exert themselves before returning to play without reoccurrence of symptoms.¹⁹ This protocol reflects the neurometabolic and overall physiological dysfunction evidence found following the pathological mechanism of a concussion.²⁰ Following a concussion, symptoms are typically reported to subside within 5 – 7 days, yet neurometabolic alterations may persist in the brain for up to 10 days post-injury or longer.^{17, 21} Further, recent evidence suggests that symptoms, cognition, and balance all resolve independently and complete resolution may not occur for at least 30 days post-injury.^{17, 22, 23}

In a healthy population, exercise has been shown to not only increase symptom scores, but also to impair postural stability.²⁴⁻²⁶ Symptom scores can be influenced by the intensity and fatigue accompanied by exercise, with symptom scores being normally elevated between 3 and 16 points post-exercise in healthy individuals.²⁶ Acute fatigue following exercise has been shown to impair static postural control 10-15 minutes postexercise.²⁴ High intensity exercise has resulted in significant deterioration in both static and dynamic balance, with dynamic balance appearing to resolve after 15 minutes of rest.²⁷ These effects observed in healthy individuals may possibly be intensified in a concussed population.

Animal experiments have shown premature exercise following a concussion impairs cognitive performance.²⁸ Athletes participating in high levels of physical activity following a concussion have exhibited decreased reaction time, visual motor speed, visual memory, and verbal memory scores on neuropsychological values.²⁹

Cognitive impairments on verbal memory composite scores have been observed in concussed athletes following a maximal exercise test as measured by the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) testing protocol.³⁰ Following moderate physical exertion, concussed student-athletes have demonstrated cognitive decline on ImPACT despite acquiring symptom-free status and baseline ImPACT values at rest.³¹

Performing complex high-velocity movements while maintaining dynamic restraint, characteristic of athletic activity, requires muscle pre-activation and reflex contractions via feed-forward processing.^{11, 32} Ultimately, the cerebral cortex is responsible for planning and regulating these motor control processes.³³ Some athletes suffering non-contact ACL injuries have retrospectively demonstrated decreased baseline neurocognitive performance in all areas compared to controls.¹¹ Athletes demonstrating decreased postural control, reaction time and proprioceptive awareness, also characteristic of concussions, may potentially have an increased likelihood of suffering sports-related injury if not treated properly. The conundrum of hasty return-to-play following a concussion now becomes two-fold: the risk of recurrent concussion and the potential risk of other injuries.

The central nervous system is a vital component in dynamic balance through its integration of sensory and motor pathways to coordinate postural and intentional movements during locomotion.³⁴⁻³⁶ Various physiological impairments in the sensory and motor systems may alter normal balance function and these motor disabilities may increase the vulnerability to recurring concussions.^{18, 34-36} Athletes experiencing

concussions demonstrate acute balance deficits which is likely the result of damage of the peripheral receptors providing inappropriate kinesthetic feedback or a sensory integration problem between the visual, vestibular and somatosensory systems.^{16, 37} Concussed athletes presenting with initial static postural instability typically return to their baseline levels within three to five days.^{17, 37, 38} However, multiple studies have indicated delayed recovery, well exceeding 3 – 5 days, suggesting more sensitive measures of postural control are required.

One measure of dynamic postural stability is gait variability, defined as the fluctuation in gait characteristics between steps.³⁹ During level over ground walking in healthy adults, gait variability is low and generally consistent over time, with normal stride time gait variability reported as usually below 3% among young healthy adults.⁴⁰⁻⁴⁴ An increased variability in step width, length and time has been suggested to reflect impairments in the postural control system.⁴⁵⁻⁴⁷ An insult to the central nervous system may reduce the ability to perform a repetitive pattern of movements, thus increasing gait variability.⁴⁸ Changes in gait variability have been observed in a wide variety of populations with neuro-degenerative disorders, including elderly fallers, older frail adults, Parkinsons disease, Alzheimer's disease, post-stroke victims, and those suffering from moderate to severe traumatic brain injury.^{45, 49-53} Further, increased gait variability has been associated with increased challenges during walking, such as increasing gait speed or walking with the eyes closed.⁵⁴ Since a concussion is a brain disturbance and has been linked to motor cortex inhibition, it may be beneficial to also examine gait variability following a concussion.^{55, 56}

Following a concussion, symptoms typically resolve within 5-7 days, yet the body remains in a state of reduced cerebral blood flow and glucose levels for up to 10 days post-injury. Once symptoms have resolved, the Fourth International Consensus Statement on Concussion in Sport recommends completing a progressive exertional program before full return to play.¹⁹ Concussion recovery curves have been examined with exercise and found to exacerbate symptoms and decrease neuropsychological values;²⁵ however, how this exertional phase of the return to play process affects dynamic postural control remains unknown. Therefore, the purpose of this study was to examine the influence of the initiation of a graded exercise program on dynamic postural control following a concussion. We hypothesized that asymptomatic concussed athletes would demonstrate changes in dynamic postural control via gait variability with the initiation of a graded exercise protocol as compared to uninjured control participants, whom we expected to display relative consistency across the testing period.

CHAPTER 2

Methods

Participants

We recruited nine student-athletes from an NCAA Division I university who recently suffered a diagnosed concussion, as well as nine physically active control participants. (Appendix C: Table 1) The inclusion criteria for the experimental group included student-athletes diagnosed with a concussion by the institution's medical staff and followed the institution-specific progressive return-to-play protocol. The control group consisted of nine participants matched to the concussion group that fit the American College of Sports Medicine (ACSM) criteria of a physically active population, defined by participating in moderate-intensity aerobic activity for a minimum of 30 minutes per day on five days each week or vigorous-intensity aerobic activity for a minimum of 20 minutes per day on three days each week.⁵⁷ Participants in the experimental group were excluded if they were currently suffering from a lower extremity injury, or any neurological pathology that would negatively affect postural control, including vestibular, metabolic, and balance disorders. The exclusion criteria for participation in the control group included a self-reported lower extremity injury in the previous 3 months, self-reported concussion history, or any self-reported neurological pathology that would negatively affect postural control, including vestibular and metabolic disorders. All participants provided written informed consent prior to participation, approved by the university's institutional review board.

Instrumentation

Participants performed the walking trials along a 7.9 meter instrumented GAITRite walkway (Gaitrite, CIR Systems Inc., Clifton, NJ) which is valid and reliable for examining spatial and temporal gait parameters in adults.^{58, 59} Demographic data including height, weight, and leg length was recorded for each participant prior to the first testing session. Height and weight was assessed for each participant using a standard physician eye level scale (Detecto Scale, Missouri) and recorded in centimeters and kilograms. Leg length was measured from the anterior superior iliac spine to the medial malleolus of the ankle for each participant.

The initial day of exercise for all participants was on a stationary bike (StairMaster Stratus 3900 RC) housed in the Athletic Training facilities of the university. The second day of exercise for all participants in this study was on an elliptical trainer (Precor EFX 544) housed in the Athletic Training facilities of the university.

Procedures

All participants in the study reported to the biomechanics laboratory on the day of testing and completed a brief health history form to confirm they met the inclusion criteria for the study. (Appendix C; Figure 1) Control participants also completed an ACSM Par-Q questionnaire to ensure each met the criteria for a physically active population as defined by the ACSM.⁵⁷ (Appendix C; Figure 2) Each testing session consisted of practice trials for comfort with the testing protocol, followed by ten walking

trials along the instrumented GAITRite walkway at a self-selected “normal pace,” and ten walking trials of a self-selected “fast pace.” Normal pace was defined to the participants as how they would normally walk during everyday activity. Fast pace was defined to the participants as the speed they would walk if they were late to class or to an important meeting. The initial (Baseline) testing session occurred when the athlete begins intercollegiate athletic competition in conjunction with the pre-participation physical examination. The second testing session (Day 1) for the concussion group occurred within 24 hours of the concussive event. In order for the individual to be tested again, the athlete must have achieved symptom-free status as measured by a Graded Symptom Checklist, and must have achieved values that met or exceeded those recorded at baseline on both the BESS testing and the SAC. The third testing session (Pre-Exercise Day) was the day before the participant began the exercise protocol, and the fourth session (Exercise Day 1) was the day the participant began the exercise protocol, which was the next consecutive day after Pre-Exercise Day. On Exercise Day 1, the participant was tested after the completion of the first return-to-play workout on a stationary bike, which lasted 10 to 15 minutes. After a rest period of 10 minutes, walking trials were performed. On Exercise Day 2, the participants were tested after the completion of a 15-20 minute workout on an elliptical trainer, and a brief rest period of 10 minutes was observed before performing the walking trials.

Participants in the control group were recruited based on matching criteria to the concussion group. For the first three testing sessions (Baseline, Day 1 and Pre-Exercise), the control subjects only completed normal activities of daily living, and did not exercise

that day. Participants in the control group were required to refrain from exercising during the same time period as their match in the concussion group. For example, if concussion subject 2 took five days to self-report being asymptomatic, then the match in the control group refrained from exercising for five days as well. For the fourth testing period (Exercise Day 1), control subjects completed the first workout of the exercise protocol followed by a ten minute period of rest, then performed the walking trials. For the fifth and final testing session (Exercise Day 2), control participants completed the second workout of the exercise protocol, followed by a period of rest and the walking trials.

Participants completed the trials barefoot, beginning by standing quietly on the force platforms. (Appendix C; Figure 3) Participants initiated movement in response to a verbal cue at a self-selected pace and continued down the 7.9m GaitRITE walkway, stopping 2-3 steps past the end of the walkway. Practice walking trials were performed to ensure the participant's familiarity and comfort with the procedure prior to data collection. Ten trials of self-selected, "normal paced" gait as well as ten trials of "fast paced" walking were collected for each participant. Any partial footfalls that did not have a clearly defined beginning and ending, or were in contact with the edge of the mat were edited out of data collection.

Data Analysis

This study was a prospective longitudinal study, performed over 5 different testing days (Baseline, Day 1, Pre-Exercise, Exercise Day 1, and Exercise Day 2).

Independent variables of interest included groups (concussion, control) and test dates. The dependent variables of interest included the variability of step length, step width, and step time. Step length was measured as the distance traveled between the heel strike of one limb to the heel strike of the opposite limb.⁶⁰ Step width was measured as the displacement in the frontal plane between the line of progression and the heel location of the contralateral foot.⁶⁰ Step time was measured as the time elapsed between the heel strike of one foot to the heel strike of the contralateral foot.⁶⁰ Gait variability measures were expressed as a coefficient of variation (CoV),⁴⁸ which is:

$$\text{CoV} = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100$$

Descriptive means were also recorded for step velocity, stride length, heel-to-heel base of support, stance time percentage, double support percentage, step length, step time, and step width.

Statistical Analysis

Descriptive statistics were calculated for height, weight, and age for all subjects. Descriptive means were also reported for group and day on the following variables: step velocity, stride length, heel-to-heel base of support, stance time percentage, double support percentage, step length, step time, and step width. The mean of the ten normal paced and ten fast paced walking trials for each individual were calculated for each dependent variable. Six 2x5 (group x day) ANOVAs were performed to test the

dependent variables of interest for this study: step length variability, step width variability, and step time variability. Repeated contrasts were performed as a follow-up if there was a significant day effect. The alpha level was set at $p < .01$ a-priori to have a more conservative estimate of significance given the number of statistical tests examined. All statistical testing was completed using SPSS 17.0 for Windows (Chicago, Illinois).

CHAPTER 3

RESULTS

All participants completed all trials of normal and fast speed walking without incident or difficulty, and demographics were recorded for each participant. (Appendix C; Table 1) Descriptive means and standard deviations were calculated for step velocity, stride length, heel-to-heel base of support, stance percentage, double support percentage, step length, step time and step width. (Appendix C; Tables 2 and 3)

For normal speed, a 2x5 (group x day) ANOVA displayed no significant interaction between the groups for step length ($F=.690$, $p=.526$), step time ($F=.750$, $p=.562$), or step width ($F=1.360$, $p=.271$) variability across the testing days. (Appendix C; Figures 4-6) There was no main effect for testing session for step length ($F=.100$, $p=.925$), step time ($F=.594$, $p=.669$), or step width ($F=.238$, $p=.808$) variability. Test of between-subjects effects found a significant difference between the groups for step length variability ($F=9.748$, $p=.007$), with the concussion group averaging 3.26 (SD .98) and the controls measuring 2.48 (SD .375). There was no significant difference found for step time ($F=5.940$, $p=.027$) or step width ($F=3.742$, $p=.071$) variability between the two groups.

For fast speed, a 2x5 (group x day) ANOVA displayed no significant interaction between the groups for step length ($F=.818$, $p=.518$), step time ($F=.316$, $p=.866$), or step width ($F=.439$, $p=.780$) variability across the testing days. (Appendix C; Figures 7-9) There was no main effect for testing session for step length ($F=2.130$, $p=.087$), step time ($F=.288$, $p=.884$), or step width ($F=2.795$, $p=.033$) variability. Test of between-subjects

effects found no significant differences for step length ($F=.802$, $p=.384$), step time ($F=3.705$, $p=.072$) or step width ($F=.291$, $p=.597$) variability between the two groups.

CHAPTER 4

DISCUSSION

Current post-concussion assessment tools may lack sensitivity in identifying recovery and those who demonstrate impaired postural control may have an increased likelihood of suffering further sports-related injury.⁶¹⁻⁶⁴ Exercise disturbs static postural stability and may increase symptom scores in healthy individuals, yet current post-concussion assessments are only administered at rest and dynamic postural stability is not currently a widely practiced concussion assessment tool. This study examines the hypothesis that the initiation of exercise may increase gait variability following a concussion. The main finding of this study was that the initiation of a graded exercise program did not significantly affect gait variability post-concussion. This finding is encouraging, suggesting that athletes appear to show adequate recovery from a concussion once the graded exercise protocol begins as compared to healthy controls.

There were no significant changes in gait variability observed post-concussion or in response to initiating exercise. Gait variability changes have been observed in moderate to severe traumatic brain injuries, so we would expect sports-related concussions to show similar, perhaps more subtle differences between baseline and initial post-injury testing.^{47, 48, 54, 60, 65-67} Changes in gait variability have been observed in individuals with central nervous system impairments, specifically cerebral palsy, Parkinson's disease, Alzheimer's, traumatic brain injury, and post-stroke.^{41, 43, 45, 48-54, 60,}

^{66, 68-72} Most literature to-date has been cross-sectional in nature and either in children or elderly adults which limits extrapolation of the data in this study. Children with severe traumatic brain injury have exhibited an estimated 8% in step length variability, 4% in step time variability, and 3% in step width variability as compared to typically developed children.^{48, 60, 65} These findings formed the foundation of this study as gait variability was expected to be sensitive in identifying postural control impairments post-concussion.^{39, 42, 48, 60, 65} A study in healthy young adults reported normal gait velocity to be 1.3 m/s and normal stride time gait variability to be around 1.8%.⁷³ Stride time gait variability was reported as an average of 2.8% across testing sessions in the concussed group and 2.4% in the control group; however, the current study examined step time variability instead. Direct comparisons between these two groups cannot be made due to the dissimilar dependent variables studied.

Children post-severe traumatic brain injury have shown increased step length and step time variability following a 6 minute treadmill walking exercise intervention, with a 1.3% increase in step length variability and a 2.8% increase in step time variability as compared to typically developed children.⁶⁶ It is important to note that the typically developed children displayed an overall decrease, following the treadmill training, in step length variability by 1.8% and step time variability by 1.4%.⁶⁶ The decrease observed in the typically developed controls is likely attributed to the fixed treadmill rate, stimulating “automatism control” of the central nervous system in which movement motor routine is recruited, a response generated by central pattern generators.⁶⁶ It would be expected that gait variability would also display impairments in response to exercise in post-concussive

athletes. A few athletes displayed increased gait variability following a concussion both initially and after initiating exercise, with more pronounced alterations being observed at faster speeds by an increase in both step length and step time variability. It is important to note that every concussion has a unique presentation, and whereas postural instability is a common concussion symptom, this deficiency is not always manifested in the post-concussive state. The changes observed in gait variability measures were relatively small and not exhibited in every participant and therefore not statistically significant in the final analysis.

The neurophysiological mechanisms that control gait are complex and current literature presents conflicting arguments.⁷⁴⁻⁸⁵ The rhythmic and cyclic aspect of gait is generally accepted to be controlled by the central pattern generators of the spinal cord; however this is debated by dynamic systems analysis.⁷⁴⁻⁷⁶ The spinal cord neural circuits are capable of generating a rhythmic motor pattern, yet supraspinal centers are involved in the planning and execution of the initiation and termination of gait.^{74, 77-85} Bernstein's principle of initiative states that input for gait must be a function of intrinsic input and initiative coordinated with reactions and adjustments from external stimuli.^{75, 86} Therefore, coordination and control must coexist in human gait, allowing for active movement generation and adjustments for coordination and control in response to environmental demands.⁷⁵

Neuropsychological testing following fatiguing exercise post-concussion has identified impairments in verbal and visual memory.^{30, 31, 74-76} In previous studies, neuropsychological testing has been examined following moderate (60-80% HR)

cardiovascular exercise in post-concussive athletes who demonstrated cognitive decline despite acquiring baseline ImPACT values and symptom-free status at rest.³¹ These athletes exhibited decreased verbal and visual memory performance, thought to be attributed to fatigue, yet these subjects observed a 5-10 minute rest period before beginning neurocognitive testing.³¹ ImPACT has also been examined immediately following supramaximal exercise in healthy athletes and found deficits in verbal memory composite scores likely due to difficulty focusing on the first sub-test administered after the exertional protocol was completed.³⁰ Observed postural control alterations in healthy adults have been following more strenuous cardiovascular exercise than the exercise intervention employed by this study, which could possibly explain the larger changes seen in other studies.^{24, 27, 87} These studies had athletes exert themselves between 75% of age-predicted maximum heart rate and exhaustion, yet the current study encouraged participants to exercise below 70% of maximum heart rate as recommended by the 4th CIS.¹⁹

Impairments in gait characteristics have been observed following sport-related concussion.^{18, 88-95} In longitudinal post-concussion studies, concussed athletes have demonstrated increased stride time and step width as well as a decrease in overall gait velocity and stride length, yet these studies did not include pre-injury data.^{18, 88-92} One study revealed apparent recovery of gait characteristics at day 6, yet showed a recurrence of impairments at days 14 and 28.⁹¹ While an exact mechanism for these recurrent impairments was not presented, it is possible they were associated with return to participation. Subtle changes were observed in our descriptive data reported initially

post-concussion for normal and fast speeds, with greater changes being exhibited at fast speeds. Concussion subjects also exhibited these same changes following the initiation of exercise, whereas the control group did not. It would be interesting to see if these changes reported in the descriptive data would potentially show significance between the two groups.

There was no statistical analysis performed on our descriptive data to examine potential relationships between gait velocity and gait variability. Gait velocity and variability tends to exhibit a U-shaped response curve, in which higher variability is exhibited during both increased and decreased walking speeds compared to preferred speed.^{44,96} In older adults, a meaningful change in step length variability has been reported as 0.25cm.⁹⁷ If this value is applied to the experimental group in this study, the average change between baseline and post injury assessments were meaningful with a 0.45cm increase in fast speed as compared to a 0.11cm increase in the control group. No meaningful changes were observed between pre and post exercise. This finding, although not statistically significant in this study, suggests that gait variability may potentially be sensitive in identifying impairments in dynamic postural control following a mild traumatic brain injury.

Limitations

This study utilized healthy physically active young adults as control participants, as opposed to NCAA Division I intercollegiate athletes, due to the requirement of

physical activity cessation involved in this study. This may hereby limit the extrapolation of the results due to the differing nature of physical activity in the two groups, yet each group regularly participated in physical activity at a relatively high intensity. Despite employing cardiovascular exercise as the primary intervention in this study, no physical measurement of exertion was taken such as rate of perceived exertion (RPE), VO₂ max or RHR. The inherent time elapsed since the baseline and initial post-concussion assessment was larger in the concussion group compared to control participants. In an effort to minimize this limitation, two participants were used in the control group that had baseline gait data in our database. Gait and gait variability have been demonstrated to be fairly consistent over time, and therefore this limitation is considered minimal.⁴⁰⁻⁴³ On occasion, the recommended rest period was not completely observed in the concussed participants due to time constraints of impending intercollegiate obligations such as practice or team meetings, which is almost an innate limitation of a clinical study. Another possible limitation of data extrapolation from this study is the amount of steps used per trial, which averaged between 5 and 8. Previous studies have recommended a continuous walking protocol of over 30 steps in order to achieve adequate reliability.⁷⁰ In this study, we used 10 trials per speed for each testing session, which would average more than the recommended 30 steps. In an effort to minimize this limitation, the principal investigator attempted to minimize the time between trials, only allowing enough time for the subject to turn around and face the walkway before beginning the next trial in response to a verbal cue.

There were 54 total concussions in the university database over three years of collection, yet only nine subjects were used for this study. Four participants dropped out of the study, 5 were missing data from one or more testing sessions of interest, and 36 participants were missing baseline data. If baseline data was not used in this study, 19 more participants could have potentially been utilized. Other gait variability studies have utilized 15-29 subjects, whereas gait studies have utilized 6-14 subjects following concussion.^{44, 47, 48, 53, 54, 60, 65, 66, 70, 18, 92}

Future studies

This study opens the opportunity for numerous follow-up studies. Future studies on this topic should include a larger sample size; other populations have shown sample sizes between 15 and 25 for each group in gait variability measures.^{47, 48, 54, 60, 65, 66, 70} It would be a potentially interesting study to compare gait variability measures to static postural stability assessments such as the BESS testing protocol scores, and also neurocognitive scores such as ImPACT. The 4th CIS stresses the importance of employing a multifaceted concussion assessment, and comparing assessment tools could direct future concussion management recommendations.¹⁹ The 4th CIS also recommends a graduated return-to-play protocol progressing from light aerobic exercise to sport-specific exercise, and non-contact training drills before fully returning to participation. Examining concussed individuals at each phase of the return-to-play process could

potentially show lingering impairments in post-concussive symptoms that are no longer expressed at rest.

Conclusions

In conclusion, the participants in the current study appear to have sufficient compensatory strategies to minimize gait variability following a concussion and in response to exercise. Extrapolation of this data is limited because of the small sample size, and that the dependent variables of interest were not sensitive in detecting the presence of a concussion. Therefore this study cannot conclude that post-concussive athletes are adequately healed at the time the graded return-to-play protocol begins, and should be studied further to ensure athletes are returning at a safe rate to competition.

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APPENDIX A

RESEARCH HYPOTHESES, DELIMITATIONS, ASSUMPTIONS

Research question

- Do concussed athletes exhibit changes in dynamic postural stability following the initiation of a graded return-to-play exercise protocol as compared to a control group?

Hypotheses

- Null hypotheses
 - There will be no significant interactions between concussed and control participants on any testing day for step length gait variability of normal walking speed.
 - There will be no significant interactions between concussed and control participants on any testing day for step time gait variability of normal walking speed.
 - There will be no significant interactions between concussed and control participants on any testing day for step width gait variability of normal walking speed.
 - There will be no significant interactions between concussed and control participants on any testing day for step length gait variability of fast walking speed.
 - There will be no significant interactions between concussed and control participants on any testing day for step time gait variability of fast walking speed.
 - There will be no significant interactions between concussed and control participants on any testing day for step width gait variability of fast walking speed.
- Alternate (real) hypotheses
 - There will be a significant interactions between concussed and control participants for step length gait variability of normal walking speed.
 - There will be a significant interaction between concussed and control participants for step time gait variability of normal walking speed.

- There will be a significant interaction between concussed and control participants for step width gait variability of normal walking speed.
- There will be a significant interaction between concussed and control participants for step length gait variability of fast walking speed.
- There will be a significant interaction between concussed and control participants for step time gait variability of fast walking speed.
- There will be a significant interaction between concussed and control participants for step width gait variability of fast walking speed.

Limitations

- Only athletes at one university
- Utilization of physically active control subjects instead of intercollegiate athletes
- Inherent variation of days elapsed between baseline and initial post-injury testing
- Rest period after exercise in concussion subjects
- No physical measurement of exertion (RPE, VO₂ max, etc.)

Delimitations

- Control subjects with no known history of:
 - Known neurological, metabolic, or vestibular disorders
 - Recent lower extremity injury
- Only Division I intercollegiate athletes & physically active controls at one university
- Only athletes that we can have all relevant, accurate data from & follow RTP protocol

Assumptions

- Participants will perform as best they can
- Participants will not take meds, consume alcohol, etc. that affect testing
- Participants will accurately report history
- Control subjects will not participate in physical activity outside of study during study period

APPENDIX B

REVIEW OF LITERATURE

Concussions are commonly defined as a complex pathophysiological process, induced by traumatic biomechanical forces, usually resultant of an acceleration or deceleration injury of the head.^{98,99} The first definition of a concussion was made in the 10th century when Rhazes defined a concussion as an abnormal physiological state.¹⁰⁰ Every attempt made to define a concussion has been debated and scrutinized since the original; however, this has also led to a deeper understanding of the specific pathological processes that occur as a result of a concussion.

Neurobehavioral abnormalities occur as a result of a concussion, but the pathophysiologic cascade has only recently begun to be studied in humans.²¹ The pathophysiologic cascade of a concussion is a complex sequential process.²¹ The brain suffers a biomechanical insult, which depolarizes the neurons resulting in action potentials.²¹ Then an ionic shift occurs in which there is a massive efflux of potassium,²¹ arguably where loss of consciousness (LOC) occurs. The membrane ionic pumps (sodium and potassium) increase their activity in order to restore homeostasis.²¹ This step alone only occurs for a total of 30 to 60 minutes, yet it takes hours or days to recover.²¹ Next, hyperglycolysis starts to generate more ATP in order to supply the energy demands of the sodium-potassium pump, triggering a cellular energy crisis when combined with the calamity of diminished cerebral blood flow.²¹ Magnesium levels are further depleted, causing impairment of the glycolytic and oxidative ATP generation. Lactate accumulation occurs as a result of the increased utilization of anaerobic

metabolism.²¹ The brain normally functions between 95 to 98% aerobically, yet during the neurometabolic cascade it begins to function anaerobically because the brain needs additional energy.²¹ Concurrently, there is a calcium influx and sequestration in the mitochondria that leads to impaired oxidative metabolism, which taints the mitochondria and reduces the aerobic capacity of the cells.²¹ The decrease in the ATP consequently impairs brain function.²¹ The brain is now in a state of glycolytic energy crisis, in which there is a decreased ATP production aerobically.²¹ Finally, calpain is activated, initiating apoptosis in which the cell voluntarily dies in order to get rid of some of the exorbitant amount of calcium.²¹ The calcium influx also causes engorgement and crushing of the neurofilaments resulting in axonal injury.²¹ Cerebral blood flow, which is coupled to neuronal activity and cerebral glucose metabolism, is decreased during this time to between fifty and eighty percent of homeostatic levels, which further impairs this complicated process.²¹ These physiological changes in the brain have not yet been definitively linked to any specific symptoms in human subjects.

There are an estimated 1.6 – 3.8 million concussions that occur annually in the United States.¹ In regards to all injuries, concussions account for around 5% of injuries in high school and college football⁹⁹ and 10% in total reported injuries.¹⁰¹ More conservative estimates of annual concussion incidence are around 300,000 annually, based solely on LOC.¹⁰² Normal LOC rate associated with concussion ranges from 8% to 19.2%.¹ One study estimates around 60% of high school seniors have suffered at least one concussion.¹⁴ Differences have been found between collegiate and high school football concerning the overall injury rate: 11.5% of high school injuries were head and face, and 8.2% of collegiate injuries involved the head and face.¹⁰³ Of these head and

face injuries, 96.1% were concussions.¹⁰³ Another study found a concussion rate of 5.6% in high school, 5.5% in Division III, 4.5% in Division II, and 4.4% in Division I football.⁹⁹ Including other sports, concussion rates average from 5.5 to 5.9% in overall high school and collegiate athletes.^{104, 105} It has been suggested that there may be a higher rate of concussion in collegiate athletics, yet concussions comprise more injuries sustained overall in high school athletics.¹⁰²

A common mechanism of injury for concussions is direct contact to the head, including helmet-to-helmet contact typically observed in football. Guskiewicz found the average number of helmet impacts was 27.7 during a competitive collegiate football season.¹⁰⁶ He also found the typical concussive force to be at least 60g to 80g with a mean magnitude of 102.8g in a sample of collegiate football players, with one “g” being the normal force of gravity at 9.8 newtons of force per kilogram of mass.¹⁰⁶ Of interest, he discovered that lower magnitude impacts resulted in slightly higher symptom scores within the initial 48 hours post-impact as compared to baseline.¹⁰⁶ This same sample was determined to be 6.5 times more likely to sustain an impact succeeding 80g to the top of the head than the sides of the head.¹⁰⁶

Pellman conducted the National Football League concussion studies from 1996 to 2001, reconstructing NFL game head impacts. He found an elevated range for concussion in the NFL as compared to Guskiewicz’s collegiate study, around 70 to 75g.¹⁰⁷ With his data, he was able to describe a typical concussive impact in American professional football. The average impact is 9.3 m/s, head linear acceleration of 98g, head velocity change of 7.2 m/s, a peak rotational acceleration of around 6423 rad/s, and

a duration of 15 milliseconds.¹⁰⁷ Of note, the duration of the impact is the key factor in the biomechanics of helmet impacts. To put this in perspective, car crashes can be used as a collateral example. Typical automobile collisions with an unmovable structure, such as a wall, last around 6 milliseconds on average.¹⁰⁷ The use of an airbag can sustain this impact over a duration of 40 milliseconds, decreasing the risk of injury from the forces.¹⁰⁷ The fact that a typical helmet impact is sustained over a longer period of time underlies the reason why humans can sustain these large amplitude forces to the head, whereas they would be easily killed with the same impact during a car crash.

There are certain symptomatic hallmarks of concussion: loss of consciousness, headache, confusion, fatigue, unsteadiness, blurred vision, dizziness, and nausea.^{2, 14, 99, 102, 108, 109} Headache is the most commonly reported symptom following a concussion, with around 90% of patients presenting with this symptom.^{2, 14, 99, 102, 109} Around 6% of concussions result in LOC, and does not appear to be associated with the number of symptoms reported nor the overall duration of symptoms.^{2, 14, 17} Amnesia rates following a concussion are between 19% and 24%, and seem to be the biggest symptom predictor of concussion outcome.^{2, 14, 17} Symptoms alone are only 68% sensitive in the diagnosis of concussion.¹³

Symptoms are usually presented up through 5 days post injury, and normally resolve within 7 days of the onset of the concussion.¹⁷ Cognitive impairment presents the most significantly within the first 2 days, and usually resolves within 7 days of the concussion onset.¹⁷ ImPACT output scores have shown to return to baseline an average

of 7 days post injury in collegiate athletes.¹¹⁰ Balance deficits are the highest in the first 24 hours and typically return to baseline in 5 days.¹⁷

Athletes have been found to be three times more likely to sustain a concussion after receiving their first,⁹⁹ although other studies have found up to 6 times relative risk.¹¹¹ Football players have been found to be 5.8 times more likely to suffer from a concussion if they have a history of concussions within the last 5 years.¹⁰¹ The main risks associated with repeat concussion are “slowed clinical recovery characterized by persistent symptoms or functional impairments and extremely rare instances of death or severe, permanent disability associated with delayed cerebral swelling¹⁰.” The window of time for a repeat concussion has not been clearly defined, yet persistent glucose uptake decreases have been found in humans two to four weeks after injury, and ongoing axonal damage has been reported weeks later as well.²¹ As many as 80 to 92% of repeat concussions occurred within the first 10 days of the initial injury.^{2, 10}

One concussion tool for neurocognitive assessment today is ImPACT (Immediate Post Concussion Assessment and Cognitive Testing), used in high schools and colleges around the country. This is a computer based test that measures aspects of neurocognitive function, as well as administers a 22-item symptom assessment employing a 6 point Likert scale and collects demographic information.¹¹² ImPACT output variables include memory, processing speed, reaction time, and impulse control.¹¹² There are 5 subtests within the memory domain: verbal learning and recognition memory, visual working memory and recognition, visual associative memory, and letter memory.¹¹² IMPACT has been shown to be 62.5% sensitive to the presence of a

concussion when used alone, and 79.2% accurate in diagnosis when used in combination with a symptom score.¹³ Significant correlations have been found between symptom reports and ImPACT outcome variables.¹¹³ “Feeling mentally foggy” has been correlated to reaction times, “difficulty concentrating” has correlated with verbal memory score, and “difficulty remembering” has closely mirrored verbal memory score and reaction time.¹¹³

When measured with the ImPACT assessment battery, 38% of concussed athletes had decreased test performance as compared to baseline values, yet they denied experiencing any concussion-related symptoms.¹¹⁴ Another concussed sample population showed neurocognitive impairment 3 days after they reported being asymptomatic.¹¹⁵ Therefore, it has been recommended that the athlete must report asymptomatic status before post-concussion assessments such as ImPACT are administered, reducing the potential practice effect.¹¹⁴

Motor function control of the body involves a complex interaction of higher brain centers and spinal reflexes, synced with impeccable timing. The initial motivational step for any voluntary movement of the body takes place in the subcortical and cortical areas and is sent to the cortex association areas.¹¹⁶ In these association areas, a design for the movement is planned from subroutines already stored in the brain. Next, this rough draft is sent to the cerebellum and basal ganglia, where the movement plan actually becomes an executable spatial and temporal excitation program.¹¹⁷ The basal ganglia is mostly involved in slow, deliberate movements whereas the cerebellum is thought to be more involved with fast movements.¹¹⁸ This motor program is sent through the thalamus into the motor cortex, which reflects the message to the spinal neurons.¹¹⁹ The spinal neurons

take the message from the motor program and “fine tune” it with the help of feedback from the efferent pathways’ muscle receptors and proprioceptors, finally sending the motor program command to the skeletal muscle for execution via the afferent pathways.¹¹⁸ Balance is one complex constant motor program being executed in the body, involving both feed-forward and feedback mechanisms.

Balance is the process of maintaining the body’s center of gravity within the base of support, and is an essential component to athletes for adequate performance in their respective sports.¹⁵ Dynamic postural control is the ability to tolerate separation of COM and COP while transitioning from static to dynamic tasks.¹²⁰ A complex network of neuronal connections and centers related by peripheral and central feedback mechanisms control balance.¹⁵ The visual, somatosensory, and vestibular systems are regulated and coordinated by the central nervous system (CNS) in order to maintain postural equilibrium.¹⁶ The information is collected from the sensors in the three systems, and then feedback is sent from the CNS to contract the necessary muscles in order to maintain stability.¹⁶ The CNS usually only relies on one sense at a time for this orientation, and somatosensory information seems to be preferred in the healthy population.¹⁶ There are two constituents to the CNS’ balance control: sensory organization and muscle coordination.¹⁶ In sensory organization, information is obtained from the three aforementioned systems in order to determine amplitude, timing, and direction of corrective postural actions.¹⁶ The muscle coordination component determines temporal sequencing and distribution of contractile activity in the leg and trunk musculature in order to generate adequate reactions to maintain balance.¹⁶ Active muscular control and

visual-vestibular feedback are essential in stabilization of lateral balance due to its sensitivity to intrinsic perturbations.⁸⁸

There is an anatomical hierarchy involved with balance control. The involved structure of utmost importance in these feedback mechanisms is probably the cerebellum, since it receives information from the whole body.¹⁶ The hierarchy begins with the areas of the brain engaged with attention, memory, concentration, and emotion, followed by the association cortex that correlates this concoction of information.¹⁶ Next, the sensorimotor cortex, cerebellum, brainstem nuclei, and basal ganglia form two reflexive arc pathways: afferent and efferent.¹⁶ The afferent pathways constitute postural reflexes, receiving information from the eyes, vestibular apparatus, and proprioceptors.¹⁶ Alpha motor neurons of the skeletal muscles and the integrative neuronal networks in the brainstem and spinal cord compose the efferent pathways.¹⁶ Balance is achieved by the complex integration and cooperation of all structures involved in the aforementioned hierarchy.

The central nervous system is vital in dynamic balance control through its integration of sensory and motor pathways in order for the body to coordinate postural and intentional movements during locomotion.³⁴⁻³⁶ Various physiological impairments in the sensory and motor systems may alter normal balance function.^{2, 34, 106} Damage to peripheral receptors or the brain centers responsible for integration of the three systems (visual, vestibular, and somatosensory) may lead to postural instability following a concussion.^{15, 37}

Concussions produce functional neurophysiologic changes in the brain cortex and the reticular formation of the brainstem, explaining the autonomic, motor, and postural depreciation apparent with a concussion.¹⁶ It has been shown that balance problems manifest in clinical diagnosis 30% of the time following a concussion with current measurement techniques.¹⁶ Acute balance deficits are likely the result of ineffective usage of the vestibular and visual systems.³⁷ It has been suggested that the vestibular system is the most affected sensory system following a concussion, due to either damage of the peripheral receptors consequently providing inaccurate motion senses, or impairment of the brain centers engaged with the integration of visual, vestibular, and somatosensory information.¹⁶

It has been documented that postural control assessments are 62% sensitive in diagnosis when used alone.¹³ When postural stability testing is used in combination with self-reported symptoms and computerized neuropsychological testing, the assessment battery becomes over 90% sensitive in the diagnosis of a concussion.¹²¹ When used alone, self-reported symptoms and computerized neuropsychological testing are 68% and 79% sensitive, respectively.¹²¹ Moderate relationships have been found between balance and reporting symptoms of “dizziness” and “balance problems.”¹¹³ There are many different tools used to gauge balance within the concussion assessment battery.

An expensive tool used on occasion for balance assessment is the Sensory Organization Test (SOT) used in combination with the NeuroCom Smart Balance Master. This technical force plate system costing over \$60,000 measures the subject’s ability to maintain a quiet stance while altering orientation information available to the

somatosensory or visual inputs, therefore disrupting the sensory selection process.¹⁶ There are 6 testing conditions involved with the SOT, comprised of a combination of 3 visual conditions (eyes open, eyes closed, sway referenced) and 2 surface conditions (fixed, sway referenced).¹⁶ Sway referencing refers to the support surface tilting or visual surround following the subject's center of gravity sway, in which the subject must keep their support constant.¹⁶ This tool can evaluate the ability of the subject to discard the sway references' false information.¹⁶ The subject's peak sway amplitude is compared to the theoretical limit of stability, expressed as a percentage.¹⁶ Each sensory system involvement is identified by finding the relative differences between the various conditions via a ratio.¹⁶

A dual-task paradigm is another option in assessment of balance with the SOT implementation. The SOT has been used for a motor task in combination with a visual or verbal cognitive task, which divides the subjects' attention.²³ The body follows a "posture first" principle in which the allocation of attentional resources is increased with the simultaneous increase in postural task difficulty.¹²¹ In testing, increases in response times and errors have been demonstrated in accordance with the increasing difficulty of the balance task.¹²¹ With an auditory task, longer response times were observed with dual task than single task conditions following a concussion.¹²¹ Catena found that level walking in accordance with a verbal cognitive task was sensitive in distinguishing concussions immediately post-injury.⁹³ A reduced sagittal plane movement of the body's center of mass (COM) was observed, suggesting a conservative gait pattern.⁹³ By day 6, it appeared as if the concussed subjects had returned to baseline, yet at day 14 they exhibited conservative control of mediolateral COM when presented with an obstacle

crossing task.⁹³ Slobounov found visual-kinesthetic disintegration up to 30 days after the onset of injury with a second cerebral concussion, experiencing motion sickness and dizziness at days 10 and 17 even though they were asymptomatic by day 10.¹²² It appears as though the increasing difficulty of a cognitive task results in decreased performance of a motor task.

The most commonly used tool assess static balance in the suspected concussed population is the BESS, which stands for Balance Error Scoring System. The BESS was developed by researchers at the University of North Carolina at Chapel Hill, and only necessitates the use of a stop watch and a piece of medium-density foam.¹⁶ This is a test comprised of 20-second trials of 3 different stances, which are double leg, single leg, and tandem stances. Each stance trial is performed on a firm surface, and repeated on a foam or unstable surface. The trials are performed with the eyes closed and the hands on the iliac crests. In the single leg stance trials, the non-weight bearing limb must be kept in 20 to 30 degrees of hip flexion and between 40 and 50 degrees of knee flexion.¹⁶ The non-dominant foot is used as the stance leg for the single limb trials, and is placed in the rear position during the tandem stance trials. With this test, the aim is to have the lowest score possible, since a point is assigned to each error. Possible errors include: lifting the hands off the iliac crests, opening of the eyes, stepping, stumbling, falling, moving the hip into more than 30 degrees of abduction or flexion, lifting the heel or the forefoot, and remaining out of the testing position longer than 5 seconds.¹² The maximum score allowed for each test is 10.¹⁶ If the subject is unable to remain in the stance position for longer than 5 seconds during the 20-second trial, then the trial is considered incomplete and assigned a maximum error score.¹⁶

The BESS has been shown to be moderately reliable, with an interrater reliability of .60 to .92 and an intrarater reliability of .57 to .85 using intraclass correlation coefficients.¹²³ When BESS is administered by the same tester it has been shown to be a more sensitive test for concussion diagnosis, with the firm single leg (.88), firm tandem (.77), and foam double leg (.83) being the most reliable stances.¹² Another study modified the BESS protocol and found that removing the double leg stance for both the foam and firm surfaces increases the reliability from .60 to .71,¹²⁴ suggesting the usage of a modified BESS testing protocol. It can be concluded that a minimum detectable change of 7.3 points is required to detect a postural stability change when the same tester is scoring the complete BESS test, and a subject must have a 9.3 point change in the complete BESS test when different testers are administering the test in order to detect an actual change.¹² Overall, the complete BESS protocol has been shown to have moderate to good reliability, and is considered today to be one of the cornerstones of concussion assessment.¹²³

The concussed population has shown significantly more errors post-injury on the BESS testing as compared to control groups, creating construct validity within the population of interest.¹²³ Broglio conducted a study on the concussion battery as a whole and found the BESS to be 61.9% sensitive in the diagnosis of a concussion when used alone.¹³ Concussed subjects typically return to baseline values within 3 to 5 days, with the foam surfaces requiring the most time.¹²³ There is an effect of fatigue on BESS scores. Postural control remains altered for 8 to 13 minutes post exercise compared to baseline with both aerobic and anaerobic regimens.¹²³ The BESS assessment does not discriminate between concussed athletes with and without the presence of a headache.¹²³

Researchers at Old Dominion University put their collegiate baseball team through the BESS test in a controlled environment (the locker room) and an uncontrolled environment (sideline), finding impaired performance in the sideline environment.¹²⁵ The argument was presented was the increased external stimuli influenced the attentional control of the athlete, creating a subconscious dual-task situation.¹²⁵ Considering the fact that postural instability clinically manifests itself more significantly with increasing attentional demands, it is not surprising that these athletes showed impaired BESS scores while in an uncontrolled environment. Therefore, testing environment should always be considered with the administration of post-concussion assessment tools, especially those concerning balance.

Balance impairments have been shown to resolve within 3 to 10 days after injury.¹⁶ More specifically, athletes have demonstrated sensory interaction and balance deficits with the SOT that resolve normally within 3 to 5 days post-concussive injury.¹⁶ On the BESS, concussed college football players have an average of 5.7 point change from baseline values following injury, returning to baseline within 3 to 7 days.¹⁶ This shows the BESS protocol requires a large scale change in order to determine significance in this test. In this same study, 24% remained impaired on day 2, and 9% were still impaired at the day 7 mark post-injury.¹⁶ Concerning the dual-task testing, one study found an abnormal response to visual field motion at day 30, despite symptoms and neuropsychological assessment parameters had already returned to baseline.²³ Another study combined neuropsychological testing and gait, finding significant differences with dual-task responses at day 28, but not with single task or neuropsychological testing alone.⁹¹

Force plate transducers are an expensive, yet very precise tool available for balance testing. Force plates measure ground reaction forces, which are produced when the body's center of mass moves around a fixed base of support.²⁴ Common variables examined during force plate analysis include center of pressure sway velocity and elliptical sway area.²⁴ Center of pressure sway velocity refers to the average velocity that the center of pressure moves within the base of support.²⁴ The elliptical sway area is comprised of an area that contains 95% of the center of pressure data points, which are contained within the axes of an ellipse.²⁴ Center of mass motion and dynamic motor assessments have been deemed as sensitive measures to assess gait stability in the incidence of concussion.⁹¹ Center of mass motion and center of pressure interaction during gait can precisely identify conservative gait characteristics and quantitatively assesses gait instability.¹⁸

A groundbreaking force plate study combined with a motion analysis parameter found that concussed individual as well as athletes participating in contact sports tend to reduce sagittal plane movement in hopes of controlling increased coronal plane sway in maintenance of balance.⁸⁸ Athletes, regardless of their concussion status, demonstrated faster sway velocity, greater sway excursion, decreased gait velocity, and allowed less separation between center of mass and center of pressure before the subsequent step as compared to non-athletes.⁸⁸ The dual task conditions of the study exacerbated the differences, and were apparent from day 2 to day 28.⁸⁸ Concussed individuals, athlete and non-athlete alike, were found to have reduced anterior center of mass velocity and displacement, increased sway, and increased sway velocity during gait.⁸⁸ Another study found significant increases in coronal plane center of mass motion in concussed

individuals.¹⁸ These changes are all reflective of diminished dynamic postural control, giving the assessment of dynamic postural control some validity for concussion research.

During gait, the displacement between COM and COP projection increases with changes in body position, diminishing the subject's stability and compels active postural control to bring the COM to a stable position within the base of support.⁸⁴ More active postural control must be expended as the COM-COP displacement increases, and those with impairments, such as stroke and Parkinson's, tend to reduce this distance during transitional movement, in hopes of reducing the demand for active postural control.⁸⁴ Persons with Parkinson's disease and stroke victims have demonstrated conservative gait strategies through extended movement preparation, diminished initial loading of the swing limb, reduction in propulsive forces, reduced step length and velocity, and less effective uncoupling of the COP and COM during gait initiation.^{82, 84, 126, 127} Transcranial magnetic stimulation has been used to identify a longer cortical silent period in those that have a history of concussions relative to controls via perturbation of the motor cortex.⁵⁵ The prolonged cortical silent period may also be linked to decreased reaction time and coordination, which could affect muscular contraction timing, requiring a longer time for postural corrections.^{18, 92} Both the displacement between COM and COP as well as the prolonged cortical silent period must be taken into consideration when evaluating postural control impairments.

Gait variability is another technique used to measure postural stability, defined as the fluctuation in gait characteristics between steps.³⁹ During level over ground walking in healthy adults, gait variability is low and gait characteristics are generally consistent

over time. Observational gait analysis has been found to be inaccurate and have a high variability in assessing gait variables in examining those with traumatic brain injury, with observer inaccuracy ranging from thirty to fifty percent.⁶⁷ Therefore, an objective assessment of gait is necessary for use in clinical practice. The Gaitrite system is a pressure sensitive electronic walkway that automates the collection of spatiotemporal gait parameters.⁴⁷ This system has been found to be valid in examining gait parameters both adults and children.^{58,59} Gait variability has been shown to provide a sensitive assessment of the neuromotor performance reflective of walking impairments and may therefore be used as a quantifiable marker to assess impaired motor performance.^{53,128}

The control of balance during walking is maintained by controlling swing limb placement both spatially and temporally, which is the fundamental reason why dynamic postural stability should be measured by examining step pattern variability.^{54,129,130} An increased variability in step width, length and time may reflect instability in the postural control system.⁴⁵⁻⁴⁷ Gait variability has therefore been suggested to predict motor disability.⁶⁹ Changes in gait variability have been observed in a wide variety of populations with neuro-degenerative disorders, including elderly fallers, older frail adults, Parkinsons disease, Alzheimer's disease, post-stroke victims, and those suffering from moderate to severe traumatic brain injury.^{45,49-53}

An insult to the central nervous system may reduce the ability to perform a repetitive pattern of movements, thus increasing gait variability.⁴⁸ Central nervous system impairments, such as cognitive functioning and motor performance, have demonstrated increased stance time variability.⁶⁹ Furthermore, decreased step width variability has been related to sensory and balance impairments during walking.^{49,69}

Following a stroke, increased gait variability has been observed and attributed to poor dynamic balance, considering step-to-step variation in one leg can be counterbalanced by the other leg in order to maintain steady-state walking.⁵³ Those with stroke also demonstrate an overall slower gait velocity.⁵³

Step variability typically increases when step velocity decreases.⁴⁷ Typically older frail adults exhibit decreased gait velocity, a common predictor of falls. The variability of gait parameters is more closely related to the risk of falls than average gait velocity, step or stride length, or step or stride time.⁴⁵ Increased gait variability has been linked to balance impairments that lead to falls.⁷¹ Stride width variability is reduced in slower walkers, and this variability reduction has been shown to predict falls.^{46, 49, 52} This population tends to walk with wide strides to provide a wider base of support for center of mass lateral motion, and also show reduced foot placement variability to ensure consistently wide steps – all indicative of a compensatory mechanism employed in order to maintain postural stability.⁵³

Increased gait variability has also been associated with increased challenges during walking, such as increasing gait speed or walking with the eyes closed.⁵⁴ Step length variability increases in the absence of visual input to guide foot placement, which suggests the visual contribution to dynamic stability is essential.⁵⁴ Variability increases at speeds that are faster or slower than the preferred walking speed.¹³¹ Step time variability significantly increases with fast walking, a challenge to postural stability due to diminished double support coupled with an increased duration of the COM being outside the base of support.¹³²

Children with more severe traumatic brain injury have demonstrated decreased balance performance, decreased gait speed and increased step length variability.⁶⁵ Children post-TBI also suffer from impaired attention, thought to be a causal factor for the decreased gait speed and increased step pattern variability characteristically observed in this population, and is also demonstrated in children with attention deficit hyperactivity disorder (ADHD).^{65, 133} These findings suggest that increased variability in physical function is indicative of neurological compromise since stride dynamics are dependant on neural control and neural maturation.⁶⁵ Since gait variability (GV) has shown sensitivity in identifying deficits in TBI, it may be beneficial to also examine GV following a mild TBI.

The researchers at the University of Oregon have conducted multiple studies on dynamic motor function following concussion. They have found that medial-lateral sway and sway velocity is greater in concussed individuals up to 28 days after injury when presented with a dual-task challenge of walking and performing a cognitive task.⁸⁹ In these same time frames, they found gait velocity to be diminished, as well a decrease in the separation distance between the COM and COP in concussed subjects.⁹⁰ Another study by this group found concussed individuals to have a diminished gait velocity and less COM to COP separation with a dual-task paradigm compared with a single task across the 28 day testing session span.⁹¹ The same study found weak relationships between neuropsychological testing from ImPACT and variables in the gait analysis, suggesting that motor and cognitive function recover at different rates.⁹¹ Yet another study found a slower, more conservative gait strategy in concussed individuals, who exhibited significantly faster center of motion velocity and center of motion sway in the

coronal plane.¹⁸ These concussed individuals increased their COM deviation by 13% during the dual task portion of the study and were 26% more deviated than the control subjects, which demonstrates significant gait instability.¹⁸ The effort to reduce the center of mass forward momentum in order to manipulate spatial/temporal and sagittal plane motion during the gait cycle indicated a diminished ability to sustain gait stability in concussed subjects.¹⁸ The argument was presented that this dual-task difficulty observed in concussed individuals were due to one of two options: a decrease in processing capacity of attention, or an increase in required locomotor information processing.¹⁸ Both of the options presented support the finding that concussions tend to diminishes the capacity of information processing for some time post injury.¹⁸

A case study was performed in Canada with a concussed 18 year old junior hockey player, specifically examining gait parameters and neuropsychological measures.²² The athlete was documented as having a mild, or “simple concussion,” and followed a return to play protocol allowing him back to full participation at day 7 post-injury.²² The gait analysis involved walking down an unobstructed or obstructed walkway, with or without a visual interference task.²² This case study found even though the athlete had no symptoms and neuropsychological testing values comparable to baseline, his locomotor navigational abilities were still impaired at 30 days post-injury,²² consistent with other studies finding these same impairments in asymptomatic patients.^{93,}¹²² The athlete diminished his gait velocity and decreased his obstruction clearance during circumvention.²² It is thought that gait velocity decreases in order to maintain a safe parameter of postural control when presented with an additional task, such as obstacle crossing.

Performing complex high-velocity movements while maintaining dynamic restraint characteristic of athletic activity requires muscle pre-activation and reflex contractions via feed-forward processing.^{11,32} Ultimately, the cerebral cortex is responsible for planning and regulating these motor control processes.³³ Athletes suffering non-contact ACL injuries have demonstrated decreased baseline neurocognitive performance in all areas compared to controls.¹¹ Animal experiments have shown premature exercise following a concussion impairs cognitive performance.²⁸ Those participating in high levels of physical activity following a concussion have exhibited decreased reaction time, visual motor speed, visual memory, and verbal memory scores on neuropsychological values.²⁹ Athletes demonstrating decreased postural control, reaction time and proprioceptive awareness characteristic of concussions may have an increased likelihood of suffering additional sports-related injuries if the concussion is not treated properly.

Athletes must be asymptomatic following a concussion before being allowed to return to play. The term asymptomatic has not yet been clearly defined in the world of sports medicine, due to the state-dependent nature of symptoms. Symptoms can vary with the time and day of measurement, emotional status and anxiety, attitude, motivation, honesty, and willingness of the individual who is reporting the symptoms.²⁶ A conservative criterion value for Symptom Severity Score has been proposed as 5 or less for males and 6 or less for females.²⁶ Multiple studies have been performed in the healthy population and have found that exercise increases symptom scores, as discussed earlier.

The University of Pittsburgh conducted a study aiming to find correlations between post-concussive activity levels, symptoms, and neurocognitive performance.²⁹ They found that athletes engaging in the highest activity levels had the worst average visual memory scores and reaction times.²⁹ They also found subjects participating in intermediate levels of activity had the best overall neurocognitive test scores and fastest reaction times.²⁹ This intermediate level of activity was defined as school activities and light activity at home, such as sweeping the sidewalk or mowing the lawn.²⁹ These findings supported and helped to form a basis for the current recommendations concerning return to participation following the incidence of concussion. Current recommendations stress that the athlete should remain asymptomatic with exercise for their activity resumption, and state that “if any post-concussion symptoms occur while in the stepwise program, the patient should drop back to the previous asymptomatic level.”⁹⁸

The current clinical cornerstone of concussion management involves both physical and cognitive rest until symptoms subside, followed by a progressive exertional program prior to medical clearance and full return to participation.⁹⁸ This progressive exertional program recommends beginning with light aerobic exercise, then progressing to sport-specific exercise, non-contact drills, and concluding with a full-contact practice before fully returning to competition.⁹⁸ It is suggested that athletes progress through one stage every 24 hours, and digress to the previous step should any symptoms occur during the particular stage of the exertional protocol.²⁵ A progressive protocol such as the aforementioned recommendations by the Third International Consensus Statement in Sport requires the athlete to maximally exert themselves before returning to full competitive play without reoccurrence of symptoms.²⁵

One challenge of medical professionals today is the readiness of athletes to return to play following a concussion. The Balke protocol treadmill test has been shown to identify symptom exacerbation with 99% sensitivity and 89% specificity for ruling out concussion symptoms following a concussion.²⁵ This test is performed with a fixed speed on a treadmill, and increases incline every minute until the participant reaches exhaustion, or in this case symptom exacerbation.²⁵ Interestingly enough, the concussed participants in this study had variability in heart rates and blood pressure responses attributed to ongoing physiologic dysfunction characteristic of post-concussion syndrome.²⁰ This test is the first that provides objective physiological evidence as to an athlete's readiness to return to play following a concussion, since all current concussion assessments typically terminate in the early stages of the exertional protocol, if not before the protocol begins completely.²⁵

The neurometabolic cascade may be influenced by exercise. To restore homeostasis in the cascade, sodium and potassium membrane pumps are activated which increase glucose usage.²¹ Cerebral blood flow is coupled to neuronal activity and cerebral glucose metabolism, and following a concussion this blood flow is reduced to between fifty and eighty percent.²¹ After the initial period of hyperglycolysis following a concussion, cerebral blood glucose use decreases by 24 hours post injury, and remains suppressed in animals for 5-10 days.²¹ This glucose imbalance may explain the presence of postural stability deficits following a concussion.³⁷ During a concussive impact, the rapid deceleration of the head may cause the shearing forces to disrupt the axon, affecting the ability to transfer information to the areas of the brain responsible for balance. The presence of decreased attention and concentration following a concussion exacerbates

postural stability decrements.⁸⁹ During the cascade, low magnesium levels have also been found, which maintain the cellular membrane potential and initiates protein synthesis.²¹ The subdued magnesium levels impair the glycolytic and oxidative ATP generation. The levels allow unblocking of the NMDA receptor channel, which leads to a greater calcium influx and subsequent lactate accumulation.²¹ Exercise elevates lactic levels in the body as a result of the glycolytic and oxidative productions of ATP, which could possibly exacerbate this neurometabolic enigma.

In conclusion, a concussion is a complex pathophysiological condition following a neurometabolic cascade of events. Concussions are prevalent in sport and are marked by symptoms such as headache, confusion, dizziness, loss of consciousness, and amnesia. Concussed individuals will acutely exhibit decreased performance on neuropsychological measures and balance parameters following a concussion. Cognitive and motor function seem to recover at different rates, therefore multiple concussion assessment tools are necessary in order to adequately evaluate an individual. Also, concussion assessment tools become more sensitive to diagnosis when used together, further supporting the recommendation for a multifactorial approach in the diagnosis of concussion. Gait variability is a sensitive measure in assessing gait stability for those with higher-level gait disorders, and may increase concussion assessment sensitivity since it is a dynamic screening tool. Current return to play guidelines stress the concussed athlete must be asymptomatic at rest and with activity in order to return to full sport participation. Gait stability may alter concussion return-to-play protocols due to the ability to identify lingering concussion symptoms that current insensitive assessment measures may not.

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APPENDIX C

TABLES AND FIGURES

TABLE 1. Participant Demographics by Group

	Controls	Concussions
Height (cm)	161.74 ± 12.98	173.62 ± 9.32
Weight (kg)	77.31 ± 19.98	85.66 ± 24.68
Age (yrs)*	22.78 ± 1.99	19.44 ± 1.33
Days Elapsed	163.55 ± 328.26	377.44 ± 240.53

A significant difference was found between the groups for age ($p=0.001$). No significant differences were found between the groups for height ($p=0.04$), weight ($p=0.44$), or days elapsed ($p=0.14$).

FIGURE 1. Participant Health History Questionnaire

Subject Initials: _____ Subject ID # _____
(First MI Last)

Initial Date of Testing: ____/____/____

A. Demographics

Date of Birth: ____/____/____ Sport: _____ Age: _____

Gender: _____ Height: _____ Weight: _____

Year in School (circle one): Freshman Sophomore Junior Senior Grad Student

B. Injury History

(1) Have you ever been diagnosed with a concussion? YES NO

If YES, how many?: _____

If YES, when did your last one occur?: _____

If YES, did you ever blackout/lose consciousness?: _____

(2) Have you ever suffered an injury to either foot, ankle, leg or knee? YES NO

If YES, please describe: _____

(3) Have you ever had surgery on either foot, ankle, leg, or knee? YES NO

If YES, please describe: _____

(4) Do you have balance disorders? YES NO

If YES, please describe: _____

(5) Do you have diagnosed with a metabolic disorder? YES NO

If YES, please describe: _____

(6) Do you have been diagnosed with a neurological disorder? YES NO

If YES, please describe: _____

(7) Do you have been diagnosed with a vestibular disorder? YES NO

If YES, please describe: _____

(8) Are you currently taking any medications? YES NO

If YES, please describe: _____

FIGURE 2. Supplemental Physical Activity Questionnaire (Control Participants Only)

1995 NHIS Year 2000 Objectives Supplement---Con. (18 years and over)
 [Monitored progress toward Healthy People 2000 National Health Objectives]

Part E — PHYSICAL ACTIVITY AND FITNESS — Continued				
NOTE: ASK ALL OF 2a BEFORE GOING TO 2b-d		NOTE: ASK 2b-d FOR EACH ACTIVITY MARKED "YES" IN 2a		
HAND CALENDAR				
2a. In the past 2 weeks (outlined on that calendar), beginning Monday, [date], and ending this past Sunday, [date], have YOU done any (of the following exercises, sports, or physically active hobbies) —		b. How many times in the past 2 weeks did you (go/do) (activity in 2a)?		
YES NO		c. On the average, about how many minutes did you actually spend (doing) (activity in 2a) each time?		
		d. What usually happened to your heart rate or breathing when you (did/went) (activity in 2a)? Did you have a small, moderate, or large increase, or no increase at all in your heart rate or breathing?		
(1) Walking for exercise?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(1) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(2) Gardening or yard work?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(2) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(3) Stretching exercises?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(3) _____ Times	_____ Minutes (next activity)	
(4) Weightlifting or other exercises to increase muscle strength?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(4) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(5) Jogging or running?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(5) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(6) Aerobics or aerobic dancing?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(6) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(7) Riding a bicycle or exercise bike?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(7) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(8) Stair climbing for exercise?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(8) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(9) Swimming for exercise?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(9) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(10) Playing tennis?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(10) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(11) Playing golf?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(11) _____ Times		
(12) Bowling?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(12) _____ Times		
(13) Playing baseball or softball?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(13) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(14) Playing handball, racquetball, or squash?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(14) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(15) Skiing? <input type="checkbox"/> Yes <input type="checkbox"/> No (16)		(a) _____ Times (next activity)		
(a) Downhill?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(b) _____ Times		1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(b) Cross-country?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(c) _____ Times		
(c) Water?	1 <input type="checkbox"/> 2 <input type="checkbox"/>			
(16) Playing basketball?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(16) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(17) Playing volleyball?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(17) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(18) Playing soccer?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(18) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(19) Playing football?	1 <input type="checkbox"/> 2 <input type="checkbox"/>	(19) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(20) Have you done any (other) exercise, sports, or physically active hobbies in the past 2 weeks?				
1 <input type="checkbox"/> Yes—What were they? 2 <input type="checkbox"/> No				
Anything else?				
If activity listed above, mark "Yes" for it; otherwise, specify ^β				
(a) _____	_____	(20a) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK
(b) _____	_____	(20b) _____ Times	_____ Minutes	1 <input type="checkbox"/> Small 3 <input type="checkbox"/> Large 2 <input type="checkbox"/> Moderate 0 <input type="checkbox"/> No inc. 9 <input type="checkbox"/> DK

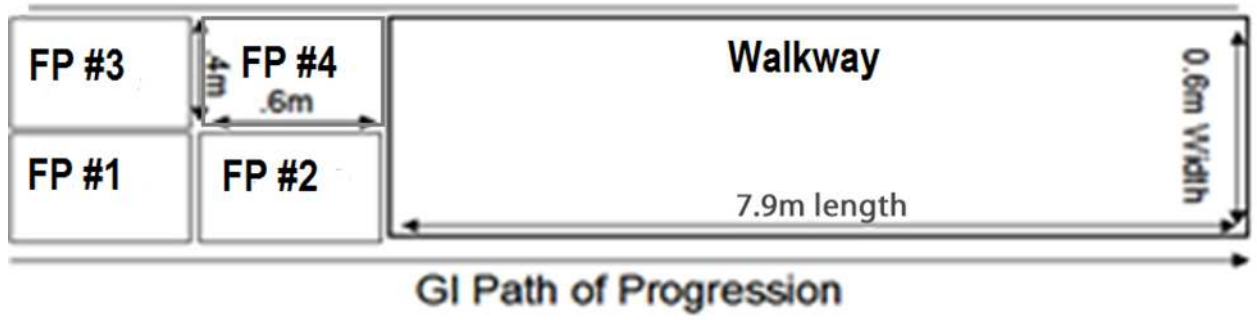


FIGURE 3 – Layout of the Biomechanics Laboratory

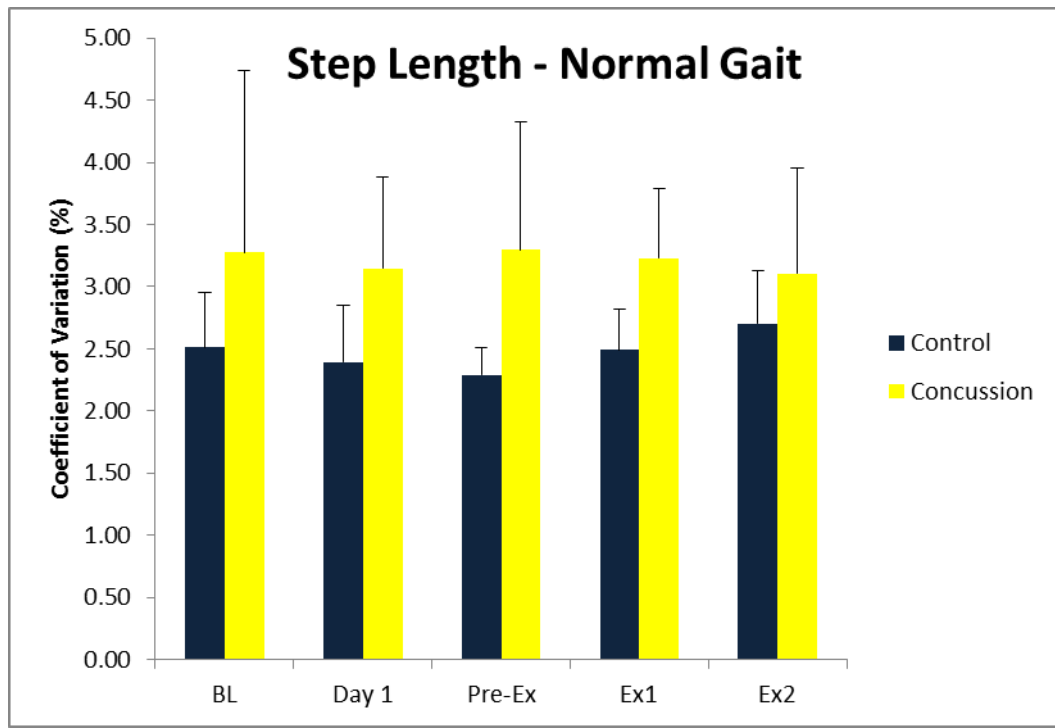
TABLE 2. Normal Speed Descriptives

	Baseline	Day 1	Pre-Exercise	Exercise 1	Exercise 2
Step Velocity (Control)	1.31 ± 0.2	1.36 ± 0.1	1.33 ± 0.1	1.33 ± 0.1	1.35 ± 0.1
(Concussions)	1.34 ± 0.2	1.22 ± 0.1	1.35 ± 0.1	1.34 ± 0.1	1.34 ± 0.1
Stride Length	136.14 ± 11.1	137.12 ± 9.8	136.54 ± 6.5	137.65 ± 8.9	135.76 ± 7.7
	144.81 ± 13.1	133.86 ± 10.2	141.35 ± 6.7	140.35 ± 8.1	142.47 ± 9.1
H-H Base of Support	11.71 ± 4.2	11.81 ± 3.9	11.3 ± 4.5	11.99 ± 4.8	11.82 ± 4.3
	12.76 ± 3.2	12.28 ± 2.2	12.04 ± 2.6	12.35 ± 2.5	11.89 ± 2.8
Stance %	60.98 ± 1.5	60.51 ± 1.7	60.38 ± 1.5	60.28 ± 1.8	60.48 ± 1.8
	61.32 ± 1.2	61.66 ± 1.0	61.21 ± 0.9	61.42 ± 1.2	61.12 ± 1.7
Double Support %	22.14 ± 2.8	21.14 ± 3.2	20.86 ± 2.8	20.63 ± 3.3	21.02 ± 3.4
	22.77 ± 2.4	23.42 ± 1.8	22.65 ± 1.7	22.89 ± 2.2	22.46 ± 3.3
Step Length	68 ± 5.5	68.49 ± 4.8	68.2 ± 3.2	68.77 ± 4.4	67.85 ± 3.9
	72.2 ± 6.6	66.84 ± 5.1	70.54 ± 3.3	70.05 ± 4.04	71.07 ± 4.5
Step Time	0.52 ± 0.03	0.51 ± 0.02	0.51 ± 0.02	0.51 ± 0.02	0.51 ± 0.02
	0.54 ± 0.04	0.55 ± 0.04	0.52 ± 0.04	0.53 ± 0.04	0.51 ± 0.1
Step Width	69.39 ± 5.3	69.87 ± 4.4	69.56 ± 2.9	70.24 ± 3.7	69.20 ± 3.3
	74.17 ± 6.0	68.39 ± 5.1	72.01 ± 3.0	71.52 ± 4.1	72.55 ± 4.4

TABLE 3. Fast Speed Descriptives

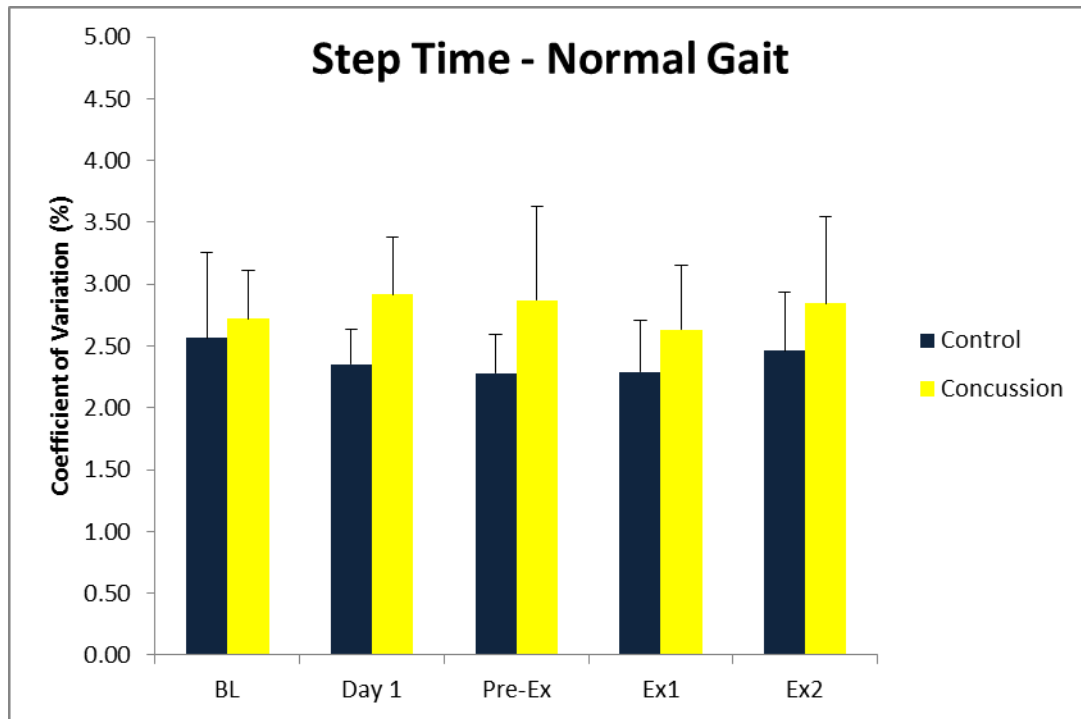
	Baseline	Day 1	Pre-Exercise	Exercise 1	Exercise 2
Step Velocity (Control)	2.01 ± 0.2	2.01 ± 0.2	1.99 ± 0.2	1.99 ± 0.2	1.99 ± 0.2
(Concussions)	1.9 ± 0.2	1.81 ± 0.3	1.96 ± 0.3	2.06 ± 0.3	2.08 ± 0.4
Stride Length	169.33 ± 8.5	166.82 ± 8.8	166.08 ± 8.8	165.83 ± 9.0	167.88 ± 8.1
	167.24 ± 17.9	150.33 ± 20.9	164.78 ± 15.8	164.2 ± 17.4	164.04 ± 15.6
H-H Base of Support	12.32 ± 4.4	12.47 ± 4.1	12.47 ± 4.3	12.48 ± 4.5	12.43 ± 3.9
	12.42 ± 3.6	13.61 ± 2.8	12.82 ± 3.0	13.33 ± 2.9	12.89 ± 3.2
Stance %	57.67 ± 0.9	57.49 ± 1.1	57.5 ± 1.2	57.32 ± 1.4	57.28 ± 1.4
	59.15 ± 1.6	60.38 ± 2.7	58.72 ± 2.2	58.91 ± 2.3	58.57 ± 2.6
Double Support %	15.33 ± 1.8	15.06 ± 2.1	15.07 ± 2.1	14.68 ± 2.7	14.64 ± 2.7
	18.27 ± 3.5	20.54 ± 5.1	17.48 ± 4.4	18.01 ± 4.6	17.22 ± 5.0
Step Length	84.46 ± 4.2	83.25 ± 4.4	83.81 ± 4.1	82.83 ± 4.5	83.86 ± 4.0
	83.48 ± 8.9	75.05 ± 10.4	82.25 ± 7.8	81.86 ± 8.7	81.89 ± 7.7
Step Time	0.41 ± 0.03	0.42 ± 0.03	0.42 ± 0.03	0.42 ± 0.03	0.42 ± 0.04
	0.46 ± 0.04	0.51 ± 0.1	0.44 ± 0.1	0.45 ± 0.1	0.43 ± 0.1
Step Width	85.67 ± 4.2	84.47 ± 4.4	84.11 ± 4.4	84.11 ± 4.3	85.00 ± 4.0
	85.76 ± 7.7	82.01 ± 8.0	84.97 ± 6.3	85.87 ± 5.8	85.84 ± 5.5

FIGURE 4. Normal Speed Step Length Variability



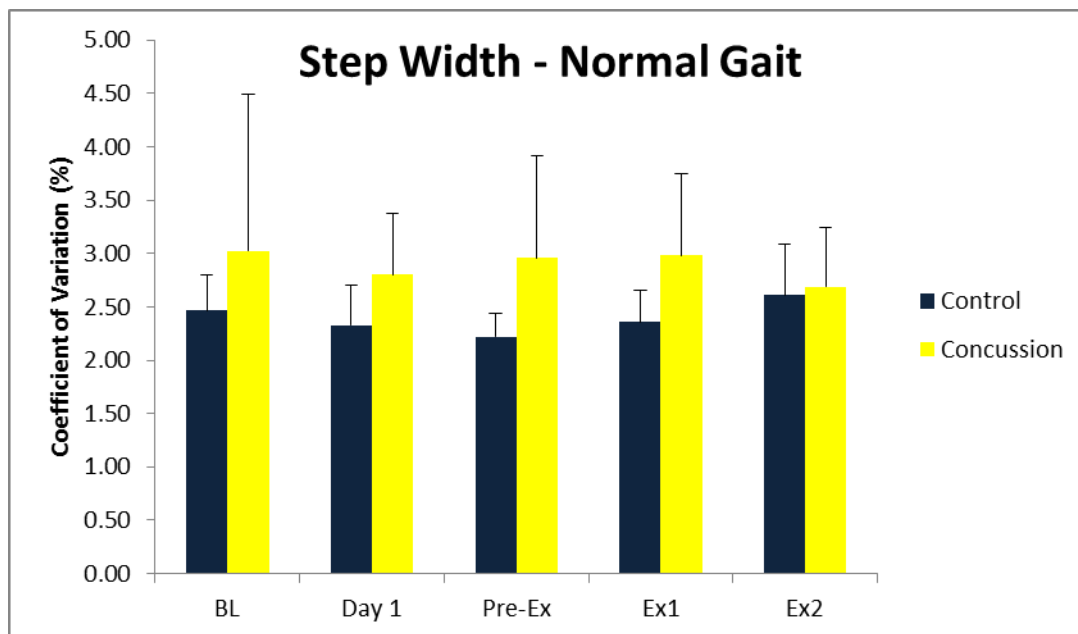
For normal speed step length gait variability, no significant interactions were found between the groups across the testing sessions ($p= 0.526$). There was also no main effect for testing session ($p= 0.925$). A significant difference was found between the groups ($p= 0.007$).

FIGURE 5. Normal Speed Step Time Variability



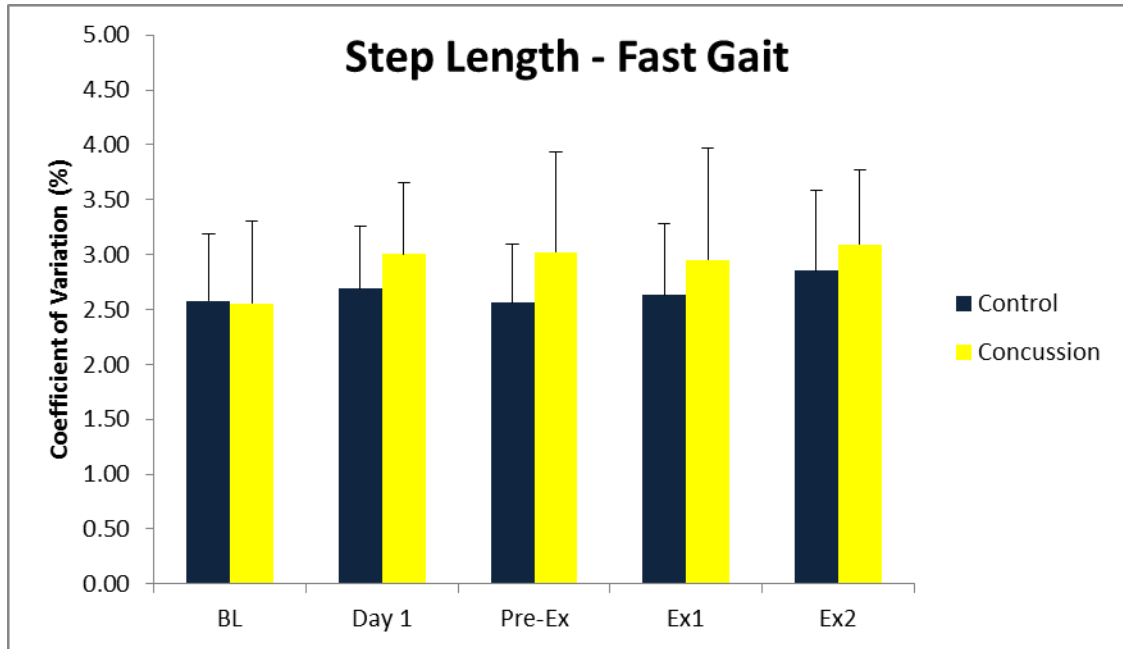
For normal speed step length gait variability, no significant interactions were found between the groups across the testing sessions ($p= 0.562$). There was also no main effect for testing session ($p= 0.669$). No significant differences were found between the groups ($p= 0.027$).

FIGURE 6. Normal Speed Step Width Variability



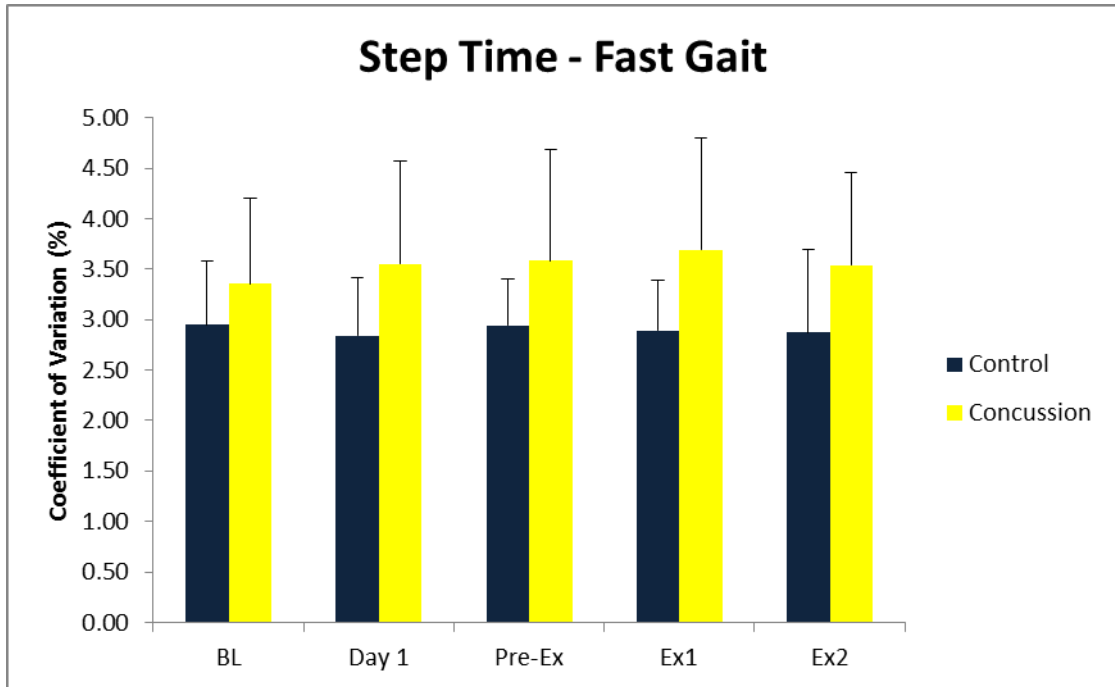
For normal speed step length gait variability, no significant interactions were found between the groups across the testing sessions ($p= 0.271$). There was also no main effect for testing session ($p= 0.808$). No significant differences were found between the groups ($p= 0.071$).

FIGURE 7. Fast Speed Step Length Variability



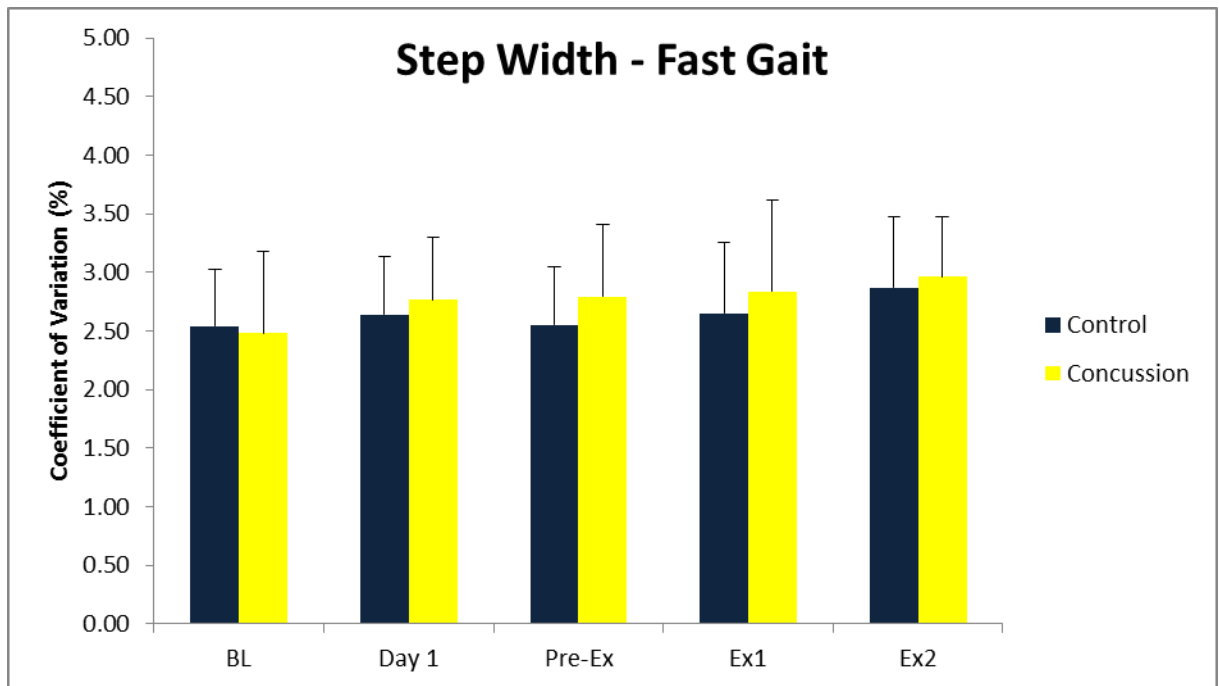
For normal speed step length gait variability, no significant interactions were found between the groups across the testing sessions ($p= 0.518$). There was also no main effect for testing session ($p= 0.087$). No significant differences were found between the groups ($p= 0.384$).

FIGURE 8. Fast Speed Step Time Variability



For normal speed step length gait variability, no significant interactions were found between the groups across the testing sessions ($p= 0.866$). There was also no main effect for testing session ($p= 0.884$). No significant differences were found between the groups ($p= 0.072$).

FIGURE 9. Fast Speed Step Width Variability



For normal speed step length gait variability, no significant interactions were found between the groups across the testing sessions ($p= 0.780$). There was also no main effect for testing session ($p= 0.033$). No significant differences were found between the groups ($p= 0.597$).