11-2023

Changes in Balance with Brain Inflammation: Sensitivity in Dual Motor Mechanisms

Hannah McDade

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Concussion assessment in athletes has gained prominence due to potential long-term consequences of traumatic brain injuries. Evaluating balance alterations is crucial for understanding post-injury motor control strategies. This study introduces a novel approach to understanding center of pressure (COP) dynamics during quiet stance tasks for assessing balance impairments in athletes recovering from concussion. Concussed athletes often experience impaired motor function and cognitive deficits, increasing the risk of orthopedic injury. Traditional balance assessments focus on total COP (COPt), overlooking nuanced hip and ankle mechanisms. This research investigates COP variations between constant loading (COPc) and variable loading (COPv) signals in concussed athletes during quiet stance. NCAA Division I athletes participated in comprehensive concussion assessments including quiet stance trials on force plates. COPc and COPv signals were analyzed for average velocity, root mean square of distance, and 95% range. Concussed athletes' data were compared to a baseline population. COPv exhibited greater sensitivity to concussion-induced balance changes compared to COPt. Bilateral stance with eyes closed on a foam surface emerged as a responsive assessment condition. Interpretation of COPv and COPc highlighted the influence of hip and ankle strategies. The findings suggest COPv analysis is valuable for assessing concussion severity and may complement existing diagnostic tools in a comprehensive evaluation. This study contributes to understanding post-concussive motor control adaptations and provides insights for improved assessment techniques.

Document Type

Masters Thesis

Degree Name

M.S.

First Advisor

Bradley Davidson

Second Advisor

Kim Gorgens

Third Advisor

Kevin Shelburne

Keywords

Traumatic brain injury, Concussion, Balance, Motor control, Center of pressure (COP)

Subject Categories

Biomechanical Engineering | Engineering | Mechanical Engineering

Publication Statement

Changes in balance with brain inflammation: Sensitivity in dual motor mechanisms

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A Thesis

Presented to

the Faculty of the Daniel Felix Ritchie School of Engineering and Computer Science

University of Denver

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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by

Hannah McDade

November 2023

Advisor: Bradley Davidson

Author: Hannah McDade
Title: Changes in balance with brain inflammation: Sensitivity in dual motor mechanisms
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Concussion assessment in athletes has gained prominence due to potential long-term consequences of traumatic brain injuries. Evaluating balance alterations is crucial for understanding post-injury motor control strategies. This study introduces a novel approach to understanding center of pressure (COP) dynamics during quiet stance tasks for assessing balance impairments in athletes recovering from concussion. Concussed athletes often experience impaired motor function and cognitive deficits, increasing the risk of orthopedic injury. Traditional balance assessments focus on total COP (COPt), overlooking nuanced hip and ankle mechanisms. This research investigates COP variations between constant loading (COPc) and variable loading (COPv) signals in concussed athletes during quiet stance. NCAA Division I athletes participated in comprehensive concussion assessments including quiet stance trials on force plates. COPc and COPv signals were analyzed for average velocity, root mean square of distance, and 95% range. Concussed athletes' data were compared to a baseline population. COPv exhibited greater sensitivity to concussion-induced balance changes compared to COPt. Bilateral stance with eyes closed on a foam surface emerged as a responsive assessment condition. Interpretation of COPv and COPc highlighted the influence of hip and ankle strategies. The findings suggest COPv analysis is valuable for assessing concussion severity and may complement existing diagnostic tools in a comprehensive evaluation. This study contributes to understanding post-concussive motor control adaptations and provides insights for improved assessment techniques.

Table of Contents

List of Figures

1 Introduction

Concussion assessment in athletes has gained significant attention in recent years due to the potential long-term implications of traumatic brain injuries. The identification and quantification of balance alterations have emerged as crucial components of concussion evaluation, offering insights into post-injury motor control strategies. Center of pressure (COP) analysis, a valuable tool in biomechanical studies, has been employed to assess balance performance in concussed athletes. This study introduces a novel approach to understanding the dynamics of COP during quiet stance tasks and investigates its potential as a sensitive indicator of balance impairments in athletes recovering from concussion.

Concussions, caused by head impact or sudden deceleration, can result in a spectrum of short term physical, emotional, and psychological symptoms (Harmon et al., 2013) and neurological deficits, including disturbances in balance control. Athletes who sustain concussions are at risk of experiencing impaired motor function, dizziness, and cognitive deficits which lead to a higher risk of lower limb orthopedic injury or repeated concussion. Timely and accurate assessment of post-concussive deficits is crucial to guide return-to-play decisions and ensure the athlete's safety. Traditional balance assessments primarily focus on total center of pressure (COPt), the location of the resultant vertical reaction force vector under the subject's feet, which only provides insight into gross motor control. This overlooks the nuanced interplay between ankle and hip based motor mechanisms, which might provide valuable insights into motor control strategies adopted by concussed individuals. Contributions from hip and ankle mechanisms are typically analyzed in perturbation tests that are too strenuous for acutely concussed patients, however, analyzing the forces and centers of pressure from two force plates in quiet stance trials may be a viable alternative.

1.1 Study Design and Objectives

The primary objective of this study was to investigate the potential of COPv and COPc analysis in differentiating alterations to motor control strategies in concussed athletes compared to a reference population of non-concussed athletes. The investigation aimed to discern patterns in COPv and COPc metrics during various quiet stance tasks and conditions. This study utilized a comprehensive concussion assessment protocol to evaluate NCAA Division I athletes from the University of Denver. The battery included instrumented standing and functional balance tasks, neurocognitive assessment, oculomotor evaluation, vestibular-ocular assessment, blood analysis, and symptom scoring. Test sessions were conducted at baseline before the commencement of the athletic season, with retesting occurring in the event of a concussion. The data collection spanned the years 2016 and 2017, following the approval of the University of Denver Institutional Review Board.

Athletes performed quiet stance trials under various conditions, including single-leg, bilateral (side-by-side), and tandem (heel-to-toe) stances. Each stance was performed on different surfaces (hard surface and foam) with eyes open and closed. Center of pressure data were collected using force platforms embedded in the laboratory floor, and the COP signals were analyzed to derive total center of pressure (COPt), constant loading center of pressure (COPc), and variable loading center of pressure (COPv) values. By unraveling the distinct contributions of loading and unloading signals, this research sought to contribute to a deeper understanding of motor control adaptations following concussion.

1.2 Thesis overview

Chapter 2 provides an overview of the current best practices for clinical assessment of sport-related concussion and what is currently known about the underlying mechanisms of balance difficulties following concussion. Chapter 3 presents the review of biomechanical measures of balance and the ankle and hip based motor mechanisms involved. Chapter 4 includes the methodology, results, and discussion of our experimental findings. Chapter 5 provides conclusions of the findings, limitations, and recommendations for future work. The appendices provide additional relevant data not included in these chapters.

2 Clinical Literature Review

2.1 Definition of Concussion

Traumatic brain injury (TBI) is defined as a change in brain resulting from mechanical energy transmission to the head from external physical forces (Alexander et al., 2007). These are caused by a bump, blow, or jolt to the head, sports injury or fall, motor vehicle accident, concussive blast, or rapid acceleration or deceleration of the brain within the skull, such as the person having been violently shaken. Concussion is commonly defined as a mild TBI (mTBI) although there is no consensus on whether this is the proper categorization (McCrory et al., 2017). The first attempt to clearly define concussion described it as a trauma induced change in mental status that may or may not include loss of consciousness. Current definitions describe the physiological brain injury resulting from the application of a force resulting in neurological impairments (Giza et al., 2013). The Center for Disease Control estimates that 1.6 to 3.8 million sports and recreation-related traumatic brain injuries (TBIs) occur each year in the U.S. and account for 5-9% of all sports related injuries (CDC website). Thirty percent of concussions in individuals between 5 and 19 years of age are sports related. The majority of concussions occurring in organized sports in the USA are sustained in football, wrestling, soccer, and basketball. For our research we have focused on field sports, court sports, swimming, and gymnastics.

2.2 Concussion in College Athletes

While the management of concussions in college athletes is well documented, the guidelines' subjectivity limits their effectiveness. The National Collegiate Athletic Association (NCAA) adopted its Concussion Policy and Legislation in 2010 (Buckley et al., 2017) which recommends that, before participation in their season, all athletes participate in a baseline assessment that includes: history of concussion or brain injury, neurologic disorder, and mental health symptoms and disorders. The athlete is given a symptom evaluation, cognitive assessment, and balance evaluation, then the team physician determines pre-participation clearance. If a concussion is suspected during the season, the student-athlete must be removed from practice or competition for evaluation by an athletic trainer or team physician including clinical assessment for cervical spine trauma, skull fracture, intercranial bleed, or other catastrophic injury, symptom assessment, physical and neurological exam, cognitive assessment, and balance exam. Post-concussion the athlete is evaluated for returning to the classroom as tolerated and a return to play schedule is determined by the team physician, after which the athlete undergoes a supervised stepwise progression from symptom-limited activity through unrestricted return to sport, typically two weeks after the concussive event.

Concussion symptoms do not always resolve quickly on their own. Returning to play too soon after sustaining a concussion increases an athlete's risk of sustaining a musculoskeletal injury or second concussion, possibly due to continued neuromuscular deficits (Smulligan et al., 2022). Post-concussion syndrome (PCS) is the persistence of signs and symptoms for weeks or months post-concussion. Psychological symptoms can include headache, dizziness, insomnia, exercise intolerance, cognitive intolerance, fatigue, and sensitivity to light and noise. Psychological symptoms may include depression, irritability, anxiety, and cognitive problems such as memory loss, poor concentration, and reduced problem solving (Harmon et al., 2013). In the long term, emerging evidence is linking mTBI to neurodegenerative diseases. A history of concussion is related to early dementia, Alzheimer's disease, violence, depression, sleep disorders, and post-traumatic stress disorder. Football players who reported three or more mTBIs had five times greater mild cognitive impairment diagnoses and three times greater reported memory problems compared to players who had no history of mTBIs. Chronic Traumatic Encephalopathy, especially in professional football players and war veterans, is tragic and horrifying.

2.3 Clinical Assessment of Concussion

Our lack of understanding of concussions (Kazl & Torres, 2019) and the variable and rapid changes in acute symptoms make concussions one of the most complex injuries to diagnose and treat (McCrory et al., 2017). Concussions are not currently visible in living subjects using known imaging techniques. As a result, researchers must rely on indirect measures of concussion symptoms to gain insight into the nature and severity of the injury. A multidomain approach to mTBI diagnosis, including clinical symptoms, cognitive testing, and physical performance, is preferred (Giza et al., 2013). For our investigation, measurements fell into five areas: subjective symptom reporting, blood biomarkers, cognitive assessment, videonystagmography (VNG), and balance kinematics and kinetics.

Self-reported concussion symptoms are a valuable but unreliable set of metrics. Symptoms are divided into four categories: Somatic (blurry vision, headache, nausea, sensitivity to light and noise, vomiting, "pressure in head"), Cognitive (feeling foggy, feeling slowed down, difficulty concentrating, and difficulty remembering), Sleep (drowsiness, fatigue, low energy, and difficulty sleeping), and Affective (feeling emotional, irritability, nervousness, sadness, depression, impulsivity, and sometimes PTSD). Because these symptoms are difficult to measure, because some subjects (specifically athletes) are incentivized to under-report their experience, and because the subject may acclimate to a "new normal" in living with lingering symptoms, these measures alone cannot be relied on to accurately diagnose the presence and severity of concussions. However, it is reasonable to hypothesize that the categories of a subject's strongest symptoms are correlated with the locations in the CNS of the damage done by the concussion.

2.4 Balance Assessment Tools

Several tests have been developed to assess balance performance. The Romberg test is intended to identify deficits in proprioception and the vestibular system. The subject stands with feet together, once with eyes open and once eyes closed. If the subject does not have difficulty in the eyes open stance but sways with eyes closed, the test is considered positive and suggests a vestibular or proprioceptive deficit (Goldberg, 2000).

This test is highly subjective (Jacobson, 2011) and the sensitivity and specificity of the test are not robust (Murray et al., 2014).

The Clinical Test of Sensory Integration in Balance (CTSIB) was designed to increase sensitivity to sensory deficits. Originally, the protocol included six standing balance tasks that block or obscure sensory information with the placement of a dome over the patient's head or by standing on a foam surface. A modified CTSIB utilizes a force platform to increase the test's objectivity. In both the original and modified protocols, balance is measured on a scale from one to four with four indicating the subject is at risk for falling. Unfortunately, the CTSIB's reliability, sensitivity, and specificity are not established in concussed athlete populations.

The Balance Error Scoring System (BESS) was designed for sport related concussion and is the most commonly used tool for sideline concussion balance testing (Guskiewicz, 2011). The BESS is a series of six 20 second trials, a single leg stance, double leg stance (side by side) and tandem stance (heel to toe), first on a hard surface and repeated on foam, all performed with eyes closed and hands on hips. The test administrator counts the number of errors the subject performs, including taking a step, opening their eyes, taking hands off the hips, hip flexion or abduction, lifting the forefoot or heel off the testing surface, and remaining out of stance for greater than five seconds. Acutely concussed athletes have a higher number of errors compared to non-concussed athletes, indicating decreased postural stability (Guskiewicz, 2011; Mccrea et al., 2003).The test lacks sensitivity, however, because substantial changes in score (9.4 points interrater or 7.3 points intrarater) are necessary before attributing changes in balance to the subject rather than the administrator (Finnoff et al., 2009). A modified BESS increases sensitivity by removing the double stance tasks and performing three trials each of the single leg and tandem tasks (Hunt et al., 2009). The total BESS has low to moderate reliability, high specificity, and low sensitivity to concussion. The sensitivity of the BESS drops to 0.07 at 1 week post-concussion (McCREA et al., 2005).

The Sensory Organization Test (SOT) increases objectivity by using dynamic force platforms. The SOT uses six conditions: three visual conditions (eyes open, eyes closed, and sway referenced) and two surfaces (fixed, sway referenced). In the sway referenced conditions, the visual field moves anterior-posteriorly in response to the subject's COP. The six conditions are used to calculate four composite scores: composite balance, somatosensory ratio, vestibular ratio, and visual ratio (Guskiewicz, 2011). Concussed athletes have lower SOT composite scores up to 5 days post-concussion compared to non-concussed athletes. Reliability, sensitivity, and specificity for the SOT have not been established in concussed athlete populations. The SOT is among the most objective clinical assessment tools available, however, it is expensive and not portable.

The Sway Balance Mobile Application (Sway Medical, Inc., Tulsa OK, USA), installed on a mobile device or tablet, uses data from the triaxial accelerometers to assess balance. The athlete presses the device against their chest and performs the stances of a modified BESS (mBESS), modified CTSIB (mCTSIB), or a customized combination of stances. A proprietary motion analysis algorithm interprets the accelerometer signals to calculate stability and provides a value on a scale of 0-100. Athletes perform a baseline assessment of balance along with a cognition test, sit to stand functionality test, and symptom survey, and are reassessed in the event of a concussion. These measures can help guide coaches and athletes in the post-concussion return to learn and return to play processes. Sway is promising as a convenient, easy to use, cost effective tool for objectively measuring balance.

2.5 Neurological Mechanisms

Our mechanical understanding of how concussions injure the brain is evolving. The traditional theory to explain the mechanism behind brain concussion is that inertial loading produces a progression of strains from the outer surface of the brain inwards towards the brain stem (Fig 1). With low inertial loading, shear strains only extend to the cortex while higher inertial loading will reach the brainstem and may result in loss of consciousness (Ommaya & Gennarelli, 1974). However, symptoms related to the brainstem have been reported in the absence of cortical systems (McCrory, 2001). The lack of consistency in structural neuroimaging results supports the hypothesis that concussion is a functional physiologic dysfunction rather than a structural lesion. Both the cortex and the brainstem are equally crucial as anatomical focus points in both low and high inertial loading concussive events (McCrory, 2001) .

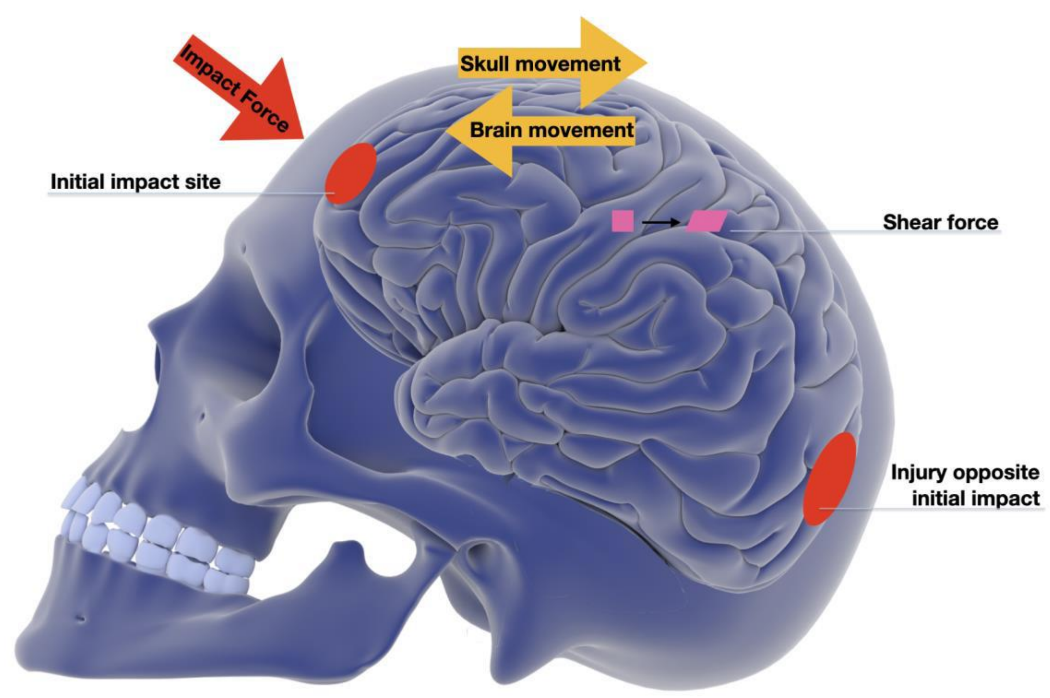

Figure 2.1 A simplified schematic demonstrating forces and injuries associated with concussion. (Pryhoda, 2020)

The study of motor control is focused on investigating the nature of movement and how movement is controlled. Motor control is defined as the ability to regulate or direct the mechanisms essential to movement (Shumway-Cook & Woollacott, 2011). It addresses how the central nervous system (CNS) receives sensory information from the environment and the body and processes it in order to organize and control many individual muscles and joints into coordinated functional movements.

2.6 Sensory inputs

Three sensory systems contribute to our balance and posture control: Visual, Vestibular, and Somatosensory. Visual sensory information is utilized in motor control in several ways. We use visual information to identify our location relative to our surroundings, especially verticality. Visual information also informs us of the motion of our head and of the location of our body parts that are in the field of view. One of the main limitations of our visual information is that it cannot distinguish between exocentric and egocentric motion (e.g., if the subject is moving or their surroundings are) (Shumway-Cook & Woollacott, 2011). Somatosensory information comes from afferent signals from muscle spindles, joint receptors, and cutaneous receptors. These signals send information about the position and motion of the body with regards to supporting surfaces and the relationship of body segments to one another. The central nervous system uses this information to build a three-dimensional model of the body in space. Somatosensory information can be ineffective if the surface under the base of support is at an incline, moving, or soft. The vestibular system receives information from the vestibular organ in the inner ear. Three roughly orthogonal, fluid filled, semicircular canals send information to the central nervous system about the position and movement of the head with regards to gravity and inertial forces. (Shumway-Cook, 2011)

2.7 Cognitive Processing

Relatively little is known regarding the neurological structures involved in balance. By examining populations with neurological disorders that co-occur with balance deficits, such as multiple sclerosis, traumatic brain injury (TBI), stroke, incomplete spinal cord injuries, and by investigating athletes with exceptional balance, researchers are able to observe structural differences in brain regions that give us some insight into what areas are critical to balance, posture, and gait. The neural control of posture is widely distributed throughout the central nervous system (CNS), specifically the cerebellum, basal ganglia and thalamus, and hippocampus.

The cerebellum plays a substantial role in regulating posture and coordination of movement. Lower gray matter volume or lesions in cerebellar lobes are associated with poorer balance and higher gray matter volume is associated with improved balance. For instance, in patients with multiple sclerosis, damage to both cerebellum and spinal cord is associated with impaired balance. With all senses available (visual, vestibular, somatosensory), deficits were related to cerebellum atrophy and lesions. However, with eyes closed, balance deficits were related to spinal cord demyelinating while lesions in the brainstem were associated with worse postural control (Prosperini et al., 2014). In children with history of TBI, reduced volume of brain stem and cerebellum were associated with poorer performance for static and dynamic postural control (Drijkoningen et al., 2015). Subjects with acute cerebellar stroke had mild to severe postural impairment and ataxia of the gate and lower limbs (Bultmann et al., 2014). Patients with incomplete spinal cord injuries had reduced white matter volume in cerebellum, medulla oblongata, and cortical thickness in primary motor cortex (Villiger et al., 2015). Recovering alcoholics have impaired postural balance associated with pathology of the anterior superior vermis of the cerebellum. Smaller anterior vermian volumes selectively correlated with longer sway paths (Sullivan et al., 2009). Meanwhile female short track speed skaters, who are required to have exceptional balance, have greater cerebellar volume (Park et al., 2018).

Basal ganglia are a group of subcortical nuclei involved in motor control, motor learning, and executive function, behavior, and emotions. Paired with the basal ganglia, the thalamus relays sensory signals from the body to the cerebral cortex. For both the basal ganglia and thalamus, gray matter volume reduction has negative effects on balance while volume increases are associated with improved balance. In Alzheimer's patients, nucleus accumbens (part of the basal ganglia) volume reduction is associated with postural instability (Lee et al., 2017). Also, white matter lesions in the basal ganglia of Alzheimer's patients were correlated with poor posture control (Ogama et al., 2014). Deficits in balance associated with thalamic white matter hyperintensities, impaired white matter integrity, and reduced gray matter volume. Like the cerebellum, individuals with expert balance had increased thalamic gray matter volume (Surgent et al., 2019).

The hippocampus is known to be critical to learning and memory, but it is also involved in spatial reasoning. Atrophy of the hippocampus, associated with impaired spatial memory, develops in patients with acquired chronic bilateral vestibular loss (Brandt et al., 2005). In athletes involved in ballet, ice dancing, or slacklining, the local volumes in the right anterior hippocampal formation correlated negatively and those in the right posterior hippocampal formation positively with the amount of time spent training (Hüfner et al., 2011). Other areas of the brain are also associated with balance. For instance, frontal and parietal cortices demonstrated gray matter volume increased with balance training (Surgent et al., 2019) and incomplete spinal cord injury patients displayed an expansion of gray matter volume in the temporal lobe associated with improvements in balance and strength of the lower limbs with training (Villiger et al., 2015). However, the cerebellum, basal ganglia, thalamus, and hippocampus have the most direct evidence of their involvement in posture and gait.

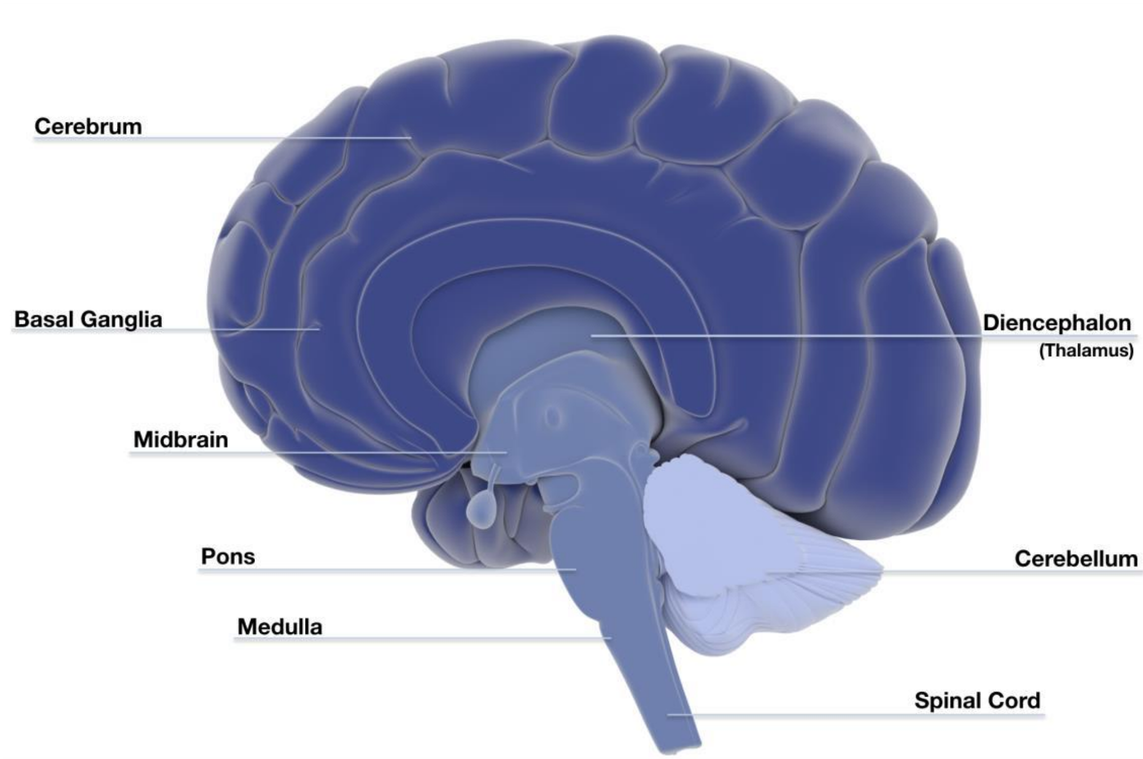

Figure 2.2: The basic location of the main structures of the central nervous system

3 Mechanical Literature Review

3.1 Balance Mechanics

Objective measures are lacking as part of a multi-system evaluation of concussion severity in athletes. Some candidates that have emerged include balance assessment, vestibular-ocular response, cognitive tests, symptom score, and blood biomarkers, and have various levels of success. There are two likely candidates for objective balance measurements. One is tools like SWAY, described in the previous chapter, which utilize data from mobile devices' micro-electromechanical systems (MEMS) to calculate movement of the athlete's trunk. Another is analyzing the athlete's center of pressure (COP) data from instrumented force plates.

It is important to first discuss the mechanics of standing balance. Standing balance is a state of static equilibrium in which there are no external forces on the body and internal forces in the body have a resultant force of zero. The center of mass, base of support, and center of pressure interrelate to maintain balance. Center of mass (COM) is the resultant average of the individual body segmental centers of mass and is where the force of gravity acts on the body, generally located slightly inferior and anterior to the naval, level with the second vertebra. Base of support (BOS) in standing balance is defined as the area underneath the feet in contact with the ground. The ground reaction force acts against the force of bodyweight underneath the feet and the resultant force vector of individual ground reaction force vectors is the center of pressure (COP).

Instrumented force platforms allow the objective measure and analysis of COP. With COP measurements, researchers are able to calculate path length, velocity, acceleration, jerk, frequency, ellipse area, and the lengths and angle of the ellipse axes(Prieto et al., 1996). Each of these variables are potentially sensitive to concussion. Concussions affect postural motor control in measurable ways. COP medial-lateral velocity in a double leg stance and COP anterior-posterior velocity in tandem (one foot in front of the other, heel to toe) stance both increase post-concussion, even six months after the event (Pryhoda et al., 2020). Center of pressure 95% ellipse area and 95% ellipsoid volume increase in concussed subjects in tandem and bilateral stance of BESS (Doherty et al., 2017).

3.2 Motor Mechanisms

Unfortunately, single point inertial measurements like SWAY and single COP measurements only indicate gross balance performance and do not indicate motor control strategy. Successful standing balance is maintained by keeping the COM within the BOS. Healthy posture involves a natural and unconscious amount of sway as muscles in the ankles, hips, and trunk make small adjustments to keep the body appropriately positioned (Winter et al., 1996).

Human posture is intrinsically unstable, often modeled as an inverted single or double pendulum which pivots about the ankle and hip joints. In perturbation based balance tests, a combination of motion capture, inertial measurement units (IMUs), electromyography (EMG), and force plates are used to capture the body's kinematics, kinetics, and muscle activity. In healthy populations, ankle control is dominant in sway oscillations below 1 Hz, with the leg segment angle and trunk segment angle (Fig. 3) moving in phase (single pendulum). Small perturbations in the COM are corrected using ankle plantar and dorsiflexors. At frequencies greater than 1 Hz, leg and trunk angles are anti-phasic, indicating a mix of ankle and hip control strategies. In this case, ankle control is ineffective and hip flexors, abductors, and adductors are engaged to correct larger perturbations. When both ankle and hip strategies fail to maintain the COM in the BOS, a step is necessary to regain balance before a fall occurs.

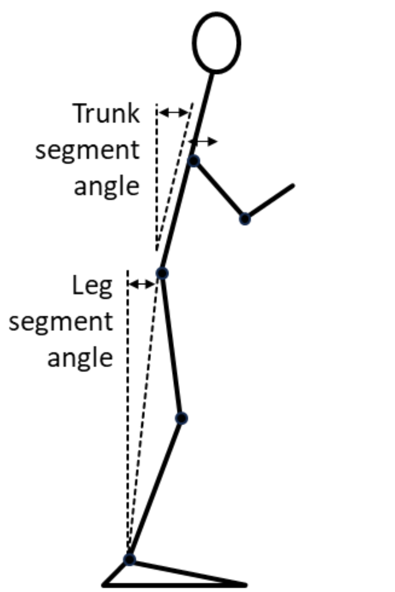

Figure 3.1: Sagittal view of participant in bilateral stance on a force plate. Trunk segment angle and leg segment angle are defined relative to vertical.

3.3 Changes to Motor Control

Changes in motor control strategies are linked to several conditions known to negatively impact balance. As humans age, deficiencies in muscle tone, disorders of the central nervous system such as Alzheimer's, cognitive decline, and loss of periphery senses all result in context specific instabilities and a heavier reliance on hip control (Horak, 2006). In patients with Parkinson's Disease (PD), responses to perturbations while standing are slowed by bradykinesia or muscle rigidityl and linked to a propensity to fall (Schoneburg et al., 2013). People with Multiple Sclerosis have increased overall postural sway in quiet stance and also show a stronger reliance on hip motor mechanisms in perturbation tests (Huisinga et al., 2018). If these effects occur in known neurological conditions that affect balance, then understanding concussion as a neurological condition can benefit from similar a framework of study.

3.4 Kinematics and dynamics

While the perturbation tests described above can give clear insight into the subject's reliance on an ankle strategy or combined ankle-hip strategy, the physical nature of the tests makes them inadvisable for concussed patients who are likely also experiencing dizziness, nausea, headache, and other concussion symptoms. Winter (Winter et al., 1996) offers a novel way to infer reliance on motor mechanisms by analyzing COP in quiet stance on two force plates which would be less invasive and far safer for our concussed population.

A free body diagram of the foot (Fig. 4) shows the forces acting on the foot segment in the sagittal plane. The total ground reaction force (GRF) acts on the foot at the location of the center of pressure in the AP direction (COP_{AP}). It's worth noting that the origin of the COP measurements is easily selected by the researcher. Outputs from the instrumented force plates place the origin at a fixed point in the laboratory space, while balance analysis commonly puts the origin of COP at the mean value of COP for the individual trial. Mean COP, however, has no anatomical meaning, so for convenience here we are assigning the origin to be the ankle joint center (AJC). Also acting on the foot are the force of gravity acting at the center of mass of the foot and the ankle joint reaction torque and forces. The foot is stationary, planted firmly on the force plate, so the linear and angular velocity and acceleration of the foot is zero. Summing the moments about the AJC yeilds

$$\sum M_{AJC} = -m * g * da + COP_{AP} * GRF - T_A = \vec{O}$$

Simplifying further, if we assume m*g*da is small and constant, we see that

$$COP_{AP} \cong \frac{T_A}{GRF}$$

In quiet stance when all body segments' angular velocities and accelerations are very small, we can assume that the GRF is constant and equal to the subject's weight. This means that the center of pressure measurement signal is a scaled equivalent of the reaction torque in the ankle joint center.

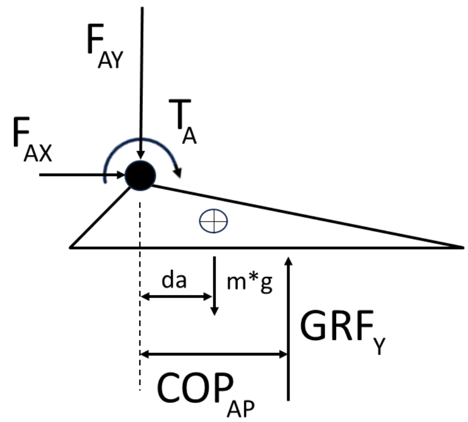

Figure 3.2: Free body diagram of foot segment. The ground reaction force in the vertical (y) direction acts on the foot at the location of the center of pressure in the AP direction measured from the ankle, gravity acts on the foot at the center of mass a fixed distance from the ankle joint, and the reaction torque and forces act at the ankle joint center.

Winter (1996) deconstructs this further by considering the independent GRF and COP under each foot. As discussed in the Methods chapter of this document, it is possible to use these data to separate a subject's total center of pressure (COPt) into contributions assuming constant loading (COPc) and variable loading (COPv). Winter hypothesizes that the COPc signal is driven primarily by ankle flexion and inversion and that COPv is driven by hip flexion and ab/adduction. In the most conservative interpretation of these signals, their most obvious contributions must come from the ankle joint and contraction of muscles in the leg segment for COPc and the hip joint and contraction of muscles in the trunk segment for COPv.

3.5 Visualizing COPt, COPc, COPv

Below are representative graphs of one of the athletes from our collection during twenty second trials in four different conditions, mimicking the data presented by Winter (1996). First is the bilateral stance with eyes open on a hard surface at baseline and in the acutely concussed timeframe (Fig. 5). Predictably, COPt in the ML direction is driven primarily by COPv, the loading/unloading signal. In the AP direction, COPt is driven primarily by COPc, the ankle flexion contribution. As sensory information is removed, with eyes closed (Fig. 6) and then eyes closed on a foam surface (Fig. 7), we see that the overall COP ranges increase but the trend in contributions remain the same.

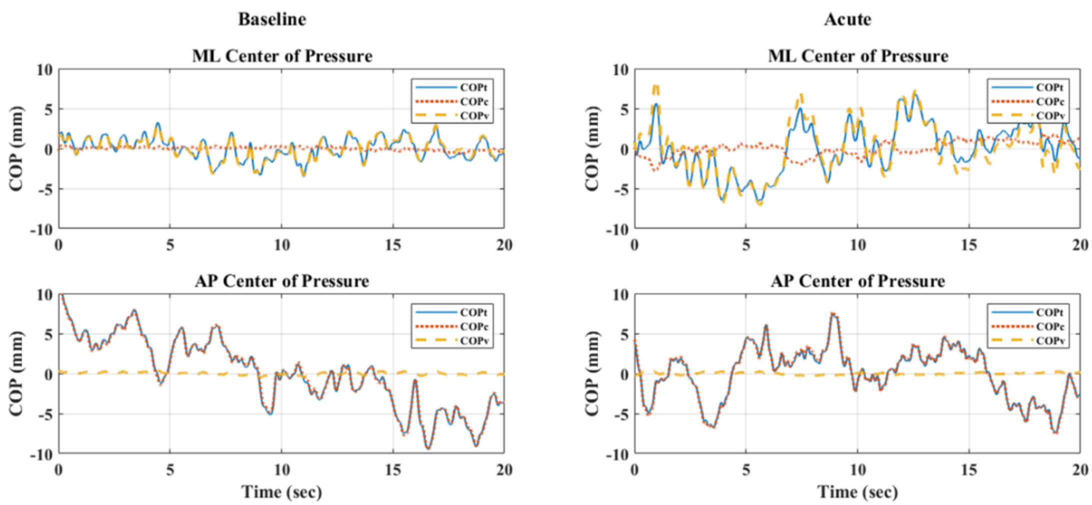

Figure 3.3: COPt, COPc, and COPv vs Time in the medial-lateral and anterior-posterior directions in the Bilateral Stance with eyes open on a hard surface. Baseline trial is shown on the left and Acutely Concussed trial is shown on the right.

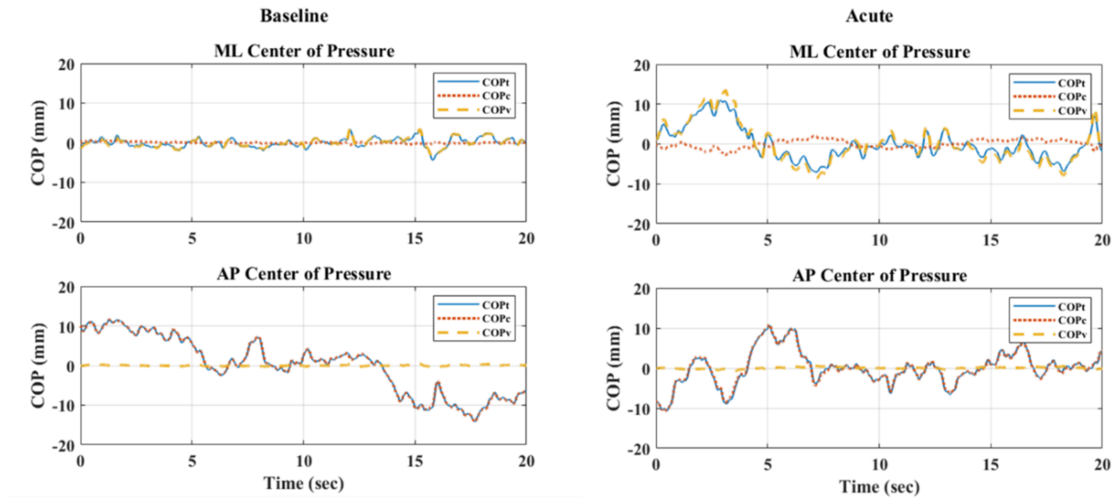

Figure 3.4: COPt, COPc, and COPv vs Time in the medial-lateral and anterior-posterior directions in the Bilateral Stance with eyes closed on a hard surface. Baseline trial is shown on the left and Acutely Concussed trial is shown on the right.

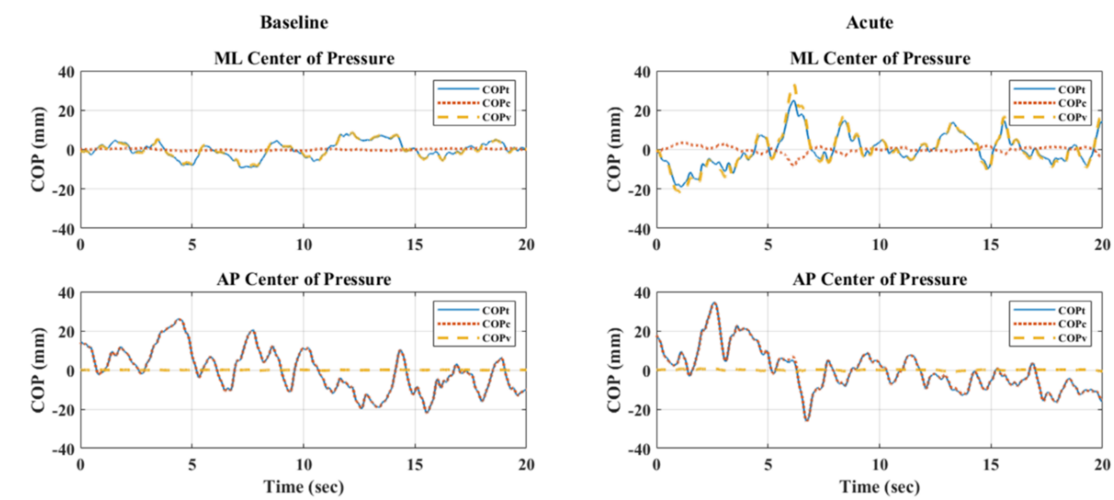

Figure 3.5: COPt, COPc, and COPv vs Time in the medial-lateral and anterior-posterior directions in the Bilateral Stance with eyes closed on a foam surface. Baseline trial is shown on the left and Acutely Concussed trial is shown on the right.

In the tandem stance, ankle inversion in COPc is the largest contributor to COPt in the ML direction. In the AP direction, COPt is a combination of COPc (ankle flexion) and COPv (loading/unloading) (Fig. 8).

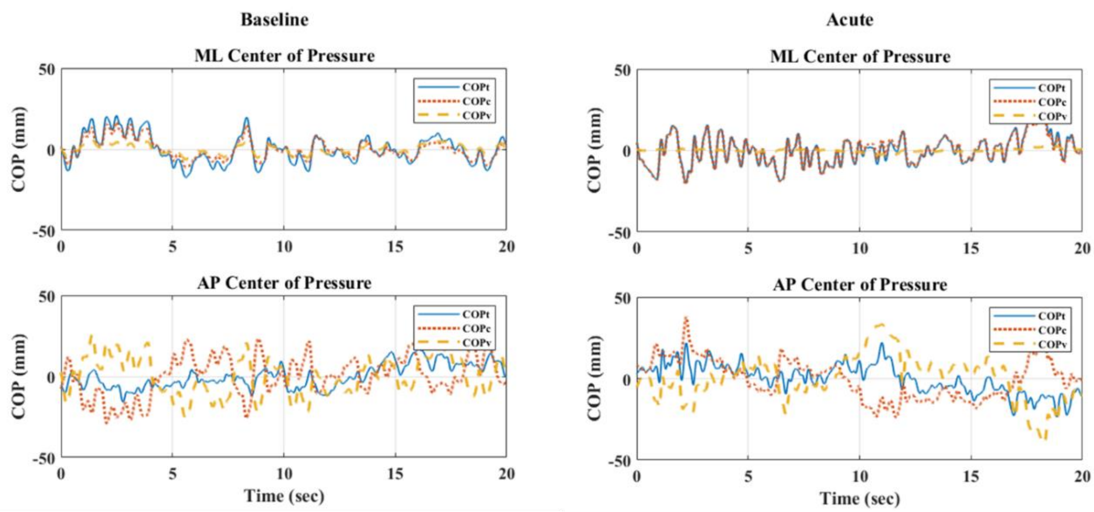

Figure 3.6: COPt, COPc, and COPv vs Time in the medial-lateral and anterior-posterior directions in the Tandem Stance with eyes closed on a hard surface. Baseline trial is shown on the left and Acutely Concussed trial is shown on the right.

One way to describe the relationship between COPt with COPc and COPv is with a cross correlation (Fig. 9). By calculating how closely the constant loading and loading/unloading signals correlate with COPt, especially where they are combined in the AP direction in the Tandem stance, we can quickly quantify how much each contributes to COPt.

	ML	ML	AP	AP
Subject	COPc vs COPt	COPv vs COPt	COPc vs COPt	COPv vs COPt
S01	1.000	0.784	-0.417	0.847
S02	0.997	0.897	0.114	0.222
S03	0.999	0.676	0.437	0.167
S04	0.983	0.731	0.634	-0.054
S05	0.980	0.900	0.383	0.225
S06	0.992	0.269	0.126	0.555
Average	0.992	0.709	0.213	0.327
SD	0.009	0.233	0.366	0.321

Figure 3.7: Cross-correlations between COPt and COPc or COPv in the Medial-Lateral and Anterior-Posterior directions for the Baseline Tandem stance with eyes closed on a hard surface.

Another common way to visualize COP is with a stabilogram. The ML vs AP values of the COP are graphed at each timeframe, tracing the path of the center of pressure during the trial. Graphing COPc and COPv can give us clear insight into how these signals contribute to COPt. In our representative subject's baseline trial in the bilateral stance, eyes open, on a hard surface (Fig. 10), COPc is nearly linear in the AP direction and COPv is nearly linear in the ML direction. This supports the interpretation that COPc reflects ankle flexion and COPv reflects loading and unloading from the hip. COPt appears as a seemingly random "squiggle" under the athlete but is actually a sum of COPc and COPv. Changes in range and average velocity are observed between the Baseline and Acute trials in this condition as well as in the bilateral stance with eyes closed on a hard surface and on a foam surface (Figs 11 & 12).

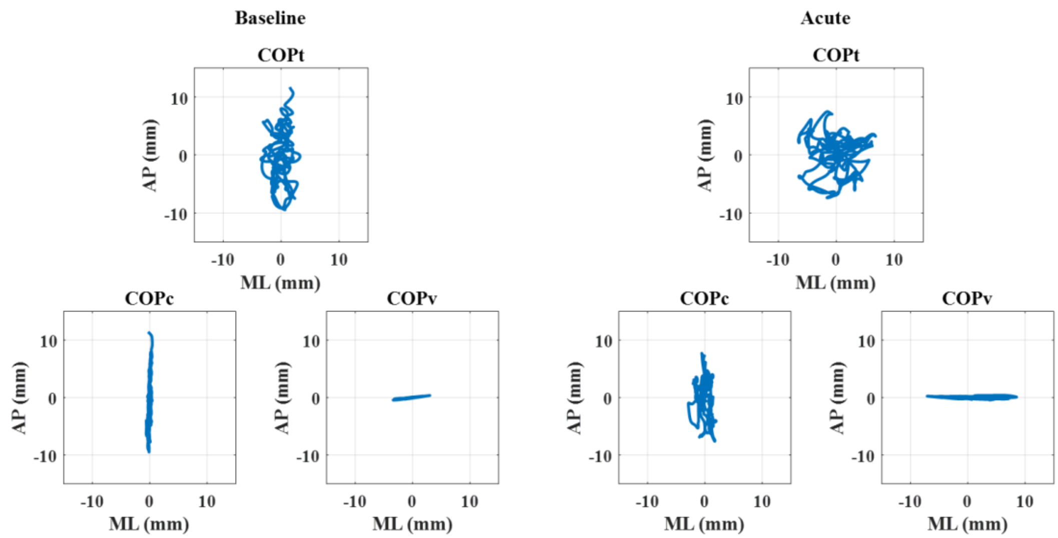

Figure 3.8: Stabilogram of COPt, COPc, and COPv in the Bilateral Stance with eyes open on a hard surface. Baseline trial is shown on the left and Acutely Concussed trial is shown on the right.

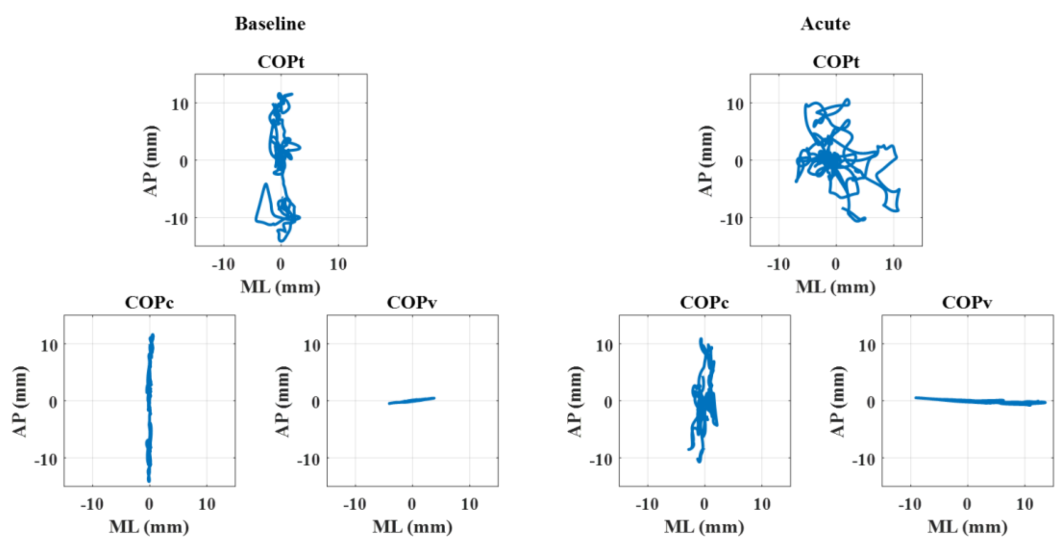

Figure 3.9: Stabilogram of COPt, COPc, and COPv in the Bilateral Stance with eyes closed on a hard surface. Baseline trial is shown on the left and Acutely Concussed trial is shown on the right.

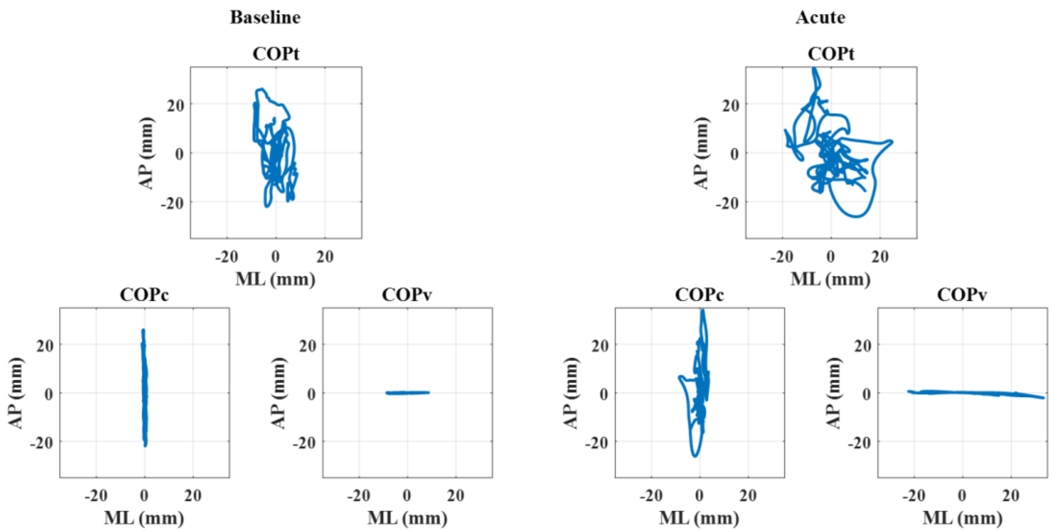

Figure 3.10: Stabilogram of COPt, COPc, and COPv in the Bilateral Stance with eyes closed on a foam surface. Baseline trial is shown on the left and Acutely Concussed trial is shown on the right.

The stabilograms of the tandem stance behave differently from the bilateral figures (Fig. 13). First we notice that COPv, while still nearly linear, is almost entirely in the AP direction. With the feet positioned one in front of the other, loading and unloading must be in the sagittal plane. COPc is a combination of ML and AP, indicating a combined involvement of ankle flexion and inversion. The change in shape of COPc and COPv between the Acute and Baseline trials is mysterious. We observed a change in angle of COPv in some but not all of our subjects as well as the development of the "U" shape in COPc.

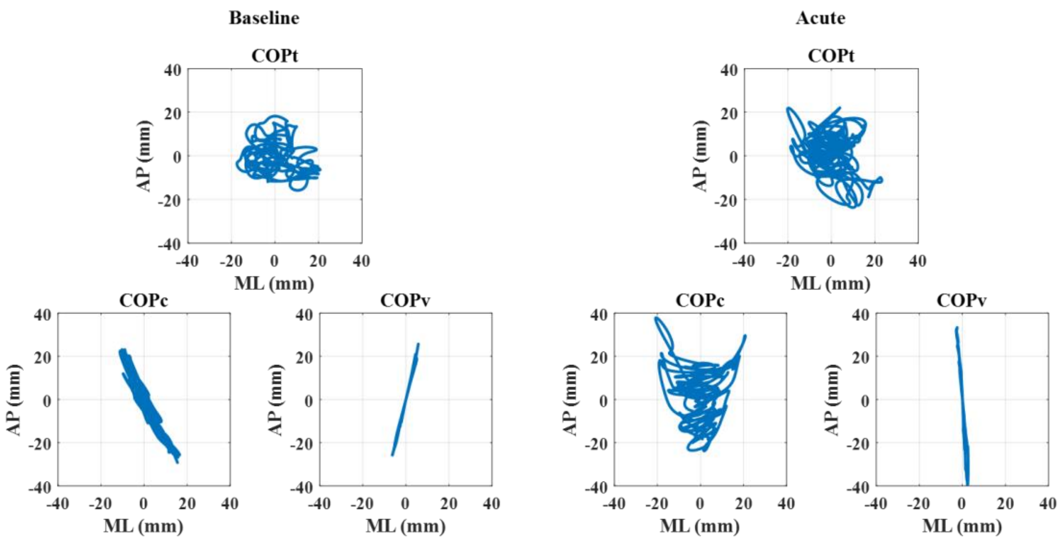

Figure 3.11: Stabilogram of COPt, COPc, and COPv in the Tandem Stance with eyes closed on a hard surface. Baseline trial is shown on the left and Acutely Concussed trial is shown on the right.

3.6 Future Work

It is possible that the COPv signal may be analyzed in a way that provides sensitivity and objective understanding of motor control mechanisms in concussed athletes. If, as in other neurological conditions that affect balance, the concussed athlete experiences a shift from ankle to ankle-and-hip balance strategies, and if COPv does correspond with increased hip involvement in balance, then this is potentially a useful tool for concussion analysis.

4 Manuscript

4.1 Introduction

Concussion assessment in athletes has gained significant attention in recent years due to the potential long-term implications of traumatic brain injuries. The identification and quantification of balance alterations have emerged as crucial components of concussion evaluation, offering insights into post-injury motor control strategies. Center of pressure (COP) analysis, a valuable tool in biomechanical studies, has been employed to assess balance performance in concussed athletes. This study introduces a novel approach to understanding the dynamics of COP during quiet stance tasks and investigates its potential as a sensitive indicator of balance impairments in athletes recovering from concussion.

Concussions, caused by head impact or sudden deceleration, can result in a spectrum of short term physical, emotional, and psychological symptoms (Harmon, 2013) and neurological deficits, including disturbances in balance control. Athletes who sustain concussions are at risk of experiencing impaired motor function, dizziness, and cognitive deficits which lead to a higher risk of lower limb orthopedic injury or repeated concussion. Timely and accurate assessment of post-concussive deficits is crucial to guide return-to-play decisions and ensure the athlete's safety. Traditional balance assessments, such as the Balance Error Scoring System (BESS), primarily focus on total center of pressure (COPt), which only provides insight into gross motor control. This overlooks the nuanced interplay between ankle and hip based motor mechanisms, which might provide valuable insights into motor control strategies adopted by concussed individuals. Contributions from hip and ankle mechanisms are typically analyzed in perturbation tests that are too strenuous for acutely concussed patients, however, analyzing the forces and centers of pressure from two force plates in quiet stance trials may be a viable alternative.

4.2 Methods

National Collegiate Athletic Association (NCAA) Division I (DI) athletes at the University of Denver visited the DU Human Dynamics Laboratory to participate in a comprehensive concussion battery that included instrumented standing and functional balance tasks, neurocognitive assessment, oculomotor assessment, vestibular-ocular assessment, a blood draw, and symptom scoring. The test sessions were conducted at baseline before the start of their season, and retesting was performed in the event of a concussion. The study was conducted in 2016 and 2017, with each testing session lasting approximately an hour and a half with the approval of the University of Denver Institutional Review Board (IRB 854307). Athletes were excluded if they were under 18, trained fewer than seven hours per week for their sport, were unwilling to give blood, or were taking any medications that caused dizziness or otherwise affected balance. We limited this analysis to a novel assessment of balance performance during the quiet stance trials.

In the quiet stance trials, each athlete stood as still as possible during the 3 stances from the Balance Error Scoring System (BESS) for 30 seconds—single leg, bilateral (side by side), and tandem (heel to toe) stances (Fig 14). Each athlete performed the stances under multiple sensory conditions: on a hard surface and a standard foam (Airex AG, Sins, Switzerland), and with eyes open and closed. During the trials, each foot was placed on an independent force platform (40 cm x 70 cm) embedded side by side in the laboratory floor (Bertec Corp) while centers of pressure from each force platform were sampled at 1000 Hz.

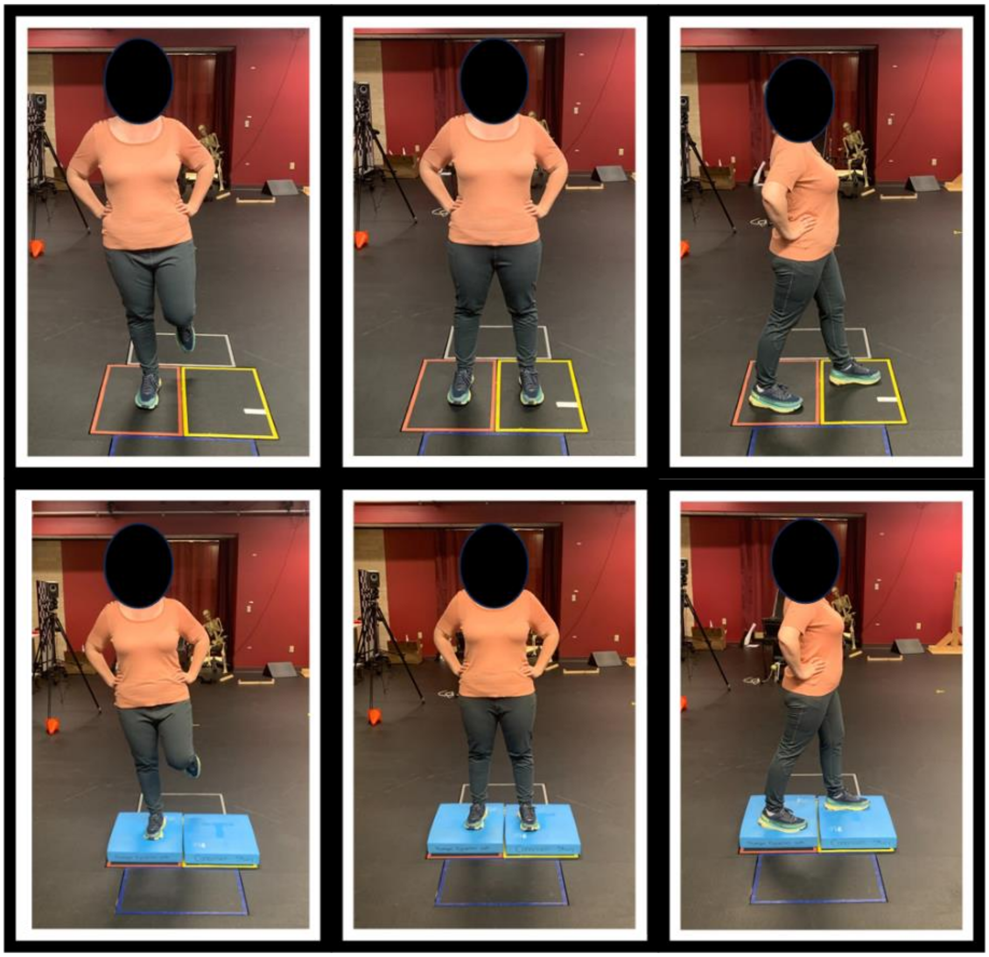

Figure 4.1: BESS stances: One foot, bilateral, and tandem stances on in-ground force plates, with and without a foam surface.

Before calculating the dependent variables, the first and last five seconds of each 30 second trial were removed, and the COP data were filtered using a 4th order zero-phase-lag low-pass Butterworth with a cutoff frequency of 5 Hz.

The "Total" COP (COP_t) signal was calculated by combining the COP signals from the force platforms, creating a weighted average of the COPs under the left and right feet as

$$COP_t(t) = COP_l(t)\frac{F_{zl}(t)}{F_{zl}(t) + F_{zr}(t)} + COP_r(t)\frac{F_{zr}(t)}{F_{zl}(t) + F_{zr}(t)}$$

where COP_l and COP_r are the COP signals under the left and right foot, respectively, and F_{zr} and F_{zl} are the vertical reaction forces under the left and right feet, respectively.

Because the shift from left and right reaction forces represents a loading/unloading in the COPt, we can assume contributions exist from a "constant loading COP" (COPc) and a "variable loading COP" (COPv). Winter et al. (1996) defined these two signals as:

$$COP_c(t) = COP_l(t) \cdot 0.5 + COP_r(t) \cdot 0.5$$

and

$$COP_v(t) = COP_t(t) - COP_c(t)$$

However, in tandem stance, where unequal but constant weight distribution was assumed, the average left and right forces were used to calculate COP_c.

$$COP_c(t) = COP_l(t) \cdot \overline{F_{zl}} + COP_r(t) \cdot \overline{F_{zr}}$$

where $\overline{F_{zl}}$ and $\overline{F_{zr}}$ are the average vertical force under the athlete's left and right feet.

We defined the COP_v as the loading/unloading portion of the COPt and used these signals to calculate three dependent variables —average velocity, root mean square of the distance, and 95% range—for each trial.

The average velocities for both COPt and COPv were determined by summing the distances between individual COP points.

$$Average\ Velocity = \frac{\sum((COP_{ML_{i+1}} - COP_{ML_i})^2 + (COP_{AP_{i+1}} - COP_{AP_i})^2)^{\frac{1}{2}}}{t}$$

where t is the duration of the trial (in seconds) and COP_{ML_i} and COP_{AP_i} are the Medial-Lateral and Anterior-Posterior COP signals measured from the origin in the lab's coordinate system at individual time points during the trial.

The range of 95% of the data was calculated by finding the resultant distance between each COP point and the mean COP.

$$Dist(t) = (COP_{ML}(t)^2 + COP_{AP}(t)^2)^{1/2}$$

The COP_{ML} and COP_{AP} data were then filtered to retain only the 95% of points closest to the center. Then a PseudoDiameter (Gibbs et al., 1976) algorithm was applied to identify the point furthest from the initial point, designating it as the new primary point. The process was iterated to find subsequent furthest points until the desired number of iterations was completed. Root Mean Square (RMS) was found

$$RDIST = (\frac{1}{N}\sum Dist(t)^2)^2$$

where N is the number of data points.

Time courses of each dependent variable for the concussed athletes were plotted and labeled as either "Elevated" or "Typical" based on whether they exceeded the threshold set by the 75th percentile value calculated from a database of 27 NCAA athletes without concussion history (Pryhoda, 2020). Because each distribution from the database was right-skewed, the 75th percentile represented a threshold in which data in a long tail were labeled as Elevated (Fig 15). This threshold was used to interpret the values of our concussed athletes' tests by counting how many were at Typical or Elevated levels at their Baseline and Acute trials.

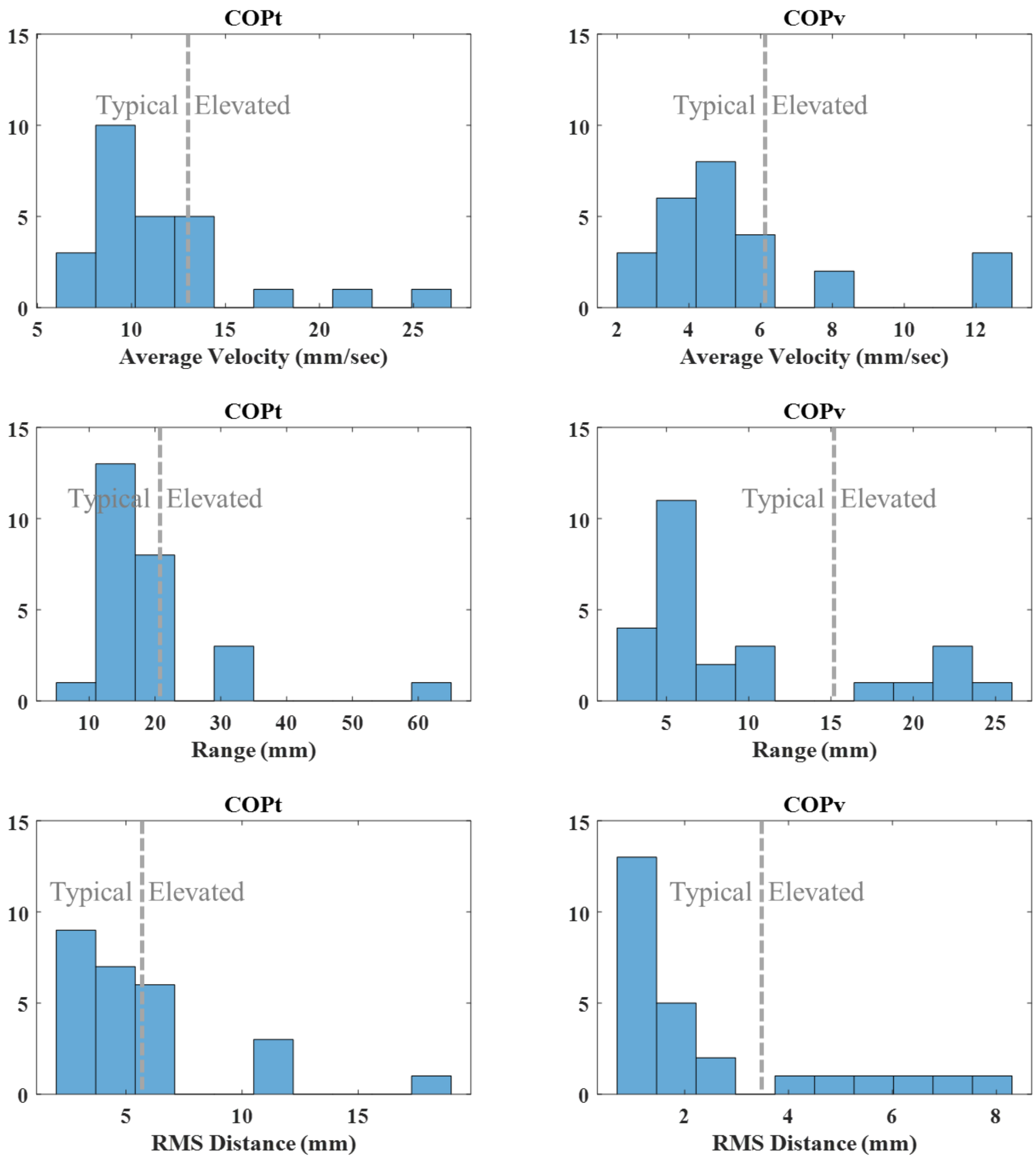

Figure 4.2: Histogram of the average velocity, range, and RMS distance of COPt and COPv in the Bilateral stance with eyes closed on a hard surface in the reference population of Division I athletes with no history of concussion. The dotted line indicates the location of the 75th percentile.

4.3 Results

During this study, six athletes who completed the baseline assessment experienced a sport related concussion and were retested. (Table X)

Subject	Sport	Sex	Age (years)	Weight (lb)	Height (ft)	History of concussion
1	Lacrosse	F	18	133	5’8”	2
2	Basketball	F	missing	180	6’0”	missing
3	Lacrosse	F	20	170	5’9”	2
4	Swimming	M	18	191	6’3”	0
5	Lacrosse	F	19	135	5’9”	2
6	Ice Hockey	M	19	221	6’4”	1

Figure 4.3: Concussed athlete demographics

4.3.1 Average Velocity

In the bilateral stance with eyes open on a hard surface, average velocity from the baseline to acute condition performed similarly with the COPt and COPv signals—slightly larger change in COPv compared to COPt. For the COPt, average velocity increased from baseline to the acute condition in all six (range: 27-138%) (Fig. 17). Average velocity in four subjects transitioned from Typical at baseline to Elevated in the acute condition while two remained typical values despite the increase. For the COPv, average velocity increased from baseline to the acute condition in 4 of 6 subjects (range: 52-247%). Average velocity in three subjects transitioned from the Typical at baseline to Elevated in the acute condition while one maintained elevated values. In the subject with a decrease (16%) from baseline to acute, the baseline average velocity was elevated above typical and remained elevated in the acute condition.

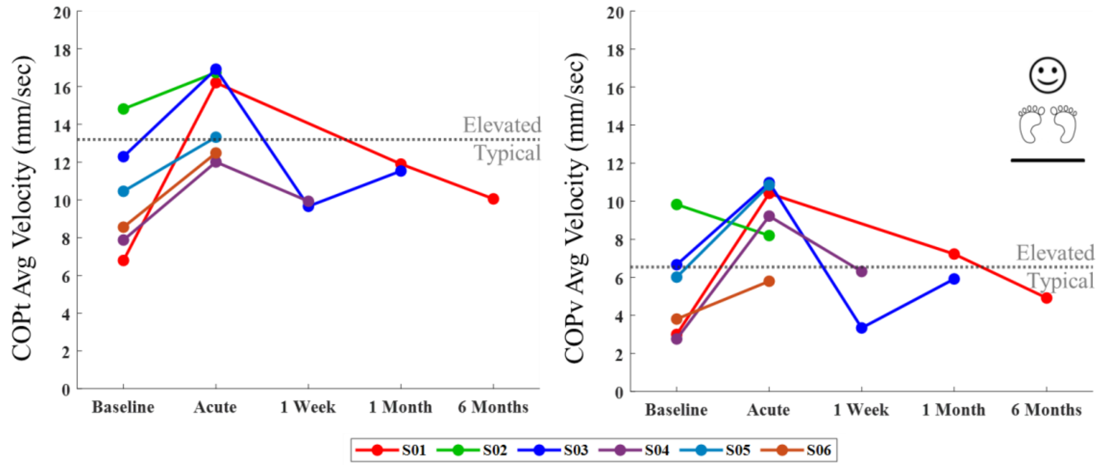

Figure 4.4: Time course of average velocity of COPt and COPv in the Bilateral Stance with eyes open on a hard surface.

In the bilateral stance with eyes closed on a hard surface, average velocity from the baseline to acute condition performed similarly with the COPt and COPv signals—slightly larger change in COPv compared to COPt. For the COPt, average velocity increased from baseline to the acute condition in 5 of 6 subjects (range: 25-182%) (Fig. 18). Average velocity in four subjects transitioned from Typical at baseline to Elevated in the acute condition while one remained typical values despite the increase. In the subject with a decrease (29%) from baseline to acute, the baseline average velocity was elevated above typical and remained elevated in the acute condition. For the COPv, average velocity increased from baseline to the acute condition in 5 of 6 subjects (range: 32-193%). Average velocity in two subjects transitioned from the Typical at baseline to Elevated in the acute condition while three maintained typical values despite the increase. In the subject with a decrease (21%) from baseline to acute, the baseline average velocity was elevated above typical and remained elevated in the acute condition.

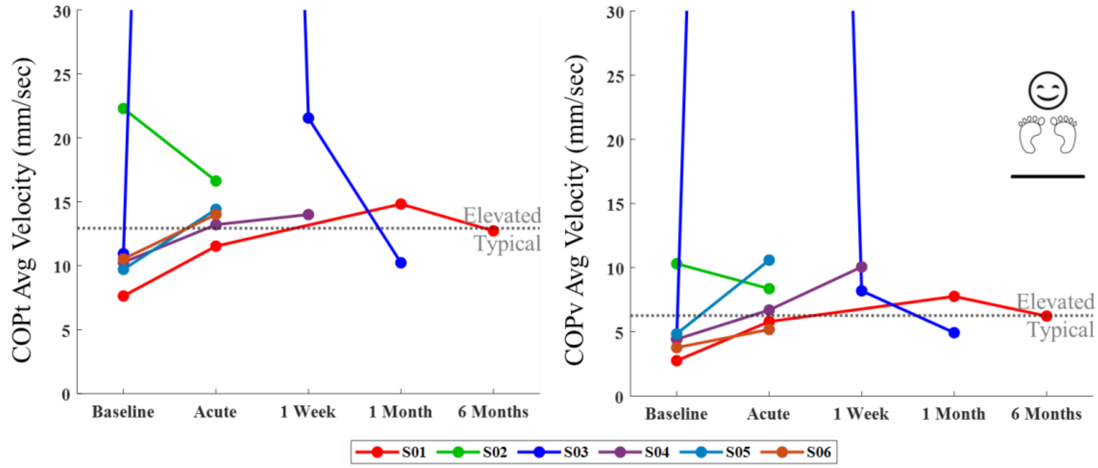

Figure 4.5: Time course of average velocity of COPt and COPv in the Bilateral Stance with eyes closed on a hard surface.

In the bilateral stance with eyes closed on a foam surface, average velocity from the baseline to acute condition was much more sensitive in the COPv than the COPt—elevated values in more concussed subjects and a larger percent increase. For the COPt, average velocity increased from baseline to the acute condition in 3 of 6 subjects (range: 21-147%) (Fig ##). Average velocity for two of those subjects remained Typical at baseline and in the acute condition despite increasing, the other subject was Elevated in both the baseline and acute conditions. In the three subjects with a decrease (range: 7-17%) from baseline to acute, the baseline average velocity was within the typical range and remained typical in the acute condition. For the COPv, average velocity increased from baseline to the acute condition in 5 of 6 subjects (range: 1-182%) (Fig. 19). Average velocity in three subjects transitioned from Typical at baseline to Elevated in the acute condition while two remained typical values despite the increase. In the subject with a decrease (28%) from baseline to acute, the baseline average velocity was elevated above typical and transitioned to typical in the acute condition.

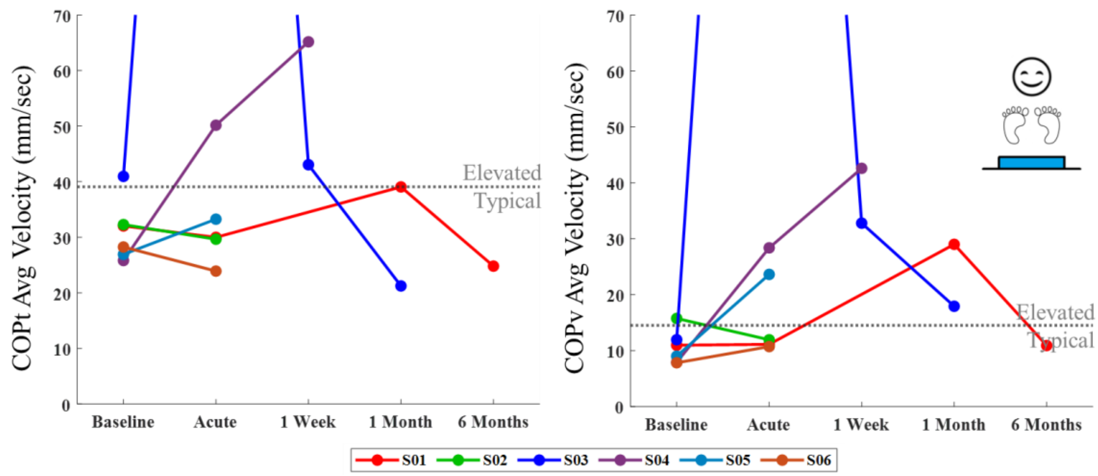

Figure 4.6: Time course of average velocity of COPt and COPv in the Bilateral Stance with eyes closed on a foam surface.

In the tandem stance with eyes closed on a hard surface, average velocity from the baseline to acute condition was more sensitive in the COPv than COPt – elevated values in more concussed subjects with similar percent increase. For the COPt, average velocity increased from baseline to the acute condition in 4 of 6 subjects (range: 7-88%) (Fig. 20). Average velocity in two subjects transitioned from Typical at baseline to Elevated in the acute condition while two remained typical values despite the increase. In the two subjects with a decrease (33-36%) from baseline to acute, the baseline average velocity was elevated above typical and remained elevated in the acute condition. For the COPv, average velocity increased from baseline to the acute condition in 3 of 6 subjects (range: 48-114%) (Fig. 20). Average velocity in one subject transitioned from Typical at baseline to Elevated in the acute condition while two remained typical values despite the increase.

In the three subjects with a decrease (10-55%) from baseline to acute, the baseline average velocity was typical and remained typical in the acute condition.

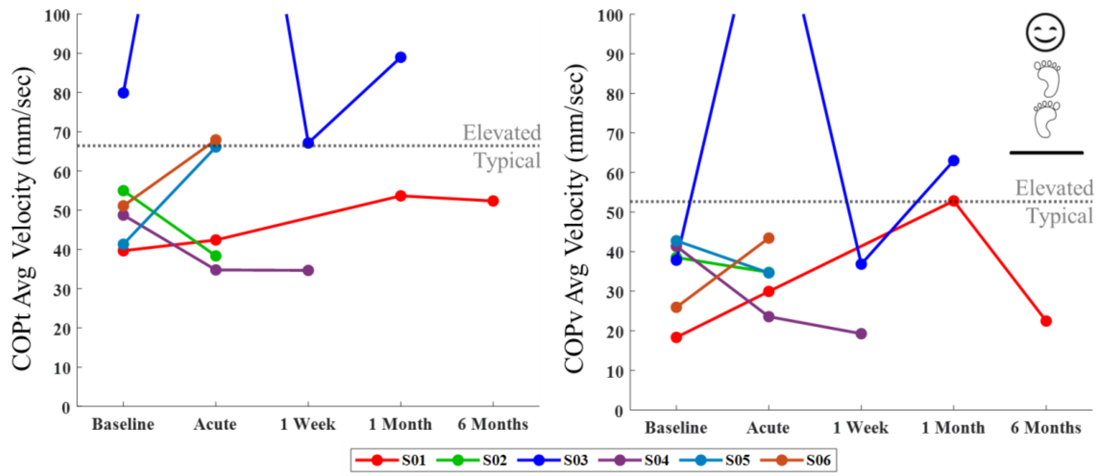

Figure 4.7: Time course of average velocity of COPt and COPv in the Tandem Stance with eyes closed on a hard surface.

4.3.2 Range (95%)

Change in 95% Range from baseline to acute conditions performed similarly across COPt and COPv—slightly larger change in COPv compared to COPt—in the bilateral stance with eyes open on a hard surface. For the COPt, 95% Range increased from baseline to the acute condition in 5 of 6 subjects (range: 20-83%) (Fig. 21). 95% Range in three subjects transitioned from Typical at baseline to Elevated in the acute condition while two remained typical despite the increase. In the subject with a decrease (12%) from baseline to acute, the baseline 95% Range was Typical and remained Typical in the acute condition. For the COPv, 95% Range increased from baseline to the acute condition in 5 of 6 subjects (range: 140-536%) (Fig. 21). 95% Range in five subjects transitioned from Typical at baseline to Elevated in the acute condition. In the subject with a decrease

(30%) from baseline to acute, the baseline 95% Range was elevated above typical and remained elevated in the acute condition.

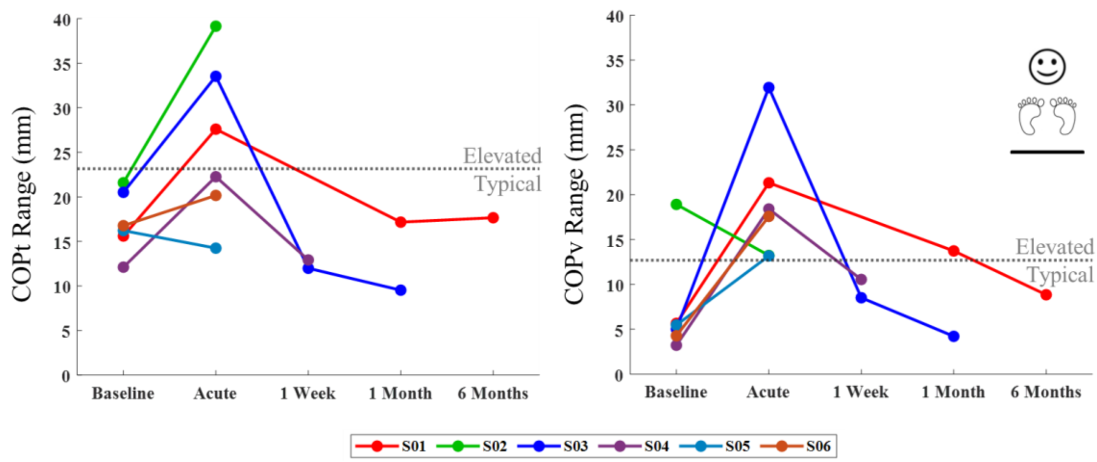

Figure 4.8: Time course of 95% Range of COPt and COPv in bilateral stance with eyes open on a hard surface.

Change in 95% Range from baseline to acute conditions performed similarly across COPt and COPv—slightly larger change in COPv compared to COPt—in the bilateral stance with eyes closed on a hard surface. For the COPt, 95% Range increased from baseline to the acute condition in 5 of 6 subjects (range: 23-167%) (Fig. 22). 95% Range in four subjects transitioned from Typical at baseline to Elevated in the acute condition while one remained typical values despite the increase. In the subject with a decrease (4%) from baseline to acute, the baseline 95% Range was Typical and remained Typical in the acute condition. For the COPv, 95% Range increased from baseline to the acute condition in 5 of 6 subjects (range: 86-191%) (Fig. 22). 95% Range in three subjects transitioned from Typical at baseline to Elevated in the acute condition while two remained typical values despite the increase. In the subject with a decrease (45%) from baseline to acute, the baseline 95% Range was elevated above typical and remained elevated in the acute condition.

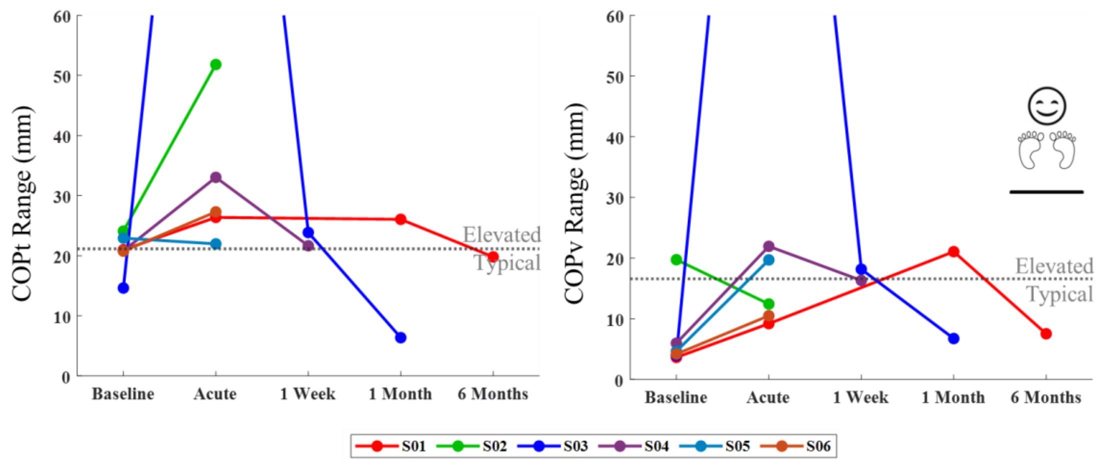

Figure 4.9: Time course of 95% Range of COPt and COPv in bilateral stance with eyes closed on a hard surface.

In the bilateral stance with eyes closed on a foam surface, 95% Range from the baseline to acute condition was much more sensitive in the COPv than the COPt—elevated values in more concussed subjects and a larger percent increase. For the COPt, 95% Range increased from baseline to the acute condition in 4 of 6 subjects (range: 12-128%) (Fig. 23). 95% Range in three subjects transitioned from Typical at baseline to Elevated in the acute condition while one remained typical values despite the increase. In the two subjects with a decrease (0-28%) from baseline to acute, the baseline 95% Range was Typical and remained Typical in the acute condition. For the COPv, 95% Range increased from baseline to the acute condition in 5 of 6 subjects (range: 86-191%) (Fig. 23). 95% Range in four subjects transitioned from Typical at baseline to Elevated in the acute condition while two remained typical values despite the increase. In the subject with a decrease (16%) from baseline to acute, the baseline 95% Range was Typical and remained Typical in the acute condition.

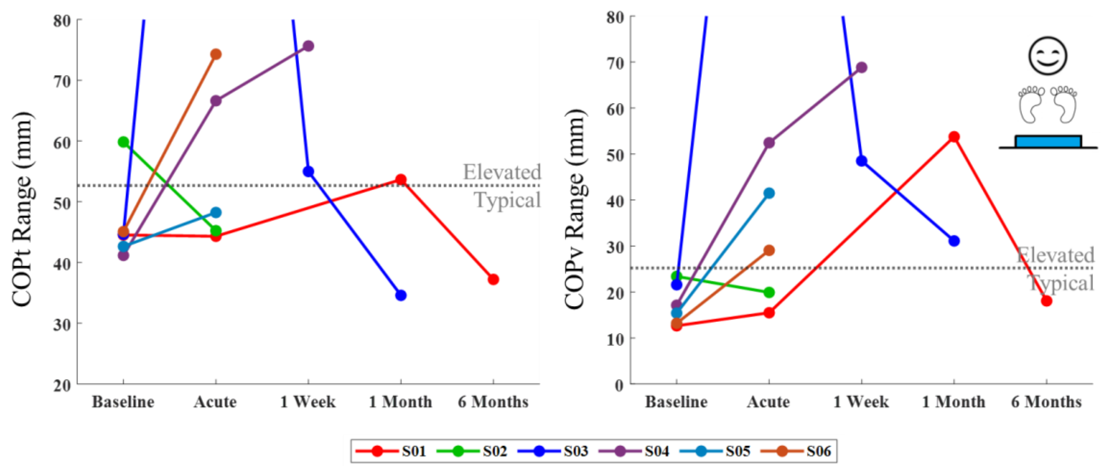

Figure 4.10: Time course of 95% Range of COPt and COPv in bilateral stance with eyes closed on a foam surface.

Change in 95% Range from the baseline to acute condition was more sensitive in the COPv than the COPt—elevated values in more concussed subjects and a slightly larger percent increase - in the tandem stance with eyes closed on a hard surface. For the COPt, 95% Range increased from baseline to the acute condition in 3 of 6 subjects (range: 26-139%) (Fig. 24). In the three subjects with decreases in 95% Range (range: 8-34%), their values were Typical at baseline and remained Typical in the acute condition. One subject transitioned from Typical at baseline to Elevated in the acute condition while the other two were Typical in both baseline and acute conditions. For the COPv, 95% Range increased from baseline to the acute condition in 4 of 6 subjects (range: 10-126%) (Fig. 24). 95% Range in two subjects transitioned from Typical at baseline to Elevated in the acute condition while two remained typical values despite the increase. In the two subjects with a decrease (range: 3-39%) from baseline to acute, the baseline 95% Range was Typical in both baseline and acute conditions.

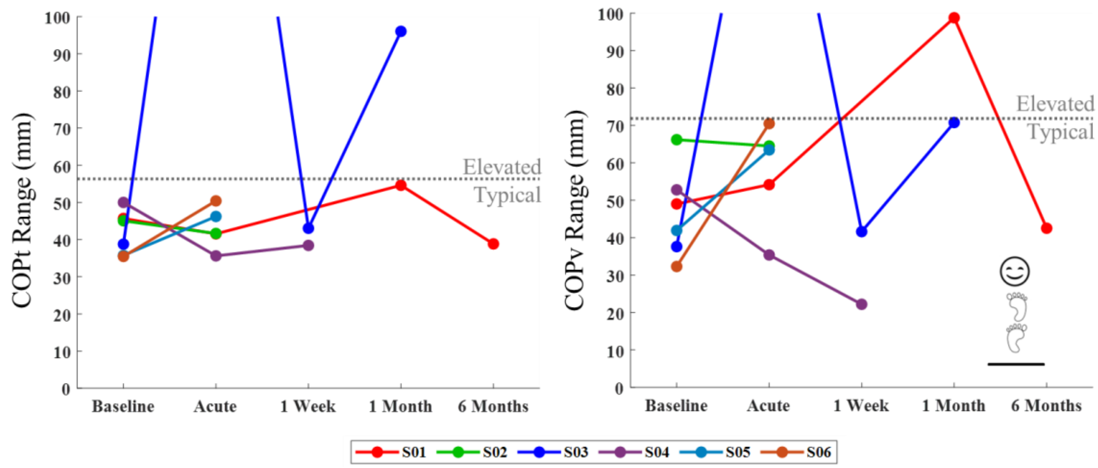

Figure 4.11: Time course of 95% Range of COPt and COPv in Tandem Stance with eyes closed on a hard surface.

4.3.3 RMS DIST

In the bilateral stance with eyes open on a hard surface, average RMS DIST from the baseline to acute condition performed similarly with the COPt and COPv signals – slightly larger change in COPv compared to COPt. For the COPt, RMS DIST increased from baseline to the acute condition in 5 of 6 subjects (range: 33-107%) (Fig. 25). Three subjects transitioned from Typical at baseline to Elevated in the acute condition. RMS DIST for two subjects were Elevated at baseline and remained Elevated in the acute condition. In the subject with a decrease (6%) they were Typical at baseline and remained Typical in the acute. For the COPv, RMS DIST increased from Typical at baseline to Elevated in the acute condition in 5 of 6 subjects (range: 143-538%) (Fig. 25). In the subject with a decrease (28%) from baseline to acute, the baseline RMS DIST was Elevated above typical and remained Elevated in the acute condition.

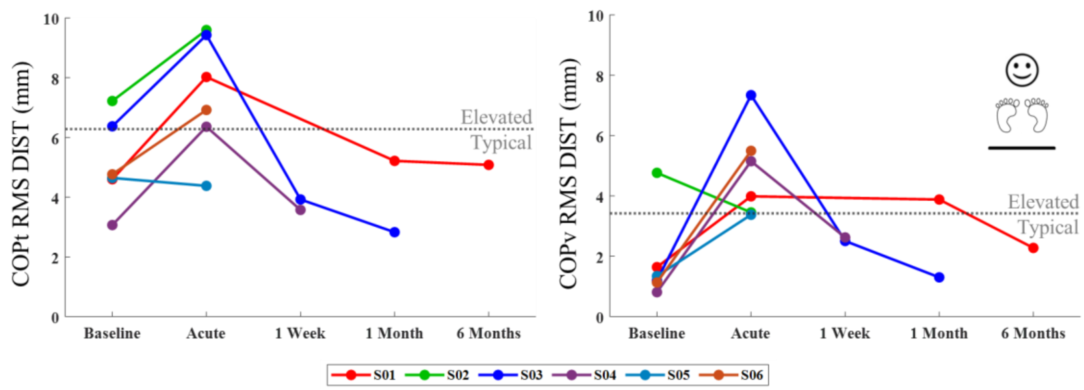

Figure 4.12: Time course of RMS Distance of COPt and COPv in Bilateral Stance with eyes open on a hard surface.

In the bilateral stance with eyes closed on a hard surface, average RMS DIST from the baseline to acute condition performed similarly with the COPt and COPv signals – slightly larger change in COPv compared to COPt. For the COPt, RMS DIST increased from baseline to the acute condition in 5 of 6 subjects (range: 28-166%) (Fig. 26). Two subjects transitioned from Typical at baseline to Elevated in the acute condition. RMS DIST for four subjects were Elevated at baseline and remained Elevated in the acute condition, including the subject with a decrease (20%). For the COPv, RMS DIST increased from baseline to the acute condition in 5 of 6 subjects (range: 65-191%) (Fig. 26). RMS DIST in three subjects transitioned from Typical at baseline to Elevated in the acute condition while two remained typical values despite the increase. In the subject with a decrease (38%) from baseline to acute, the baseline RMS DIST was elevated above typical and transitioned to typical in the acute condition.

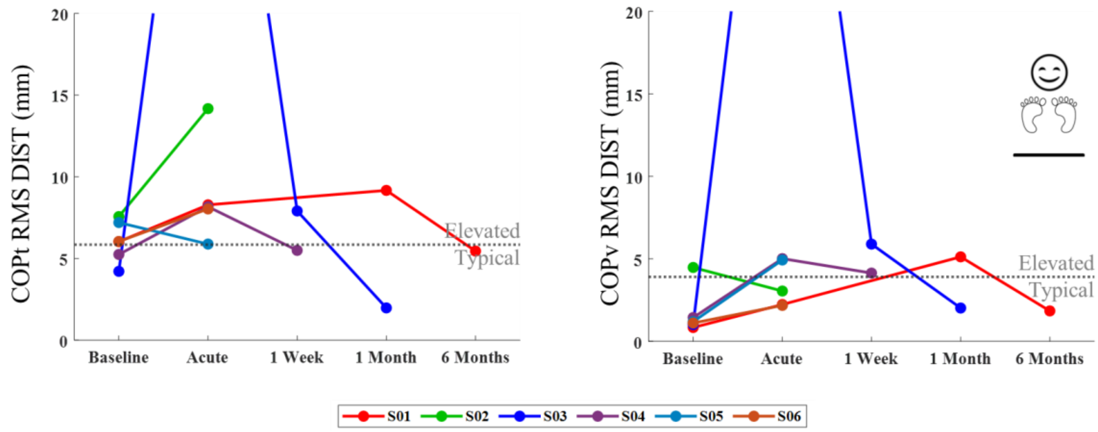

Figure 4.13: Time course of RMS Distance of COPt and COPv in Bilateral Stance with eyes closed on a hard surface.

Change in RMS DIST from baseline to acute conditions performed similarly across COPt and COPv—slightly larger change in COPv compared to COPt—in the bilateral stance with eyes closed on a foam surface. For the COPt, RMS DIST increased from baseline to the acute condition in 5 of 6 subjects (range: 1-127%) (Fig. 27). RMS DIST in three subjects transitioned from Typical at baseline to Elevated in the acute condition while two maintained typical values despite the increase. In the subject with a decrease (16%) from baseline to acute, the baseline RMS DIST was elevated above typical and transitioned to typical in the acute condition. For the COPv, RMS DIST increased from baseline to the acute condition in 5 of 6 subjects (range: 24-168%) (Fig. 27). RMS DIST in four subjects transitioned from Typical at baseline to Elevated in the acute condition while one maintained Typical values despite the increase. In the subject with a decrease (16%) from baseline to acute, the baseline RMS DIST was Typical and remained Typical in the acute condition.

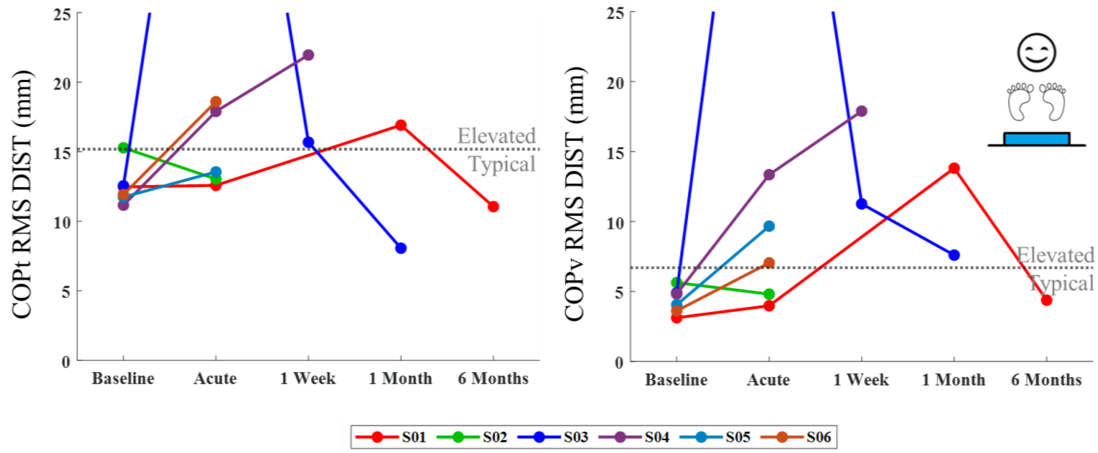

Figure 4.14: Time course of RMS Distance of COPt and COPv in Bilateral Stance with eyes closed on a foam surface.

In the tandem stance with eyes closed on a hard surface, change in RMS DIST from the baseline to acute condition was more sensitive in the COPv than the COPt—elevated values in more concussed subjects and a larger percent increase. For the COPt, RMS DIST increased from baseline to the acute condition in 3 of 6 subjects (range: 9-131%) (Fig. 28). One subject transitioned from Typical at baseline to Elevated in the acute condition while the other two were Typical in both baseline and acute conditions despite increasing. In the three subjects with decreases in RMS DIST (range: 2-40%), their values were Typical at baseline and remained Typical in the acute condition. For the COPv, RMS DIST increased from baseline to the acute condition in 5 of 6 subjects (range: 2-113%) (Fig. 28). RMS DIST in two subjects transitioned from Typical at baseline to Elevated in the acute condition while two remained typical values despite the increase. In the subject with a decrease (32%) from baseline to acute, the baseline RMS DIST was Typical in both baseline and acute conditions.

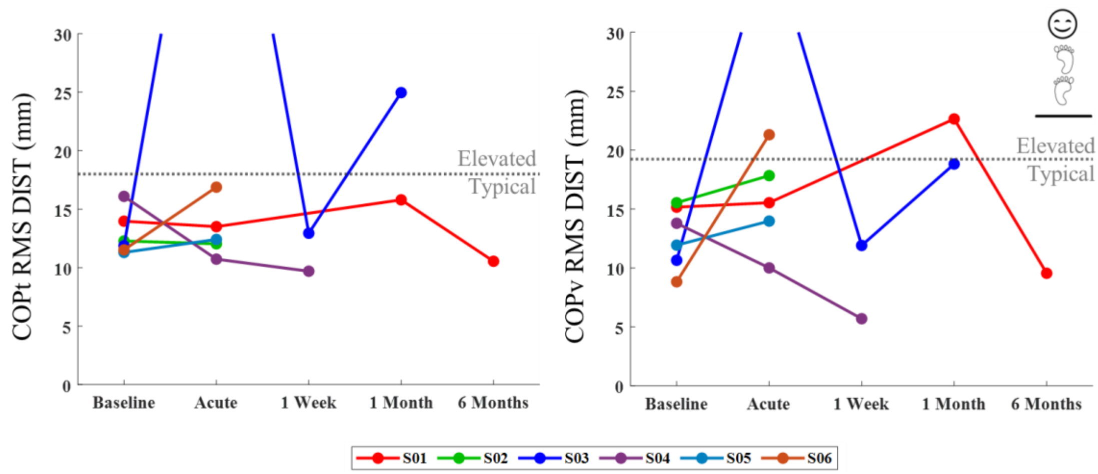

Figure 4.15: Time course of RMS Distance of COPt and COPv in Tandem Stance with eyes closed on a hard surface.

4.4 Discussion

Traditional balance assessment for concussion only considers gross motor performance, ignoring changes in motor control. Following a concussion, athletes increased reliance on a loading/unloading balance mechanism was observed in the measurable contribution of the unequal loading (COPv) to the traditional center of pressure (COPt). The dependent variables of loading/unloading calculated from the COPv were a more sensitive signal to concussion than dependent variables calculated form the traditional COPt. The bilateral stance in multiple sensory conditions appears sufficiently sensitive for detecting continuous changes in balance performance with concussion while the tandem stance is too challenging of a task to meaningfully interpret. COPv more accurately reflected the concussed state of these athletes and may be useful in concussion assessment.

4.4.1 Interpreting COPv, COPc:

The dependent variables exhibited distinct trends that aligned with neurological conditions affecting balance, notably the shift to a stronger reliance on the hip strategy. The interpretation of COPv and COPc sheds light on the mechanisms underlying balance alterations in concussed athletes. In concussion research, COPt is commonly analyzed, observing some changes in dependent variables. COPv in the concussed state followed similar trends to COPt except more pronounced with more acute trials falling in the Elevated state. This emphasized the significance of the loading/unloading signal component of the center of pressure, particularly driven by the hips and trunk. Our findings suggested that increases in COPv were indicative of an exaggerated hip strategy. On the other hand, interpreting COPc proved more intricate due to its presumed dependence on ankle flexion and inversion. Variations in ankle involvement led to unpredictable changes in COPc variables among subjects, suggesting the influence of multiple contributing factors.

4.4.2 Preferred Stance

Among the stances evaluated, bilateral stance with eyes closed on a foam surface emerged as the most responsive for assessing concussed athletes. In addition, it is the most interpretable by providing a clearer view of the shift to hip strategy than the tandem stance. The bilateral stance offered a challenging yet feasible condition for athletes to maintain balance. While tandem stance presented a combination of ankle and hip strategies, bilateral stance highlighted the distinct roles of these strategies in AP and ML movement. Furthermore, the removal of visual input and disruption of proprioception intensified the challenge, compelling athletes to rely more heavily on proprioceptive cues. Notably, the completion rates for this stance underscored its feasibility for balance assessment.

4.4.3 Defining Typical and Elevated Values:

The establishment of Typical and Elevated values based on the baseline population set offered a reliable framework for clinical comparison. The utilization of quartiles revealed a clear transition to the long right tail in the histogram at the 75% mark, indicating the potential for defining Elevated values above this threshold. While the concussed population largely exceeded the upper quartile in acute trials, subsequent recovery brought the values below this threshold. Trends in variable graphs highlighted the consistency of responses in bilateral stances, where athletes transitioned from Typical to Elevated and eventually resolved states. However, tandem stance exhibited less predictable trends, with some athletes showing decreased values even in cases of acute concussion.

4.4.4 Recommending COPv analysis and Future Use:

Our findings support the integration of COPv analysis in assessing concussion severity. Notably, Average Velocity and 95% Range emerged as robust metrics, offering sensitivity in capturing alterations in balance. The combination of ML and AP ranges for a more comprehensive analysis was deemed valuable, as it accounted for the directional dependency of COPv on stance. Furthermore, the inclusion of RMS Distance provided an additional layer of sensitivity. The future use of COPv and COPc in comprehensive screening and assessment tests holds promise, as their sensitivity outperforms traditional COPt analysis. These metrics, alongside symptom surveys and cognitive tests, could contribute to a holistic evaluation of concussion status.

4.4.5 Unusual Subjects

Large deviations in the nonconcussed group and concussed athlete group reduce the confidence of using a single balance collection as a diagnostic and balance collections across multiple days may be warranted. S02 had a "bad baseline" by viewing the consistently elevated values in Average Velocity, Range, and RMS Distance in Bilateral stance with eyes open and eyes closed. Although the baseline values were unexpectedly high compared to the acute collection, notice that they were comparable to 2-8 (7-30%) nonconcussed athletes (Fig. 15). Similarly, all dependent variables for S03 in the acute collection were extremely high (Figures 18 – 28), which suggests that this session was not reliable and perhaps an assessment on the following day may better represent balance performance. Any of these anomalies could be the result of confounding factors that may or may not be related to pathology—motivation (Voss, 2015) (Higgins et al., 2017), fatigue(Steib et al., 2013), time of day(Doan et al., 2023), respiration rate(Hodges et al., 2002), emotional state(Zaback et al., 2019), and rater instructions(Ming Choi et al., 2014). Both COPt and COPv had extreme values, isolating COPv did not help reduce the extreme values inference. We often don't know why a participant has a "bad day".

Balance assessments are already part of the standard of care (SCAT- 5) and may warrant more than one assessment to provide confidence in the in the observations.

4.4.6 Limitations

Several limitations warrant consideration. The selection of the upper quartile as the cutoff for Elevated values may warrant refinement as more data is collected. The relatively small sample size for both concussed and reference populations, although not uncommon in similar studies, limits the generalizability of our findings. While COPv and COPc exhibit sensitivity, their specificity in diagnosing concussion remains a challenge due to potential confounding factors. Athlete testing limitations, including potentially intentionally underperforming in their baseline assessments, further complicate the interpretation of results. There were some extreme values in the data, which reduce the confidence in the data. Despite the extreme values, sensitivity of the COP dependent variables was still improved by considering the COPv signals along with COPt.

4.5 Conclusion

By investigating the separation of constant loading (COPc) and dynamic loading and unloading signals (COPv), we aimed to uncover nuanced motor control adaptations that could serve as sensitive indicators of post-concussive deficits. The findings of this study shed light on the potential of COPv and COPc analysis as valuable tools in the assessment of athletes recovering from concussion.

Our investigation into COPv and COPc yielded several noteworthy insights. Notably, the analysis of COPv exhibited distinct trends that aligned with neurological conditions affecting balance, emphasizing the significance of the loading/unloading component of the center of pressure. Athletes in the concussed state showed an increased reliance on shifting weight between legs, signifying the intricate role of hip and trunk contributions to motor control adaptations. Our results underscored the feasibility of utilizing the bilateral stance with eyes closed on a foam surface as a responsive assessment condition for concussed athletes. This stance challenged athletes' proprioceptive and visual cues, providing a sensitive platform to capture post-concussive alterations in balance.

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Nonetheless, this study is not without limitations. The relatively small sample size of both the concussed and reference populations warrants caution in generalizing the findings. The potential influence of confounding factors, such as motivation, fatigue, and emotional state, could impact the results, and future research should consider these variables. Additionally, the presence of extreme values in the data prompts further investigation into the reliability of a single balance assessment as a diagnostic tool.

This study's findings offer numerous promising avenues of explorations. Broadening the set of tests by collecting data from a larger number of concussed athletes would lead to more robust conclusions in changes to motor mechanisms following concussion. Additionally, expanding the baseline control population to encompass a wider range of sports, ages, and demographics would further enhance the reliability and applicability of the established Typical and Elevated values.

Exploring Winter's (1996) suggestion of a stance angle of 45-degrees may capture hip and ankle involvement in balance and could provide a standardized framework for future research. Incorporating the analysis of two force plates in quiet stance trials alongside perturbation testing could serve as a valuable validation step, confirming the interpretation of COPc and COPv relative to the mechanisms of hip and ankle engagement.

The potential of these tests extends beyond the realm of concussion research. Exploring the application of COPv and COPc analysis to other disorders that affect balance, such as Parkinson's Disease or Multiple Sclerosis, could broaden our understanding of the underlying mechanisms of various conditions. Future studies could aim to retrain balance strategies in concussed subjects during the recovery phase. For example, balance training interventions involving tools like wobble boards could be designed to target the specific alterations identified in COPv and COPc metrics.

In conclusion, this study highlights the potential of COPv and COPc analysis as valuable tools for enhancing the assessment of concussed athletes' balance performance. By deciphering the dynamic and static components of center of pressure, we have contributed to the evolving field of concussion evaluation. Our findings suggest that COPv and COPc metrics, in conjunction with existing clinical measures, offer a more comprehensive understanding of motor control adaptations following traumatic brain injuries. As the understanding of concussion continues to evolve, the integration of biomechanical insights holds promise for advancing our ability to diagnose, monitor, and guide the rehabilitation of athletes recovering from concussions.

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Appendix: Additional Data

Histograms of baseline control population variables.