THE EXAMINATION OF MOVEMENT, SOMATOSENSORY, AND NEUROMUSCULAR FUNCTION THROUGHOUT CONCUSSION RECOVERY

by

LANDON BRYCE LEMPKE

(Under the Direction of Robert C. Lynall)

ABSTRACT

Movement, somatosensory, and neuromuscular function are theorized to be altered and directly relate to the heightened musculoskeletal injury risk following concussion, but to date, limited research exists. The purpose of this dissertation was to examine functional movement (gait and single-leg hop), somatosensory (passive joint repositioning, touch-sensation threshold, pressure-pain threshold), and neuromuscular (superimposed burst technique) function among concussed and healthy, matched-control cohorts acutely (0-7 days post-injury) and asymptomatic (± 72 hours of symptom resolution). Eight concussed and 8 controls completed all assessments across the two clinical timepoints. Concussed individual’s asymptomatic status (symptom severity ≤ 3) was determined by comparing daily symptom severity to their retrospective baseline proxy symptom severity, and controls were yoked to their matched counterpart. Gait occurred on an instrumented walkway with spatiotemporal outcomes calculated. Single-leg hop occurred in a motion capture space with kinematic and kinetic outcomes derived. Passive joint repositioning occurred on a Biodex, with absolute joint angles recorded. Touch sensation was assessed using standard Semmes-Weinstein monofilament procedures, and pressure-pain threshold assessed via algometry. The superimposed burst technique examined voluntary knee extensor torque production and maximum torque capability via supramaximal electrical stimulation. Mixed model ANOVAs were used to examine differences between groups over time among functional movement and somatosensory outcomes, and independent t-tests among neuromuscular outcomes (completed only at asymptomatic timepoint). Gait demonstrated slower and shorter spatiotemporal outcomes acutely for concussed individuals that resolved once asymptomatic. We observed subtle, but potentially important, joint moment differences during single-leg hop between groups. Touch sensation was significantly higher (i.e. more force needed to detect) among concussed individuals across both timepoints. No statistically different pressure-pain thresholds or joint repositioning joint angle errors were observed, though potentially important effect size magnitudes were identified. No statistically different voluntary knee extensor torque production or maximum torque capability were observed. The cumulative dissertation findings indicate potentially important biomechanical and somatosensory deficits following concussion, but not neuromuscular outcomes. These findings provide novel biomechanical, somatosensory, and neuromuscular insights for future research to utilize and optimize longitudinal investigations aimed at examining the heightened musculoskeletal injury risk after concussion phenomenon.

INDEX WORDS: Mild Traumatic Brain Injury, Interpolated Twitch, Sensorimotor, Recovery, Lower Extremity Injury.

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DEDICATION

To my grandmother, Louise Tharp. Without having you throughout my childhood, I wouldn’t be in the position I am today. We all love and miss you.

To my parents, Lyndell and Lynette Lempke. Thanks for allowing me the freedom to pursue my interests on my own terms, even though my dream job since kindergarten was to “be retired”. Glad I grew up a bit and pursued higher education thanks to your support and gentle guidance along the way. I have finally found the career path I truly enjoy every day.

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CHAPTER 1

INTRODUCTION

Background

Concussion is defined as a subtype of traumatic brain injury induced by forces to either the body or head that result in rapid, transient neurological impairment (McCrory et al., 2017). Over 2.5 million concussions present to emergency rooms and approximately 3.8 million occur in sports in the United States alone, costing over $17 billion annually (Cancelliere, Coronado, Taylor, & Xu, 2017; Langlois, Rutland-Brown, & Wald, 2006; US Department of Health & Human Services; Centers for Disease Control (CDC); National Center for Injury Prevention and Control, 2003). Concussions present with clinical signs and symptoms manifesting most frequently as headache, dizziness, and/or difficulty concentrating (Kerr, Zuckerman, et al., 2016; Wasserman, Kerr, Zuckerman, & Covassin, 2016), impaired postural stability or motor function (Riemann & Guskiewicz, 2000; Teel, Gay, Arnett, & Slobounov, 2016), and/or altered neurocognitive capabilities across cognitive domains (Covassin, Schatz, & Swanik, 2007; Schatz, Pardini, Lovell, Collins, & Podell, 2006). Post-concussion impairments measured by standard clinical assessments of signs and symptoms, postural stability, and neurocognitive performance resolve promptly for the majority, with full medical clearance occurring on average 14 days across age groups in sport, but large variance exists (Garcia et al., 2018; Kerr, Zuckerman, et al., 2016; Wasserman et al., 2016). Though concussion recovery on standard clinical assessments commonly occurs within this time frame, emerging research indicates there are residual movement deficits that could have vital implications for patient outcomes (Howell, Lynall, Buckley, & Herman, 2018; Parker, Osternig, Van Donkelaar, & Chou, 2006).

Gait (i.e. walking) assessments are a popular clinical tool across numerous pathological populations due to the daily functional nature and gross sensorimotor demands required (Büttner et al., 2019; Riemann & Lephart, 2002). Gait is often thought of as a simplistic task, but it requires complex integration of somatosensory input, cognitive processing and planning, and neuromuscular output to produce smooth and efficient movement (Kraan, Tan, & Cornish, 2017). A growing number of studies have examined spatiotemporal gait outcomes following concussion and have identified gross impairments (Büttner et al., 2019; Fino, Nussbaum, & Brolinson, 2016; Howell, Buckley, Lynall, & Meehan, 2018; Howell, Osternig, & Chou, 2015). Cumulatively, researchers have identified impaired movement speed, center of mass displacement, and inhibited dual-task (i.e. completing a motor and cognitive task simultaneously) performance during gait assessments up to two-months after concussion (Büttner et al., 2019; Howell, Lynall, et al., 2018; Parker et al., 2006).

Gait assessments provide insight to a functional activity of daily living, but they might not address sport-related demands. Numerous sport-specific functional movement assessments have been explored among individuals with a history of concussion to address this gap (Avedesian, Covassin, & Dufek, 2020; DuBose et al., 2017; Lapointe et al., 2018; Lynall et al., 2018). Cumulatively, individuals with concussion history display greater trunk flexion (Lynall et al., 2018), greater hip stiffness with concurrent decreased knee stiffness (DuBose et al., 2017), greater knee valgus and internal rotation (Lapointe et al., 2018), and less ankle dorsiflexion and knee flexion (Avedesian et al., 2020) during jumping and cutting tasks as compared to healthy controls. However, functional movement insight is limited to investigations among samples with a previous concussion between 2 months to 3 years after initial injury (Avedesian et al., 2020;

DuBose et al., 2017; Lapointe et al., 2018; Lynall et al., 2018). The wide variability coupled with heterogenous concussion recovery likely confounds previous research. To date, no research has examined concussed individuals on functional movements using biomechanical outcomes throughout concussion recovery. Furthermore, the understanding of dual-task deficits remains limited to gait assessments and therefore it is unknown if dual-task deficits linger beyond two-months when coupled with more complex, sport-like movements (Büttner et al., 2019; Howell, Lynall, et al., 2018; Parker et al., 2006). Though previous findings suggest underlying neurophysiological deficits exist, it is unknown what specific neural pathways contribute to impaired gait and functional movement outcomes. Due to the numerous neurophysiological inputs and outputs contributing to functional movement performance, more assessments specific to sensory and neuromuscular pathways are warranted to gain deeper understanding of post-concussion deficits.

Neurophysiologic factors such as somatosensory (e.g. pain, proprioception, and touch sensation) and neuromuscular (e.g. central muscle activation) function play a vital role in human movement and injury prevention (Hart, Pietrosimone, Hertel, & Ingersoll, 2010; Wikstrom, Naik, Lodha, & Cauraugh, 2010). Alterations in pain processing via lower extremity algometry (pain-pressure sensitivity) have been observed in individuals after recovery from musculoskeletal injuries, indicating lingering neurophysiologic changes (Kosek & Ordeberg, 2000; Walton et al., 2011). Touch sensation deficits in the foot plantar surface and proprioception impairment (joint position sense) in the lower extremity are also commonly reported following numerous musculoskeletal injuries (Hoch, Perkins, Hartman, & Hoch, 2017; Shakoor, Lee, Fogg, & Block, 2008). It is likely that somatosensory function is impaired following concussion, similar to musculoskeletal injuries, as both pathologies demonstrate impaired primary somatosensory cortex function on advanced neuroimaging (Diekfuss et al., 2019; Wang et al., 2016). Further, central muscle activation (i.e. the ability to voluntarily recruit all muscle fibers in a given muscle during a contraction) is impaired following musculoskeletal injury after conditions where the muscle is not directly damaged, such as anterior cruciate ligament repair, and even in the unaffected limb (Drechsler, Cramp, & Scott, 2006; Hart, Pietrosimone, et al., 2010). These findings suggest long-term somatosensory and neuromuscular impairment after musculoskeletal injury, which can lead to recurrent musculoskeletal injuries (Read, Oliver, De Ste Croix, Myer, & Lloyd, 2016). Despite our understanding of somatosensory and neuromuscular impairment after musculoskeletal injury, no studies have directly examined how these systems are affected post-concussion.

Preliminary evidence suggests somatosensory and neuromuscular deficits exist post-concussion (Howell, Lynall, et al., 2018; Parker et al., 2006), but these outcomes have never been directly studied in concussed individuals. This is concerning as recent literature has identified that concussions place athletes, military service members, and the general population at over two times the risk for musculoskeletal injuries up to two years after clinical concussion recovery (Kardouni, Shing, McKinnon, Scofield, & Proctor, 2018; Lynall, Mauntel, Padua, & Mihalik, 2015; Lynall, Mauntel, et al., 2017; McPherson, Nagai, Webster, & Hewett, 2018; McPherson, Shirley, Schilaty, Larson, & Hewett, 2020). Though there is significant evidence for increased musculoskeletal injury risk following concussion (Kardouni et al., 2018; Lynall et al., 2015; Lynall, Mauntel, et al., 2017; McPherson et al., 2018), it is unknown what neurophysiologic factors remain and contribute to this phenomenon. In order to prevent long-term health consequences from both musculoskeletal injury and concussions, identifying what factors are contributing to global neurophysiologic deficits is critical.

Therefore, the overall purpose of this dissertation is to compare functional movement, somatosensory, and neuromuscular function between a cohort of college-aged individuals acutely (0-7 days) and when asymptomatic (±72 hours) following concussion, and yoked, healthy matched-controls. By understanding functional movement, somatosensory, and neuromuscular deficits following concussion, we can guide future longitudinal studies assessing how these impairments may lead to musculoskeletal injury, and ultimately develop interventions to mitigate long-term consequences.

Specific Aims, Hypotheses, and Variables

<u>Specific Aim 1</u>: To examine differences in functional movement (single-leg hop, gait) under single- and dual-task conditions between concussed young adults and yoked healthy matched-controls at two clinical time-points (acute [<7 days]; asymptomatic [±72 hours]) post-concussion.

Hypothesis 1a: Concussed individuals will display slower reaction time, worse dynamic postural stability indices, greater joint angles and moments, and greater peak ground reaction force during the single-task single-leg hop assessment compared to healthy matched-controls acutely and when asymptomatic.

Hypothesis 1b: Concussed individuals will display slower reaction time, shorter stride length, wider stride width, slower gait velocity, and worse center of pressure path efficiency during the single-task gait assessment compared to healthy matched-controls acutely, but not when asymptomatic.

Hypothesis 1c: Concussed individuals will demonstrate significant improvement on single-leg hop and gait assessment outcomes at asymptomatic compared to acute, but will still demonstrate impairments relative to the healthy control group.

Hypothesis 1d: Concussed individuals will perform significantly worse on single-leg hop and gait outcomes under dual-task conditions both acutely and when symptom-free compared to the healthy control group.

Independent Variables: Group (concussed and healthy group), timepoint (acute [0-7 days post-injury] and asymptomatic [± 72 hours from symptom-free]).

Dependent Variables: Reaction time (s), dynamic postural stability index (unitless), sagittal and frontal ankle and knee joint angles (°), sagittal and frontal ankle and knee joint internal normalized moments (Nm/bw), and normalized vertical ground reaction force (N/bw) during single-leg hop; reaction time (s), stride length (cm), stride width (cm), gait velocity (m/s), and center of pressure efficiency (%) during gait. All analyzed under single- and dual-task conditions separately.

Specific Aim 2: To examine differences in somatosensory (pressure-pain threshold, touch sensation threshold, and passive joint repositioning) function between concussed young adults and healthy matched-controls at two clinical time-points (acute [<7 days] and at asymptomatic [±72 hours]) post-concussion.

Hypothesis 2a: Concussed individuals will display decreased somatosensory function compared to healthy matched-controls acutely and when asymptomatic.

Hypothesis 2b: Concussed individuals will not demonstrate significant improvement on somatosensory assessments at asymptomatic compared to acute.

Independent Variables: Group (concussed and healthy group), timepoint (acute [0-7 days post-injury] and asymptomatic [± 72 hours form symptom-free]).

Dependent Variables: Pressure-pain threshold (lbf/cm^2), touch sensation threshold (gm), and passive joint repositioning accuracy (|°|).

Specific Aim 3: To examine differences in neuromuscular function between concussed young adults and healthy matched-controls when asymptomatic (±72 hours) post-concussion.

Hypothesis 3a: Concussed individuals will display decreased neuromuscular function compared to healthy matched-controls acutely and when asymptomatic.

Hypothesis 3b: Concussed individuals will not demonstrate significant improvement on neuromuscular assessments at asymptomatic compared to acute.

Independent Variables: Group (concussed and healthy group), timepoint (acute [0-7 days post-injury] and asymptomatic [± 72 hours form symptom-free]).

Dependent Variables: Maximal voluntary isometric contraction torque (Nm), superimposed burst torque (Nm), central activation ratio (%).

Operational Definitions

- *Asymptomatic*: The moment someone reports being symptom-free (± 3 symptom severity) on a symptom checklist relative to their retrospective baseline signs and symptoms proxy where participants indicate their signs and symptoms typically experienced on a regular basis > 3 times a week (Hoffman, O’Connor, Schmidt, Lynall, & Schmidt, 2018, 2019; Schmidt et al., 2017).
- *Reaction time*: The time between a visual (single-leg hop) or auditory (gait) stimulus and initial body movement as measured by either sacral (single-leg hop) or center of pressure (gait) movement ≥ 3cm from the mean position prior to the stimulus (Lempke, Johnson, Schmidt, & Lynall, 2020; Lynall et al., 2018)
- *Center of pressure*: A single point where the ground reaction force vector falls between a participant’s base of support.
- *Dynamic Postural Stability Index*: Composite score that combines ground reaction force

from all three planes across time and represents an individual’s capability to maintain balance when rapidly changing from a dynamic to a static movement (Wikstrom, Tillman, et al., 2010; Wikstrom, Tillman, Smith, & Borsa, 2005). A higher composite score indicates greater balance variability.

- *Stride length*: The distance between heel contact of one limb and contact of the ipsilateral heel during gait.
- *Stride width*: The perpendicular distance between the medial aspect of a participant’s heel and the medial aspect of the next ipsilateral heel during gait.
- *Gait velocity*: The average distance traveled over time (m/s) during gait.
- *Center of pressure path efficiency*: The percentage ratio of center of pressure (CoP) distance divided by CoP displacement. Higher percentage indicates greater efficiency.
- *Joint angle*: The angle (°) between a distal segment relative to a proximal segment.
- *Joint Moment*: The force times moment arm (i.e. torque) produced within a general muscle group producing that motion derived from kinematic (positional) and kinetic (force) data from 3D motion analysis. For example, an internal knee extension moment would be torque produced from the muscles contributing to knee extension (i.e. primarily the quadriceps).
- *Normalized peak ground reaction force*: The maximal peak ground reaction force divided by the participant’s body weight (N/bw) to correct for weight-based biases.
- *Pressure-pain threshold*: The minimum amount of force (lbf/cm^2) needed for a participant to perceive the pressure has transitioned to the start of a painful stimulus using an algometer (Xiong, Goonetilleke, & Jiang, 2011).
- *Touch sensation threshold*: The minimum amount of force (gm) a participant can detect

using Semmes-Weinstein monofilaments (Collins, Visscher, De Vet, Zuurmond, & Perez, 2010; Snyder, Munter, Houston, Hoch, & Hoch, 2016).

- *Passive joint repositioning*: Somatosensory assessment where a Biodex dynamometer moves the participant's lower leg automatically from a starting position, to a target position for 10s, then back to the starting position. Then the test moves the limb at 1 °/s until the participant believes their limb is back at the target position and presses a trigger to stop (Callaghan, Selfe, McHenry, & Oldham, 2008).
- *Maximal voluntary isometric contraction (MVIC)*: Maximal torque (Nm) produced by the participant's voluntary neuromuscular activation in a fixed joint position.
- *Superimposed burst*: Additional amount of torque (Nm) produced during a MVIC and supramaximal electrical stimulation above just a MVIC.
- *Central Activation Ratio (CAR)*: The ratio of $\frac{MVIC}{(MVIC + \ Superimposed\ Burst)} \times 100$ as a percentage.

Assumptions

1. Participants provided maximal effort across all assessments.
2. Accurate and honest symptom reporting among participants to determine asymptomatic assessment timepoint.
3. Minimal to no difference on assessments attributed to variable time accruing at the acute (0-7 days post-injury) timeframe.

Limitations

1. Findings may not be generalizable outside general, college-aged populations.
2. Principal investigator was not blinded to participant's group level and administered all assessments.

3. No pre-injury outcomes measured among concussed or control cohorts (i.e., preexisting differences may have already been present).
4. Small sample size collected due to COVID-19 pandemic and greatly reduces general conclusions able to be drawn.

Delimitations

1. Participants recruited from a single, large public university in the state of Georgia and are between the age of 18 and 35 years old.
2. Assessment timepoints are based on clinical timepoints rather than fixed days following injury due to the heterogeneous symptom recovery patterns of concussion.
3. Study design limited to relatively early timepoints post-injury.

CHAPTER 2

LITERATURE REVIEW

Concussions are a prevalent pathology across all populations resulting in transient symptom presentation, impaired postural stability, and/or diminished neurocognitive function (Cancelliere et al., 2017; Langlois et al., 2006; McCrory et al., 2017). Post-concussion impairments on standard clinical assessments of signs and symptoms, postural stability, and neurocognitive performance resolve around 14 days for the majority of individuals in athletics (Garcia et al., 2018; Kerr, Zuckerman, et al., 2016; Wasserman et al., 2016), however, emerging research indicates lingering movement deficits that could have vital implications for patient outcomes (Howell, Lynall, et al., 2018; Parker et al., 2006).

Growing studies have examined gait spatiotemporal outcomes following concussion and have identified gross impairments (Büttner et al., 2019; Fino et al., 2016; Howell, Buckley, et al., 2018; Howell et al., 2015). Similarly, individuals with a concussion history have displayed altered movement and landing biomechanics during jumping and cutting tasks (Avedesian et al., 2020; DuBose et al., 2017; Lapointe et al., 2018; Lynall et al., 2018). Cumulatively, these findings indicate underlying neurophysiological deficits during functional tasks that likely stem from somatosensory input (e.g., pain, proprioception, and touch sensation) and/or neuromuscular output (e.g., muscle activation and recruitment) impairment (Chmielewski et al., 2020). To date, no studies have directly assessed somatosensory or neuromuscular function. This may be a critical missing piece from our understanding of the heightened musculoskeletal injury risk after concussion (Kardouni et al., 2018; Lynall et al., 2015; Lynall, Mauntel, et al., 2017; McPherson et al., 2018). To promote positive health outcomes after concussion, identifying the factors contributing to global neurophysiologic deficits is critical. Accordingly, this literature review will focus on: 1) concussion epidemiology, assessment, and recovery, 2) functional movement deficits following concussion, and 3) somatosensory and neuromuscular deficits following musculoskeletal injuries and their relationship concussion.

Concussion Epidemiology, Assessment, and Recovery Overview

Concussion Epidemiology

Concussion is a widespread pathology affecting many athletes across sport, competition level, and sex (Rosenthal, Foraker, Collins, & Comstock, 2014; Wasserman et al., 2016), as well as the general population and military service members (Cancelliere et al., 2017; Harman, Hooper, & Gackstetter, 2005; Langlois et al., 2006). Differences between concussion rates among sports and sexes have been established, with male American football, women's soccer, and men's soccer frequently having the highest rates across traditional sports in the United States (Castile, Collins, McIlvain, & Comstock, 2012; Gessel, Fields, Collins, Dick, & Comstock, 2007; Zuckerman et al., 2015). Females have approximately two times greater concussion rates than males among sex-comparable sports with similar rules and regulations, such as soccer or basketball, and therefore being a female participating in sport could be considered a risk factor (Castile et al., 2012; Gessel et al., 2007; O'Connor et al., 2017; Zuckerman et al., 2015). Numerous other concussion risk factors have been examined among large epidemiological datasets, with concussion history (Brett, Kuhn, Yengo-Kahn, Solomon, & Zuckerman, 2018; Guskiewicz et al., 2003; Van Pelt et al., 2019), contact sport (Brett et al., 2018; Wasserman, Coberley, Anderson, Grant, & Hardin, 2018), Attention Deficit Hyperactivity Disorder (Brett et al., 2018), and game/competition participation (Wasserman et al., 2018; Zuckerman et al., 2015) being significant risk factors. These findings provide researchers and clinicians insight into concussion incidence and risk factors to 1) provide appropriate medical staffing for higher risk sports, and 2) understand certain demographic factors that place individuals at greater risk for concussion.

Concussion Assessment

Current best-evidence and expert consensus statements call for a multidimensional standardized clinical assessment battery consisting of, at minimum, symptom, postural stability, and neurocognitive assessments (Broglio et al., 2014; McCrory et al., 2017). Each component assesses a unique aspect of an individual's function to provide the clinician insight into the possible concussion. Numerous symptom checklists have been developed over time, with the most frequently used symptom checklist being the 22-item Post-Concussion Symptom Scale (PCSS) (Lempke, Schmidt, & Lynall, 2020; Lovell et al., 2006) that is also imbedded in the Sport Concussion Assessment Tool 5th edition (SCAT5) (Echemendia et al., 2017). Symptom checklists have been identified as having the strongest diagnostic accuracy (sensitivity: 0.78-0.93, specificity: 0.97-1.00) of any assessment tool to date (Garcia et al., 2018; Resch et al., 2016). Relying solely on symptom checklists however is a subjective assessment and depends upon individuals to accurately report their symptoms, with concussion underreporting occurring frequently (21-82% non-reported rate) (Delaney, Caron, Correa, & Bloom, 2017; Kerr, Register-Mihalik, Kroshus, Baugh, & Marshall, 2016; LaRoche, Nelson, Connelly, Walter, & McCrea, 2016; McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004; Register-Mihalik et al., 2013). Due to the subjective nature of symptom assessments, more objective approaches have been developed.

Postural stability assessments have been implemented into clinical practice to provide objective insight into impaired motor control after concussion. One of the most commonly used (Lempke, Schmidt, et al., 2020) and recommended assessment tools (Broglio et al., 2014; McCrory et al., 2017) is the Balance Error Scoring System (BESS). The BESS was developed in 1999, and since has become a keystone in concussion assessment due to being free and clinically feasible (Guskiewicz, Ross, & Marshall, 2001; Riemann, Guskiewicz, & Shields, 1999). However, the BESS has faced scrutiny due to poor intra-, inter-, and test-retest reliability when implemented clinically (Broglio et al., 2017; Finnoff, Peterson, Hollman, & Smith, 2009). More objective, computationally advanced assessments such as the Sensory Organization Test have been developed and implemented, but do not appear to have additional clinical utility over BESS (Guskiewicz et al., 2001). Though the BESS is an imperfect assessment, to date, it is still recommended for clinical assessment as it is the only measure of postural stability and motor control employed.

Computerized neurocognitive assessments have been recommended for clinical practice since 2002 (Aubry et al., 2002). Numerous computerized neurocognitive testing platforms exist such as CNS Vital Signs (Gualtieri & Johnson, 2006), Automated Neuropsychological Assessment Metrics (ANAM) (Bryan & Hernandez, 2012), Immediate Post-Concussion and Cognitive Testing (ImPACT) (Iverson, Lovell, & Collins, 2003), and several others. Approximately 84% of sports medicine professionals use ImPACT (Lempke, Schmidt, et al., 2020). Widespread implementation of ImPACT likely stems from the numerous reliability, validity, and diagnostic accuracy studies performed throughout development (Iverson et al., 2003; Schatz et al., 2006). Early research demonstrated ImPACT has strong diagnostic accuracy (sensitivity: 0.82, specificity: 0.89) when considering all cognitive domains and the built-in

PCSS and was generally believed to be the best assessment tool to date. More contemporary work has indicated computerized neurocognitive testing, regardless of platform used, has lower diagnostic accuracy than a symptom checklist (Garcia et al., 2018; Resch et al., 2016). Using only cognitive domains from ImPACT, both the sensitivity and specificity are 0.53 for concussion diagnosis (i.e. 3% better than chance alone) (Resch et al., 2016). This work indicates previous ImPACT diagnostic accuracy reports (Schatz et al., 2006) were likely inflated by the embedded symptom checklist, but overall indicate a multidimensional assessment battery is better than relying on one specific assessment.

Using a symptom checklist along with postural stability and computerized neurocognitive assessments improves diagnostic accuracy (Broglio, Macciocchi, & Ferrara, 2007; Garcia et al., 2018; Resch et al., 2016). The sensitivity and specificity of this multidimensional battery range from 0.80 – 0.93 to 0.96 – 0.98, respectively (Broglio et al., 2007; Garcia et al., 2018; Resch et al., 2016). Although a multidimensional assessment battery has been recommended since 2009 (McCrory et al., 2009), clear discrepancies exist between evidence-based practice and clinical practice. Athletic trainers have greatly improved their multidimensional assessment battery utilization from 21% in 2011 (Lynall, Laudner, Mihalik, & Stanek, 2013) to 53% in 2018 (Lempke, Schmidt, et al., 2020), however, this also indicates 47% of athletic trainers are not using this approach. Improper concussion assessment and management is widespread across all healthcare professionals involved. For example, only 26% of physicians utilized standardized concussion assessment tools (Zemek et al., 2014), only 27% of speech-language pathologists knew a Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) could not identify a concussion (Duff & Stuck, 2015), 65% of physician medical residents failed to recognize concussion signs and symptoms (Mann, Tator, & Carson, 2017), and 13% and 0% of chiropractors used a SCAT version or BESS for their concussion assessments, respectively (Taylor & Wynd, 2018). Clinicians and researchers must strive to remain up to date on current best practices to ensure optimal concussion assessment and patient safety.

Concussion Recovery

Concussions have been demonstrated in animal and human models to initiate a complex neurophysiologic response to the initial insult (Barkhoudarian, Hovda, & Giza, 2016; Giza & Hovda, 2014). Previous work has outlined seven distinct pathophysiologic concussion phases: 1) ionic flux of potassium, sodium, calcium, and excitatory neurotransmitter release, 2) an energy crisis where cerebral blood flow is throttled when axons are in a hypermetabolic state, 3) cytoskeletal damage which leads to 4) axonal dysfunction and 5) altered neurotransmission which is presumably the post-concussion clinical manifestations observed, and possible 6) inflammation and 7) axonal cell death (Barkhoudarian et al., 2016; Giza & Hovda, 2014). Although clinical assessments are used as surrogates to understand concussion recovery and promote a safe return to pre-injury status, it is unknown if recovery on clinical assessments represent neurometabolic recovery.

Concussion recovery can be separated into two general categories: *clinical recovery* and *physiological recovery* (Kamins et al., 2017). *Clinical recovery* can broadly be defined as a return to normative or baseline values on the multidimensional assessment battery (symptom checklist, postural stability, neurocognitive testing) and unrestricted return to pre-injury activities (Kamins et al., 2017; McCrory et al., 2017). Symptom recovery should be considered a sub-category under clinical recovery as it typically contributes the majority of days required for clinical recovery to occur. Symptom recovery can be defined as a return to pre-injury sign and symptom levels experienced. Lastly, *physiological recovery* can be defined as return to normative or baseline values on neurophysiological measures such as electroencephalogram (EEG), magnetic resonance spectroscopy (MRS), functional magnetic resonance imaging (fMRI), or functional near-infrared spectroscopy (fNIRS), but consensus on an operational definition currently does not exists (Kamins et al., 2017). However, these neurophysiological measures are considered research tools and currently do not have clinical utility due to the unknown implications of neurophysiological deficits (Kamins et al., 2017; McCrory et al., 2017).

The majority of athletes *clinically recover* within 10-14 days (Garcia et al., 2018; O'Connor et al., 2017). In contrast, *physiological recovery* may last approximately one-month, though more research is needed (Meier et al., 2015; Vagnozzi et al., 2010). Studies using fMRI to examine oxygenated hemoglobin, a surrogate for cerebral blood flow, have observed impaired hemodynamics acutely that approach normalization at 30-days post-injury among football players recovering from concussion, though the study timepoints ended before complete resolution (Meier et al., 2015). Similar MRS findings suggest metabolites within the brain recover for the concussed group around 28 days post-injury (Vagnozzi et al., 2010). Clinical and physiologic deficits during the acute (0-7 day) period following concussion are correlated with each other; however, the physiological time to recovery is approximately twice the time of clinical recovery (Wang et al., 2016, 2018). Despite physiologic recovery taking longer than clinical recovery, current consensus does not suggest waiting for physiologic recovery to occur before returning to activities as the true meaning of physiological assessments are currently unknown, and heterogeneous findings and study methods confound previous work (Kamins et al., 2017).

A growing body of research has identified correlative links to short- and long-term post-concussion negative health outcomes. Neurocognitive impairments and neurodegenerative diseases have been identified long-term after concussion (Alosco et al., 2017; Kerr, Marshall, Harding, & Guskiewicz, 2012; Stamm et al., 2015), but the true causal nature remains unclear. One negative outcome with consistent findings is heightened musculoskeletal injury risk following concussion (McPherson et al., 2018). Previous work has identified that concussions place athletes (Burman, Lysholm, Shahim, Malm, & Tegner, 2016; Cross, Kemp, Smith, Trewartha, & Stokes, 2016; Gilbert, Burdette, Joyner, Llewellyn, & Buckley, 2016; Jildeh et al., 2020; Krill, Nagelli, Borchers, Krill, & Hewett, 2018; Lynall et al., 2015; Lynall, Mauntel, et al., 2017; McPherson et al., 2018; Nordström, Nordström, & Ekstrand, 2014; Wittrup, Fox, Breedlove, Memmini, & Broglio, 2020) and military service members (Kardouni et al., 2018) at over two times the risk for musculoskeletal injuries up to two years after clinical concussion recovery. Concerningly, current clinical assessments (e.g. symptoms, balance, neurocognitive assessments) are not able to distinguish between those who go on to sustain a musculoskeletal injury and those who do not following concussion (Buckley et al., 2020; Murray et al., 2020). It is important to note that previous research methods stopped examining this phenomenon after two years, making the true post-concussion musculoskeletal injury risk timeframe unknown. Multiple previous concussions (Harada, Rugg, Arshi, Vail, & Hame, 2019; Houston et al., 2018) and sex (Houston et al., 2018) appear to be moderators to the musculoskeletal risk, with greater concussion history frequency and females experiencing greater musculoskeletal injury odds by two- to three-fold. Despite a clear relationship between concussions and musculoskeletal injury risk, no research has attempted to identify what specific neurophysiological factors contribute to this negative health concern.

Researchers have only theorized why musculoskeletal injury risk is heightened following concussion. Impaired neuromuscular control under cognitive loading post-concussion, similar to deficits identified during dual-task gait assessments (Büttner et al., 2019; Howell, Buckley, et al., 2018; Howell et al., 2015), is believed to be a factor (Howell, Lynall, et al., 2018). Perception-action coupling, the theory-driven relationship between an individual's movement and their external environment perception, has also been proposed (Eagle, Kontos, Pepping, et al., 2019). Lastly, neuromechanical coupling has been suggested as a theoretical driver for musculoskeletal injury risk after concussion (Wilkerson, Grooms, & Acocello, 2017). Neuromechanical coupling refers to the connection and action of neuromuscular control factors (e.g. Golgi tendon organs, muscle spindles) that regulate muscle tone to augment joint stiffness based on sensory input (e.g. visual, auditory, somatosensory) at the cortical level (Needle, Lepley, & Grooms, 2017). Though different theoretical processes and models have been proposed, they all revolve around the same three general factors and the interactions between them: sensory input, cognitive processing, and neuromuscular output. These three broad factors are the basis of human movement, with deficits in one area resulting in altered movement performance. For example, as the number or intensity of external and/or internal stimuli (i.e. sensory input) increases, cognitive processing and neuromuscular control are affected (Plummer & Eskes, 2015). In order to fully understand these neurophysiological factors resulting in heightened musculoskeletal injury risk, thorough exploration of functional movement deficits and each potentially contributing neurophysiological component is warranted.

Functional Movement Deficits Following Concussion

Gait Deficits Following Concussion

Residual movement deficits that extend beyond typical concussion recovery have been identified during gait and more sport-like, functional movements that could have vital implications for patient outcomes (DuBose et al., 2017; Howell, Lynall, et al., 2018; Parker et al., 2006). Gait assessments have grown in their post-concussion research use in recent years due to the daily functional nature and gross sensorimotor demands required, as well as increasing ease of access to objective assessment tools (Büttner et al., 2019; Fino et al., 2016; Howell, Buckley, et al., 2018; Howell et al., 2015). Gait consists of a complex integration of somatosensory input, cognitive processing and planning, and neuromuscular output to produce smooth and efficient movement of the entire body (Riemann & Lephart, 2002), and has been identified to be disrupted following concussion.

Gait studies involving concussed individuals have been primarily limited to spatiotemporal and center of pressure-based assessments using reliable gait mats (Lynall, Zukowski, Plummer, & Mihalik, 2017). Numerous studies have examined spatiotemporal and center of mass gait parameters post-concussion (Fino et al., 2016; Howell, Osternig, & Chou, 2013; Parker et al., 2006; Parker, Osternig, van Donkelaar, & Chou, 2007). However, no researchers have examined whole-body kinematics or kinetics post-concussion, which greatly limits our understanding of biomechanical outcomes such as joint angles and moments occurring throughout the lower extremity. When previous studies are interpreted independently, indicate heterogeneous differences during gait assessments. For example, previous work among concussed individuals has identified slower gait velocity (Catena, van Donkelaar, & Chou, 2007a; Parker et al., 2006), slower peak anterior center of mass velocities (Catena et al., 2007a), and decreased gait turning curvatures (Fino et al., 2016) compared to a healthy cohort acutely between 2-5 days post-injury. However, previous work also contradicts those findings as gait velocity (Catena, van Donkelaar, & Chou, 2009; Howell, Osternig, & Chou, 2018; Howell, Osternig, Koester, & Chou, 2014; Parrington et al., 2019) and center of mass velocities (Catena, van Donkelaar, & Chou, 2007b; Catena et al., 2009) did not differ at any clinical timepoint between concussed and control groups.

These inconsistencies may be driven by relatively small sample sizes which can either mask or inflate true effects given the direct relationship between sample size and p values (Sullivan & Feinn, 2012; The Cochrane Collaboration, 2011). The different gait assessment techniques (motion capture vs. pressure mats), various populations, and variable time to examination post-injury are also plausible contributors to the discrepancies in the literature. However, a recent meta-analysis pooled individual participant gait data (n= 1039; concussed n=516) to shed light on these concerns (Büttner et al., 2019). The authors observed subtle, but significantly slower gait and anteroposterior center of mass velocity and less anteroposterior center of mass displacement, but not mediolateral center of mass displacement or velocity, in the concussed group immediately following injury until 1-week post-injury (Büttner et al., 2019). Unfortunately, the meta-analysis did not include traditional measures of effect sizes which greatly limits the true understanding of meaningful changes between groups.

Gait assessments under cognitive loading (i.e., dual-task) have grown in recent years. Dual-task gait assessments have led to the identification of larger and/or longer lasting deficits (Parker et al., 2006) than single-task gait assessments (gait alone). Using dual-task gait assessments, researchers have identified deficits up to two months after injury, extending beyond single-task gait assessments and clinical recovery, potentially indicating lingering neuromuscular control deficits (Howell, Lynall, et al., 2018; Parker et al., 2006). Specifically, dual-task gait paradigms have been used to identify reduced gait velocity (Catena et al., 2007b), altered spatial gait parameters (Parker, Osternig, van Donkelaar, & Chou, 2008), and increased center of mass velocity (Howell et al., 2013) and displacement (Catena et al., 2007b) post-concussion where single-task gait assessments resulted in no observable deficits.

Similar to single-task gait, there is great variability in sample sizes, gait assessment instrumentation, populations, and time to assessment post-injury in the dual-task literature. Further, a recent systematic review identified 22 studies that examined dual-task gait using 13 different cognitive conditions for the dual-task paradigm which likely introduces variability to the findings (Howell, Lynall, et al., 2018). The same meta-analysis described earlier examined single- and dual-task gait assessments on individual participant data and identified slower walking speed, greater mediolateral center of mass displacement, and overall dual-task cost ([{dual-task – single-task outcomes}/ single-task outcome] x 100) (Howell, Buckley, et al., 2018) in concussed individuals compared to controls up to 2-months post-injury (Büttner et al., 2019).

Though significant differences exist between concussed and control participants up to 2-months post-injury, it is important to note the relatively small mean differences identified. For example, the dual-task mean difference average walking speed was 0.06 m/s (95% CI: 0.004 – 0.11) between concussed and control participants at 2-months post-concussion (Büttner et al., 2019). It is unknown at this time if the small-magnitude differences are truly indicative of underlying neurophysiological changes after concussion, or in this case, the result of overpowered data pooling from the 1,036 participants. Regardless, the body of single- and dual-task gait literature highlights the need for future studies to establish the relationship between gait assessments and pure measures of neurophysiological function.

Functional Movement Deficits Following Concussion

Gait assessments provide insight to a functional activity of daily living to assess a level of readiness to return back to daily activities. However, it is unknown if gait assessments adequately assess return to physical activity or sport readiness. The somatosensory, cognitive, and neuromuscular demands during sport activities likely exceed those required for gait due to the everchanging sport environments and highly dynamic movement required. Our previous work has identified that clinical measures (i.e. gait, computerized neurocognitive testing) and functional movements (i.e. jumping, cutting, hopping) do not correlate with each other when examining reaction time among healthy participants (Lempke, Johnson, et al., 2020). Though we only examined reaction time, our findings further support the notion that functional, sport-like movement assessments may be a critical missing piece when determining return to play readiness post-concussion. Related, heightened musculoskeletal injuries and residual deficits after concussion have been identified and theoretically connected to altered neuromuscular function and movement patterns (Howell, Lynall, et al., 2018; McPherson et al., 2018). To date, no studies have examined functional movement at any point during traditional clinical recovery, limiting our insights to true functional movement alterations post-concussion. However, recent sport-specific functional movement assessments have been explored among individuals with a history of concussion to help address this concern (Avedesian et al., 2020; DuBose et al., 2017; Eagle, Kontos, Mi, et al., 2019; Lapointe et al., 2018; Lynall et al., 2018).

Cumulatively, individuals with concussion history have displayed greater trunk flexion (Lynall et al., 2018), increased hip stiffness with concurrent decreased knee stiffness (DuBose et al., 2017), increased knee valgus and internal rotation (Lapointe et al., 2018), less ankle dorsiflexion and knee flexion (Avedesian et al., 2020), quicker time to peak knee flexion (Eagle, Kontos, Mi, et al., 2019), and slower time to stabilization (Lynall et al., 2020), a stability metric similar to the dynamic postural stability index, during jumping, landing, and cutting tasks. Though differences were observed between concussion history and control cohorts in these studies, numerous outcomes were examined that were not statistically different such as lower extremity joint angles, moments, and ground reaction forces. The lack of numerous kinematic and kinetic functional movement differences is likely driven by multiple factors. The relatively small samples (9 – 24 subjects) employed in studies can mask true differences present due to a greater signal to noise ratio (Avedesian et al., 2020; DuBose et al., 2017; Eagle, Kontos, Mi, et al., 2019; Lapointe et al., 2018; Lynall et al., 2018, 2020). Further, these studies examined individuals with a previous concussion anywhere from 2 months to 3 years after initial injury and are confounded by unknown musculoskeletal injury history among participants (DuBose et al., 2017; Lapointe et al., 2018; Lynall et al., 2018).

The highly variable post-injury assessment times coupled with small sample sizes and sometimes heterogenous concussion recovery likely confounds previous research. To date, no previous research has examined concussed individuals on functional movements using biomechanical outcomes throughout concussion recovery. Furthermore, the understanding of dual-task deficits remains limited to gait assessments and therefore it is unknown if dual-task deficits still linger or are longer lasting when coupled with more complex, sport-like movements (Büttner et al., 2019; Howell, Lynall, et al., 2018; Parker et al., 2006). Understanding kinematic and kinetic functional movement differences may provide critical insight for researchers and clinicians in order to better identify movement deficits, and ultimately utilize therapeutic rehabilitation techniques to address the deficits before returning back to sport.

No research to date has studied functional dual-task assessments post-concussion. However, understanding changes from single- to dual-task performance is critical among a healthy population first in order to truly understand pathological-driven deficits. Performance outcomes are typically reduced when a cognitive task is added (Almonroeder et al., 2018; Dai et al., 2018; McLean, Borotikar, & Lucey, 2010; Shinya, Wada, Yamada, Ichihashi, & Oda, 2011; Simon, Millikan, Yom, & Grooms, 2020; Westwood, Killelea, Faherty, & Sell, 2020). A recent studied implemented a single-leg hop assessment battery under single- and dual-task conditions and observed decreased hopping distance on a crossover, and triple- hop test, and decreased time to complete a 6m hop test during dual-task (Simon et al., 2020). Another study observed increased vertical ground reaction force during a dual-task jump landing task consisting of right- and left- handheld choice reaction time during jump takeoff (Shinya et al., 2011). Similarly, a dual-task paradigm (subtracting by 7's) jump landing assessment identified increased vertical ground reaction force coupled with decreased knee flexion and jump height when compared to single-task (Dai et al., 2018). A single-leg landing task identified greater knee abduction moments during dual-task (unanticipated cutting) as compared to single-task (McLean et al., 2010). Cumulatively, these findings indicate that increased vertical ground reaction force, joint moments, and decreased performance metrics are common for healthy participants under dual-task functional assessments. The current post-concussion battery does not include functional movement or dual-task despite movement differences between single-and dual-task in healthy individuals and identified gait dual-task deficits post-concussion. In order to ensure safe return to activity readiness following concussion, we need to explore functional movement and dual-task deficits.

Functional dual-task assessments are designed to emulate the cognitive and motor demands in sport. Dual-task deficits identified post-concussion may have vital implications for true return to sport readiness as they likely better assess concurrent cognitive and motor demands. Concussions have been identified to result in executive function and sustained attention deficits on neurocognitive testing that recovers within 14 days following injury (Garcia et al., 2018). However, these assessments are relatively simplistic, occur in quiet, static environments, and overall are unrelatable to the on-field demands of sport. Dual-task literature indicates a tradeoff between cognitive and/or motor task performance when completed simultaneously (Almonroeder et al., 2018; Dai et al., 2018; McLean et al., 2010; Shinya et al., 2011; Simon et al., 2020; Westwood et al., 2020). Dual-task performance appears to augment post-concussion cognitive and/or motor task performance beyond healthy participants (Howell, Lynall, et al., 2018; Parker et al., 2006), and may be due to the heightened complexity of assessments relative to current clinical tools. It is currently unknown whether more functional, dual-task assessments will elicit greater magnitude differences than current gait dual-task assessments post-concussion. Due to the greater neuromuscular demands required to complete functional jumping, hopping, or cutting tasks, it is likely dual-task deficits will be magnified relative to dual-task gait and may better indicate true return to sport readiness.

Somatosensory and Neuromuscular Deficits Following Injury

Before discussing somatosensory and neuromuscular deficits, it is important to outline our current understanding of contributions to each broadly defined term. Somatosensory information is one of many components contributing to the sensorimotor system. The sensorimotor system is comprised of multifactorial categories of afferent (somatosensory, vestibular, visual) and efferent (intrafusal and extrafusal muscle fibers) signals in the peripheral which lead to either interneuron synapsing at the spinal cord level and/or direct cerebral integration (Riemann & Lephart, 2002). The somatosensory system is comprised of four subcomponents; pain, temperature, proprioception, and tactile, with proprioception and tactile inputs further branching into various components (Figure 2.1).

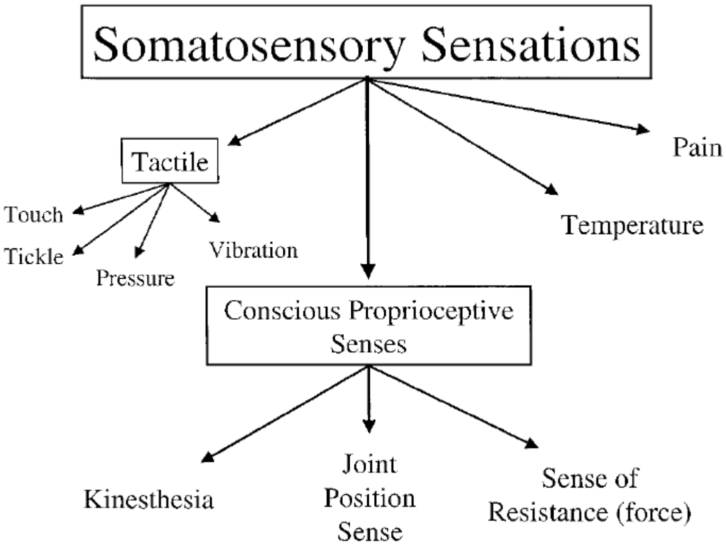

Figure 2.1. Model of Somatosensory Function Contributions from Periphery (Riemann & Lephart, 2002). Copyright 2002 by *Journal of Athletic Training*.

Proprioception is often incorrectly defined synonymously as sensorimotor, somatosensory, and joint position sense. Proprioception in summary is defined as the signals from sensory receptors specifically utilized to detect changes internal to the human body (Sherrington, 1952), whereas somatosensory is generalizable to all sensory contributions from the periphery (Riemann & Lephart, 2002). Today, proprioception can be segmented into three components; kinesthesia, joint position sense, and sense of force (Riemann & Lephart, 2002). Kinesthesia is defined as the detection of both active and passive limb motion, joint position sense is defined as the posture or position of a limb, and sense of force is defined as the joint and muscle mechanoreceptors sensing internal forces. All somatosensory sources, along with vestibular and visual input, contribute to input for the brain to process and provide the ambulation and/or correct muscle output. Although there is redundancy inherent to the somatosensory system, each receptor is specialized in either the sense or range of a sense it measures and the neuronal sampling or firing rate. For example, joint mechanoreceptors (Ruffini endings, Pacinian corpuscles, free nerve endings) overlap in function with muscle mechanoreceptors (Golgi tendon organs, muscle spindles), but the joint mechanoreceptors are more sensitive at the end ranges of motion and the muscle mechanoreceptors are more sensitive throughout the midrange of joint motion (Clark, Grigg, & Chapin, 1989; Riemann & Lephart, 2002).

Neuromuscular control can be defined as the conscious (e.g. voluntary muscle activation) and unconscious (e.g. intra- and inter-muscular firing patterns) neural and muscle contributions to task performance (Riemann & Lephart, 2002). Somatosensory contributions augment and optimize neuromuscular control, making them a necessary source of input to provide feedforward and feedback muscular output. Unfortunately, somatosensory and neuromuscular function is commonly altered after musculoskeletal injuries and may lead to recurrent musculoskeletal injuries as a result.

Somatosensory Deficits after Musculoskeletal Injuries

Somatosensory deficits globally are established across numerous acute and chronic musculoskeletal injuries. For example, acute first-time lateral ankle sprains commonly result in altered postural stability in both the injured *and uninjured limb* (Wikstrom, Naik, et al., 2010). Approximately 40% of those experiencing a first-time lateral ankle sprain go on to develop chronic ankle instability (Anandacoomarasamy, 2005), a functionally debilitating pathology hallmarked by mechanical and/or perceived joint instability, signifying disrupted somatosensory and/or neuromuscular function (Medina McKeon & Hoch, 2019). Similar somatosensory and neuromuscular function deficits are reported across other pathologies such as anterior cruciate ligament repair in both the affected *and unaffected limb* (Hart, Pietrosimone, et al., 2010), osteoarthritis (Kosek & Ordeberg, 2000), and those experiencing acute whiplash (Walton et al., 2011).

Though musculoskeletal injuries are believed to be isolated to the local tissue site, growing evidence has identified altered cognitive function on computerized neurocognitive assessments (McDonald, Wilkerson, McDermott, & Bonacci, 2019; Rosen, McGrath, & Maerlender, 2020; Swanik, Covassin, Stearne, & Schatz, 2007) and brain activation on advanced neuroimaging (Diekfuss et al., 2019; Kapreli et al., 2009; Terada, Johnson, Kosik, & Gribble, 2019) between injured and control groups. In other words, musculoskeletal injuries alter somatosensory and/or neuromuscular impairments and may also contribute to cognitive impairment. This appears as the inverse of heightened musculoskeletal injury risk post-concussion where cognitive impairment (i.e. concussion) likely leads to altered somatosensory or neuromuscular function (Howell, Lynall, et al., 2018). Concussions also demonstrate increased inflammatory protein release in the peripheral blood stream following injury and may indicate a systemic response (Di Battista, Churchill, Rhind, Richards, & Hutchison, 2019). However, no studies to date have directly examined somatosensory or neuromuscular function among early concussed individuals.

To accurately examine the numerous and closely tied somatosensory contributors in Figure 2.1, researchers have developed a wide range of instrumentation and methods (Riemann, Myers, & Lephart, 2002). Proprioception techniques can consist of active and passive methods, however, passive have been previously identified as having greater specificity to certain mechanoreceptors (Edin & Abbs, 1991). Kinesthesia is commonly assessed using a passive threshold movement detection method, where participants are given a blindfold and static-signal headphones to block confounding movement cues while their limb is slowly moved. Individuals are instructed to indicate the moment they detect movement and the direction of movement as part of the assessment (Nagai, Sell, Abt, & Lephart, 2012). Joint position sense is assessed in a similar method, but the emphasis is on accurately perceiving where the joint is in space and recreating the joint position (Cug, Wikstrom, Golshaei, & Kirazci, 2016). For example, participants are placed into a dynamometer and the limb is passively moved from a starting position to a target position. The dynamometer locks in place for a short period of time and participants are instructed to remember where their limb is in space while blindfolded. The dynamometer then returns to the starting position, and the assessment is initiated. The dynamometer then passively moves the participant's limb and the participant indicates when they believe their limb is back at the specific target position.

Pain assessments are commonly performed using a pressure-pain threshold technique which uses an algometer (i.e. calibrated force gauge) to find the minimal amount of pressure required to go from pressure to the initiation of painful stimuli (Rolke, Campbell, Magerl, & Treede, 2005; Sterling, 2011). Similarly, tactile sensation is frequently assessed clinically and in research using a touch sensation threshold method often through Semmes-Weinstein monofilaments (Collins et al., 2010; Snyder et al., 2016; Weinstein, 1993). Semmes-Weinstein monofilaments utilize a series of 20-force calibrated nylon filaments that bend at a specific force, which are utilized to find the range and then specific amount of touch sensation force someone is able to detect while blinded to the procedure. Alterations in pain processing via lower extremity algometry (pain-pressure sensitivity) have been observed in individuals after musculoskeletal injuries, indicating lingering neurophysiologic changes (Kosek & Ordeberg, 2000; Walton et al., 2011). Touch sensation deficits in the foot plantar surface via Semmes-Weinstein monofilaments, and joint position sense impairment in the lower extremity are commonly reported following numerous musculoskeletal injuries (Hoch et al., 2017; Shakoor et al., 2008).

Although acute and chronic somatosensory deficits have been identified after musculoskeletal injuries, our understanding of specific somatosensory deficits post-concussion is greatly limited. Previous work has identified altered postural stability and gait outcomes months to years after their concussion (Howell et al., 2013; Lynall et al., 2020; Parker et al., 2008). Both gait and postural stability assessments utilize comprehensive input from visual, vestibular, and somatosensory input. To date, no studies have directly assessed somatosensory outcomes described earlier, indicating a clear gap in the literature. Seminal research examining postural stability following concussion speculated balance impairment was attributed to improper sensory weighting or cognitive integration; however, assessments such as the Balance Error Scoring System (BESS) only removed visual input and manipulated somatosensory via a foam pad balance surface (Guskiewicz et al., 2001; Riemann & Guskiewicz, 2000). More advanced postural stability studies have utilized the Sensory Organization Test post-concussion to attempt to tease out visual and somatosensory function from each other (Broglio, Tomporowski, & Ferrara, 2005). However, all balance assessments require individuals to stand on a surface which activates the numerous somatosensory pathways at the feet and throughout each muscle and joint required to maintain position. Therefore, the current literature is not able to shed light on specific somatosensory alterations that may linger after injury.

Neuromuscular Deficits after Musculoskeletal Injuries

Numerous ways of assessing global neuromuscular function and voluntary muscle function have been developed and implemented over time. Previous protocols to assess muscle performance under isometric, isotonic, and isokinetic protocols have been developed, as well as more advanced methods. For example, electromyography (EMG) is a common method for assessing electrical neuronal activity related to voluntary muscle activation (Riemann et al., 2002). These assessments are limited to the participant’s volitional capabilities and may not accurately represent what their muscle is truly capable of producing.

Voluntary muscle activation is impaired following musculoskeletal injuries, *and even among pathologies where the muscle is not directly damaged*, such as anterior cruciate ligament repair limb (Drechsler et al., 2006). These findings have also been *consistently observed in the unaffected limb* (Hart, Pietrosimone, et al., 2010). Numerous factors can influence the neuronal signal or motor output being derived from the motor cortex such as altered cortical, spinal cord interneuron, or muscle excitation-contraction coupling (Rozand, Grosprêtre, Stapley, & Lepers, 2015). Therefore, several assessments have been developed to identify sources contributing to the altered neuromuscular control (Figure 2.2).

Transcranial magnetic stimulation (TMS) represents a non-invasive assessment technique designed to assess corticomotor function via magnetically-induced neuronal transmission from the motor cortex to the specific muscle being assessed (Rozand et al., 2015). Using TMS provides insight to systemic alterations contributing to injury, however, it does not provide specific insight to the generalized system being altered. Similarly, the Hoffmann reflex (H-reflex; equivalent to spinal stretch reflex) provides insight to altered neurotransmission from the muscle to the spinal cord, and back to the muscle (Palmieri, Ingersoll, & Hoffman, 2004). The H-reflex technique provides insight into motorneuron excitability when interneuron presynaptic inhibition (e.g. altered neurotransmitters) at the spinal cord is still included in the measurement (Zehr, 2002). Lastly, superimposed burst and interpolated twitch represent assessments of voluntary muscle activation relative to supramaximal electrically stimulated muscle activation to

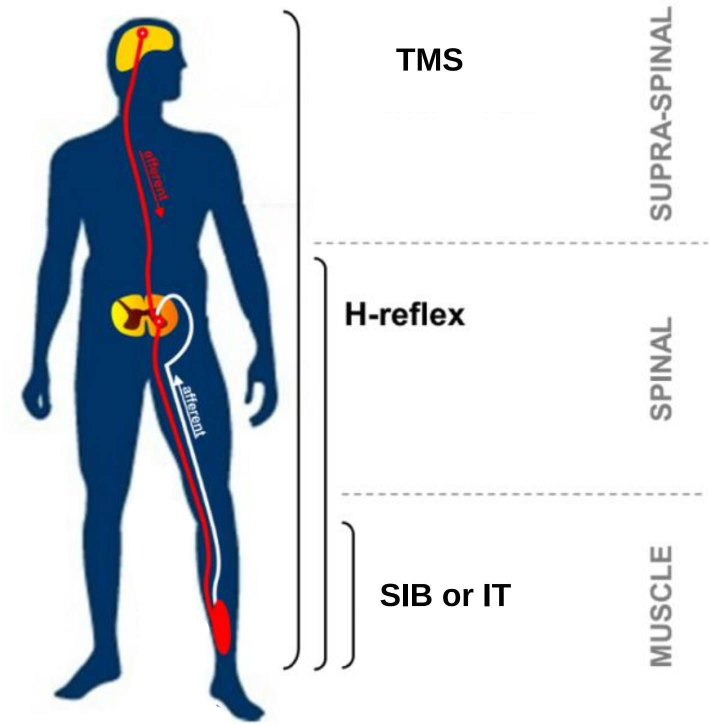

Figure 2.2. Neuromuscular function by generalized contributing systems. Gray text represents the generalized system involved; black text represents common assessment technique to assess the bracketed generalized system. TMS = Transcranial Magnetic Stimulation, H-reflex = Hoffmann reflex, SIB = Superimposed Burst technique, and IT = Interpolated Twitch technique. Figure modified from Rozand et al. 2015, Copyright 2015 by *Journal of Visualized Experiments*.

provide insight into altered neuromuscular function at the muscle level (Shield & Zhou, 2004).

Both the superimposed burst and interpolated twitch techniques specifically assess the targeted muscles disparity between voluntary and maximal muscle activation potential, with the superimposed burst technique assessing the central activation ratio and the interpolated twitch technique assessing voluntary activation. Both techniques and assessment outcomes ultimately examine the difference between voluntary muscle activation relative to maximal muscle activation potential; however, methodological differences and considerations exist. The superimposed burst technique provides the supramaximal muscle activation during a maximal voluntary isometric contraction, which ultimately reduces patient-perceived pain at the cost of potential voluntary contraction overestimation (Grindstaff & Threlkeld, 2014; Shield & Zhou, 2004). The interpolated twitch technique is considered the gold standard measurement (Shield &

Zhou, 2004), but previous work indicates increased participant pain (Grindstaff & Threlkeld, 2014; Miller, Holmbäck, Downham, & Lexell, 2006).

Superimposed burst is the most frequently utilized assessment technique within sports medicine and clinical science literature (Hart, Pietrosimone, et al., 2010), with the quadriceps most frequently being examined. The superimposed burst technique has identified decreased voluntary muscle activation, as indicated from decreased central activation ratio percentages, in individuals long after recovery from anterior cruciate ligament repair (Hart, Pietrosimone, et al., 2010; Lepley et al., 2015). Additional pathologies *not directly linked to the quadriceps* such as patellofemoral pain syndrome (Norte, Frye, & Hart, 2015), chronic ankle instability (Sedory, McVey, Cross, Ingersoll, & Hertel, 2007), and low back pain (Hart, Weltman, & Ingersoll, 2010) have demonstrated decreased quadriceps central activation. Growing research has identified altered primary motor cortex activity following musculoskeletal injuries (Diekfuss et al., 2019), and is similar to the inhibited motor cortex activity present following concussion (De Beaumont et al., 2011; Wang et al., 2016). It is likely that concussions alter neuromuscular function due to the brains direct control over our neuromuscular function. The brain sends efferent motor signals through the spinal cord and then through peripheral nerves to elicit motor unit activation. Unfortunately, any change in the efferent signal can reduce the motor unit output, as indicated in studies using TMS early post-concussion (Livingston et al., 2012, 2010) and among those with concussion history (De Beaumont et al., 2011). Due to numerous pathologies demonstrating altered quadricep central activation and the unknown neuromuscular consequences post-concussion, further research is warranted.

Current neuromuscular function studies throughout traditional clinical recovery from concussion are limited. Previous work using TMS has identified altered motor-evoked potentials at the end of their testing protocol (10 days post-injury) that did not follow the same traditional clinical recovery trajectory (Livingston et al., 2012). Another study observed weaker hand grip strength and decreased jump height among concussed patients when symptomatic relative to controls, but were no differences were identified once asymptomatic (Reed, Taha, Monette, & Keightley, 2016). Lastly, a study examining military personnel with concussion history relative to a match control group did not observe any knee extension or flexion isokinetic strength deficits (Eagle, Kontos, Mi, et al., 2019). These are the only identified studies specifically examining neuromuscular function following concussion which greatly limits our understanding of the true neurophysiological deficits post-concussion.

Study Rationale Summary

Concussions result in a complex neurophysiologic cascade that alters sensory, cognitive, and motor function (Garcia et al., 2018). Residual functional movement deficits have been identified far beyond clinical recovery (DuBose et al., 2017; Howell, Lynall, et al., 2018; Lynall et al., 2018), which may relate to the heighted musculoskeletal injury risk after concussion (McPherson et al., 2018). Somatosensory and neuromuscular function are likely impaired following concussion, similar to musculoskeletal injury, as both pathologies demonstrate impaired primary somatosensory and motor cortex function on advanced neuroimaging (Diekfuss et al., 2019; Wang et al., 2016). Current static postural stability assessments do not isolate somatosensory function. Similarly, no post-concussion clinical methods directly assess neuromuscular function. Unidentified somatosensory and neuromuscular function post-concussion leaves critical understanding to heightened musculoskeletal injury risk unexplored.

Transcranial magnetic stimulation has identified inhibited motor activation acutely and among those with concussion history relative to controls (De Beaumont et al., 2011; Livingston et al., 2012), suggesting neuromuscular function is initially altered and remains impaired. Though preliminary evidence indicates functional movement deficits post-concussion, it is unknown whether somatosensory and neuromuscular deficits are altered following concussion. Somatosensory and neuromuscular function have never been directly studied in concussed individuals. By understanding functional movement, somatosensory and neuromuscular deficits following concussion, we can guide future longitudinal studies assessing how these changes may lead to musculoskeletal injury, and ultimately develop interventions to mitigate negative long-term outcomes.

Methodological Considerations

The discussed methods for assessing functional, somatosensory, and neuromuscular function are considered reliable and valid assessments; however, they are subject to confounding variables. Psychological factors such as diagnosed anxiety or depression, or kinesiophobia (the fear of movement) are potential confounders to overall and functional movement outcomes (Geisser, Haig, Wallbom, & Wiggert, 2004). Individuals with pre-existing and diagnosed psychological factors should be excluded from study participation to isolate outcome variables. The 11-item, Tampa Scale of Kinesiophobia (TSK-11; Appendix C) is a reliable and valid measure for assessing kinesiophobia and is frequently employed to control for movement fear, if warranted (Woby, Roach, Urmston, & Watson, 2005). Pre-injury physical activity levels and training methods can greatly alter movement patterns, muscle performance characteristics (e.g. peak torque, endurance), and somatosensory function (Nicola Relph & Herrington, 2016). Matching participants based on height and mass can aide in reducing influential force-based characteristics, but does not account for lean muscle mass or neuromuscular function adaptations from training. To combat underlying physical activity levels and related training differences, physical activity scales are commonly employed (Nicola Relph & Herrington, 2016). The Tegner activity scale (Appendix D) is a reliable and valid patient-reported outcome commonly employed to assess pre-injury and current individual activity levels (Briggs et al., 2009; Tegner & Lysholm, 1985).

Measurement reliability is also a critical concern when utilizing and interpreting outcome measures. The previously outlined somatosensory outcomes have strong inter-, intra-rater reliability (Nagai et al., 2012; Rolke et al., 2005; Snyder et al., 2016; Xiong et al., 2011). The neuromuscular assessments via interpolated twitch or superimposed burst techniques have mixed reliability evidence. Previous research has identified the intraclass correlation coefficients to range from 0.48 – 0.91, but the 95% confidence intervals are either not reported, or encompass 0.00 and participants are excluded if they cannot produce reliable, plateaued torque for each trial (Luc et al., 2016; Norte et al., 2015; Snyder-Mackler, Binder-Macleod, & Williams, 1993), which may demonstrate skewed reliability. Given the discomfort or pain frequently reported with these neuromuscular assessments (Grindstaff & Threlkeld, 2014), it is not plausible to repetitively administer supramaximal stimulation to participants who may not tolerate it well, and especially among symptomatic concussed patients. Previous methodological considerations have been suggested to improve neuromuscular assessment reliability such as a minimum of two-pulse stimulation, torque production visual feedback, verbal encouragement during contraction, warm up and practice trials, consistent electrode placement, and allowing for at least one-minute of rest between trials (Grindstaff & Threlkeld, 2014; Luc et al., 2016; Pietrosimone, Selkow, Ingersoll, Hart, & Saliba, 2011; Shield & Zhou, 2004).

CHAPTER 3

METHODS

The methods employed for the three specific aims were all part of the same prospective, longitudinal study design consisting of functional movement, somatosensory, and neuromuscular assessments conducted among a concussed cohort and healthy, matched-control cohort at two clinical timepoints: acutely (0-7 days post-injury) and asymptomatic (± 72 hours). The overall study is described below.

Participants

All participants were recruited through the University Health Center (UHC; concussed participants) or from the student body at the University of Georgia (control participants) between August 2019 and February 2021. Concussed participants were included if they experienced a concussion diagnosed by a UHC physician independent from the research team in line with expert consensus guidelines (McCrory et al., 2017), and were seen within the UGA Concussion Research Laboratory for evaluation within 7 days of injury. Participants were given academic and physical activity restrictions consistent with current guidelines (McCrory et al., 2017). Control participants were recruited using approved verbal, flyer, and word-of-mouth methods and were included if they matched with a concussed participant on sex, age (± 1 year), height (10%), mass (5%), and concussion history (± 1 year) (Lynall et al., 2018, 2020). All participants were excluded if any of the following were met: were a National Collegiate Athletic Association athlete, had a history of any neurologic, memory, anxiety, or depression disorder, history of a lower extremity musculoskeletal injury <6 months that resulted in >24 hours of time-loss from physical activity, history of any lower extremity orthopedic surgery in the past year, and any contraindications to electrical stimulation (open wounds, deep vein thrombosis, potential pregnancy, malignancy, learning disability, cardiopulmonary history, infection, implanted electronic devices, and impaired sensation in the lower extremity). Participants received honorarium ranging between $10-$45 for their acute timepoint and $25-$85 for their asymptomatic timepoint, with honorarium ranges dependent upon grant funding periods. All participants provided written informed consent prior to study participation, and this study was approved by the University of Georgia's Institutional Review Board (PROJECT00000469).

Procedures and Instrumentation

All participants completed the same assessment battery in order of: 1) survey assessments, 2) functional movement assessments, 3) somatosensory assessments and 4) neuromuscular assessment with *a priori* within-block (e.g., functional movement assessments randomized) randomization (Table 3.1). Assessments were not randomized between assessment blocks to minimize the multiple lab spaces being utilized and additional time and potential fatigue associated with moving to different laboratories for the participant. The assessment battery administration order was identical between a participant's acute and asymptomatic timepoints. The asymptomatic timepoint assessment occurred for concussed participants once their signs and symptoms normalized to pre-injury status as described below. Control participants completed their "asymptomatic" timepoint assessment based upon the number of days between the two timepoints of their matched concussed counterpart. The neuromuscular assessment was only completed at the asymptomatic timepoint due to the associated discomfort and/or pain which could greatly increase attrition.

Table 3.1. Assessments Across Study Protocol.

Assessments	***Timepoint 1 (Acute [0-7 days])***	***Timepoint 2 (asymptomatic [<72 hours])***
Survey Assessments		
Post-Concussion Symptom Scale (PCSS)	X	X
Tampa Scale of Kinesiophobia (TSK-11)	X	X
Tegner Activity Scale	X	X
Musculoskeletal Injury History Form	X	
Functional Movement Assessments		
Gait (single- and dual-task)	X	X
Single-Leg Hop (single- and dual-task)	X	X
Somatosensory Assessments		
Passive Joint Repositioning	X	X
Touch-Sensation Threshold (Semmes-Weinstein Monofilaments)	X	X
Pressure-Pain Threshold (Algometry)	X	X
Neuromuscular Assessment		
Superimposed Burst Technique		X

Survey Assessments

Post-Concussion Symptom Scale (PCSS)

The Post-Concussion Symptom Scale (PCSS; Appendix A) is a 22-item survey consisting of common signs and symptoms of concussion. Participants rate their 1) symptom presence (i.e. yes or no for each symptom) and 2) symptom severity via a 6-point Likert scale, with 0= “none” and 6= “severe”, based on their symptoms at that *current point in time* (Echemendia et al., 2017). Both concussed and control participants first completed the PCSS at the start of both timepoints using the aforementioned instructions prior to any assessments, and then after each assessment block to examine for any symptom provocation.

Concussed participants completed a PCSS with modified instructions (Appendix B), rate their symptoms “typically experienced (>3 times per week)”, to establish a retrospective signs and symptoms baseline proxy (Hoffman et al., 2018, 2019; Schmidt et al., 2017). All concussed participants then completed a daily PCSS via online survey (Qualtrics, Provo, UT) to allow the research team to determine when the participant was asymptomatic (Hoffman et al., 2018, 2019; Schmidt et al., 2017). Daily PCSS survey compliance was strong, with all participants completing ≥81.2% (mean=96.3%) of daily surveys. Concussed participants’ asymptomatic status was determined when their retrospective baseline proxy was within the PCSS symptom severity reliable change score (± 3 symptom severity score) of their daily PCSS (Chin, Nelson, Barr, McCrory, & McCrea, 2016).

Tampa Scale of Kinesiophobia – 11 Item

The 11-item version of the Tampa Scale of Kinesiophobia (TSK-11; Appendix C) is a reliable and valid survey designed to assess the fear of human movement (Woby et al., 2005). The TSK-11 asked participants to indicate their level of agreement on a 4-point Likert scale (1=strongly disagree, 4=strongly agree) for all 11-items. The TSK-11 was administered at each timepoint to control for movement fear that may confound outcome findings and that may change over time.

Tegner Activity Scale

The Tegner activity scale (Appendix D) is a reliable and valid numerical rating scale where participants rate their before injury and current physical activity level using pre-established levels, ranging from 0= sick leave or disability pension and 10= competitive sports (Briggs et al., 2009; Tegner & Lysholm, 1985). The Tegner activity scale was administered at each timepoint to control for pre-injury and current differences in physical activity between concussed and control participants.

Musculoskeletal Injury History Form

A musculoskeletal injury history form (Appendix E) was modified and implemented based off previously published forms for descriptive purposes (Houston et al., 2018; Houston, Hoch, Van Lunen, & Hoch, 2017). The survey asked participants whether they had ever sustained any musculoskeletal injuries (i.e., sprains, strains, fractures, dislocations, and surgery) at the ankle, knee, hip, and back/torso body regions in the past five years. If participants reported "yes" to any musculoskeletal injury, a brief description of the injury type (e.g., ankle sprain – lateral ankle sprain), how long ago it occurred, and how many times it has happened were recorded.

Functional Movement Assessments

Both the gait and single-leg hop assessments were completed under single-task (i.e., completing the movement as quickly and best as possible) and dual-task (i.e., subtract as quickly and accurately as possible while concurrently completing the movement task as quickly and best as possible) conditions. Participants completed a standardized 20s subtraction task while seated, and separately performed a minimum of 1 practice gait and single-leg hop task prior to any data collection to ensure familiarity with each component. The dual-task paradigm used was standard across all assessments, with participants subtracting from a random number between 90 and 150 by either 6's or 7's throughout the movement (Fino et al., 2016; Lempke, Johnson, et al., 2020). Single- and dual-task condition order was randomized within each movement to minimize learning effects.

Gait

Gait was assessed using a reliable and valid (Lynall, Zukowski, et al., 2017) 4.9m long by 0.6m wide pressure sensor-embedded walkway (Zeno Walkway, ProtoKinetics, Havertown, PA) sampling center of pressure at 120Hz. All participants started the assessment at a fixed location on the walkway and were instructed to walk at their normal, comfortable pace until completely off the walkway (Lempke, Johnson, et al., 2020). Participants performed all assessments with their athletic shoes on (Lempke, Johnson, et al., 2020). Participants were instructed to "get set" when at the starting position and to start walking immediately following an audible beep. The audible stimulus was randomly activated 2-5s after the participant was told to "get set". Five gait trials under single- and dual-task (10 trials total per timepoint) were recorded and averaged under each condition.

Single-Leg Hop

The single-leg hop assessment occurred in an 8-camera 3D motion capture space (MIQUIS, Qualisys Systems, Göteborg, Sweden) recording at 240Hz with two piezoelectric in-ground force plates (BERTEC, Columbus, OH, USA) sampling at 1,200Hz. Participants stood on a 30cm-tall box placed 50% of their height behind the two force plates within the 3D motion capture space at the start of each trial. Participants were fitted with a cluster of three retroreflective markers over their posterior superior iliac spines and sacral body (Lempke, Johnson, et al., 2020; Lynall et al., 2018). Participants were instructed to take an athletic stance after being told to "get set". Once participants were set, a green light-emitting diode was activated randomly between 2 and 5s. Participants were told to move as quickly as possible after seeing the visual stimulus (Lempke, Johnson, et al., 2020; Lynall et al., 2018). Participants were given at least 1 practice trial prior to data collection, but were allowed more until they understood the task and self-reported feeling comfortable.

Participants jumped off the box with both feet and landed on a single-leg. Participants were instructed to maintain the standardized static landing position (hands on hips, maintain single-leg balance, contralateral leg bent with slight hip and knee flexion and not resting on the ipsilateral limb) immediately upon foot contact on the force plate for at least 10s (Lempke, Johnson, et al., 2020; Ross & Guskiewicz, 2004; Ross, Guskiewicz, Gross, & Yu, 2008). Trials were discarded and repeated if the participant's contralateral foot made ground contact for any reason or any portion of the ipsilateral foot was off the force plate at ground contact. Four trials were completed with each limb under single- and dual-task conditions (12 trials total per timepoint).

Somatosensory Assessments

The somatosensory assessments consisted of a passive joint repositioning, touch sensation threshold, and pressure-pain threshold assessments completed within a private examination area. All somatosensory assessments were completed on the participant's self-reported dominant leg (the leg they would kick a ball the farthest for distance).

Passive Joint Repositioning

Passive joint repositioning (i.e., joint position sense) was assessed using a research dynamometer (Biodex System 4, Biodex Medical Systems, Shirley, NY, USA). All participants completed trials with their dominant leg while blindfolded to remove joint position visual cues (Nagai et al., 2012). One practice trial was completed unblinded to ensure participants understood the instructions and felt comfortable with the assessment. The dynamometer was positioned so both the dynamometer and participant knee joint axes were aligned and the dynamometer movement arm was fixated proximal to the participant's malleoli. Participants were placed in a standardized sitting position of 90° hip flexion with the trunk perpendicular to the ground. The lower leg was passively moved from a starting position to a target position where the dynamometer locked in place for 10s and participants were instructed to remember that specific joint angle. The dynamometer then returned to the starting position, and the assessment was initiated. The dynamometer passively moved the participant's lower leg at 1°/s and the participant was instructed to press a trigger when they believed their leg was at the specific target position. Three combinations of starting and target positions (105° to 70°, 30° to 60°, and 90° to 45°) were completed for three trials each (9 total trials per timepoint).

A sample of healthy participants (n=10) separate from the initial cohort completed the somatosensory and neuromuscular assessments at two timepoints within 14 days to determine intra-rater reliability. Intraclass correlation coefficients (ICC) were used with 95% confidence intervals (95% CI) to determine intra-rater reliability. The three joint repositioning angles of 105° to 70°, 30° to 60°, and 90° to 45° were demonstrated to be reliable ($ICC_{3,k}$ = 0.56, 0.82, 0.85; 95% CI = 0.00 – 1.00, 0.20 – 0.96, 0.35 – 0.97, respectively).

Touch Sensation Threshold

The touch sensation threshold was assessed using Semmes-Weinstein monofilaments, 20 unique force-calibrated nylon threads, to assess sensory detection thresholds. Each Semmes-Weinstein monofilament is calibrated to flex at a different and specific grams of force (grm-f), providing a reliable touch sensation threshold assessment (Snyder et al., 2016). Our intra-rater sample (n=10) demonstrated perfect reliability ($ICC_{3,1}$ = 1.00; 95% CI = 0.98 – 1.00). Participants laid prone with their head facing down on a treatment table while the Semmes-Weinstein monofilaments were applied over the participant's plantar surface of their first metatarsal head of their dominant foot until a "C" shaped bend occurred and was held for 1s. The same researcher (LBL) assessed all participants. The first metatarsal head was marked with a pen to ensure accurate application location. Semmes-Weinstein monofilaments were applied using a standard “4-2-1” stepping protocol (Snyder et al., 2016). For example, the examiner applied a 4.74 diameter monofilament and the choice to apply a thinner (4.08) or thicker (5.46) diameter monofilament “4 steps” away from the initial 4.74 was determined by the participant’s positive (thinner monofilaments applied) or negative (thicker monofilament applied) detection of the monofilaments. The Semmes-Weinstein monofilaments were applied in steps of 4 until 3 reversals were detected (negative response followed by a positive response), indicating a window of minimal sensory detection. The researcher then followed the same process outlined above for the “4 step” process but continued using a “2 step” process until 3 reversals, then again for “1 step”. The final Semmes-Weinstein monofilament diameter applied was the main outcome measure, with one stepping protocol being completed each timepoint (Snyder et al., 2016).

Pressure-pain Threshold

The pressure-pain threshold was determined using a digital algometer (Wagner FPX50, Wagner Instruments, Greenwich, CT, USA) with a 1cm^2 applicator applied to the participant’s dominant foot over the abductor hallicus and medial longitudinal arch (Rolke et al., 2005). The location was selected as it is a reliable and pressure-sensitive location on individuals (Rolke et al., 2005). Our intra-rater sample (n=10) demonstrated strong reliability (ICC$_{3,k}$ = 0.98; 95% CI = 0.92 – 1.00). Participants long-seated on a treatment table while the algometer was applied at a pressure ramp rate of approximately 1 lbf/s until the pressure was initially perceived by the participant as a painful stimulus. The applicator was moved slightly proximal or distal for each trial to avoid tissue sensitivity and/or bruising. Three trials were completed at each timepoint.

Neuromuscular Assessment

The neuromuscular assessment was completed only at the asymptomatic timepoint to avoid any potential for symptom provocation among concussed participants during recovery. The neuromuscular assessment was performed on a previously established, custom fabricated isometric leg extension machine and electrical stimulation system (Cureton et al., 2007; Park et al., 2008). Electrical stimulation parameters and administration were controlled by a computer system consisting of an electrical stimulator (Digitimer model DS7AH, Hertfordshire, England, UK), analog-digital board sampling at 5000Hz (Keithley Instruments model KPCI-3108, Cleveland, OH, USA), and custom TestPoint software V6.0 (Capital Equipment Co., Billerica, MA, USA) (Cureton et al., 2007; Park et al., 2008). Participants were seated on the isometric leg extension machine and secured to the machine via chest and lower leg harnessing. Participant hip and knee joint angles differed between participants due to the minimally adjustable leg extension machine, but were identical for intra-participant setup and did not alter central activation ratio (CAR). Two, 7.6cm x 12.7cm self-adhesive electrodes (ValuTrodes, Axelgaard Manufacturing Co., Ltd, Fallbrook, CA, USA) were used and placed in standardized locations to ensure reliable and maximal tetanic quadriceps contraction (Pietrosimone et al., 2011). The center of the proximal electrode's superior edge was placed at the cross-section between the participant's greater trochanter and anterior superior iliac spine. The center of the distal electrode's inferior edge was placed 3cm superior and midline to the patella.

The neuromuscular assessment followed the previously established superimposed burst technique for determining a participants CAR; the percent of voluntary quadricep muscle activation relative to maximal quadricep capability (Grindstaff & Threlkeld, 2014; Hart, Pietrosimone, et al., 2010; Pietrosimone et al., 2011). Participants completed warm-up maximal voluntary isometric contraction (MVIC) trials at 25%, 50%, 75%, and 100% of their perceived MVIC before assessing CAR to ensure stable torque output and proper assessment understanding. The computer automated superimposed burst (SIB) assessment consisted of a 2.5s MVIC followed immediately by a MVIC coupled with supramaximal electrical stimulation that recruited all quadricep motor units. The electrical stimulation was 100ms long with a 10-train, 200µs pulse duration at 500mA and 200V (Grindstaff & Threlkeld, 2014). The neuromuscular assessment was completed for up to three trials, with a minimum of two trials needed to be included for analysis. Our intra-rater sample (n=10) demonstrated acceptable reliability for the MVIC ($ICC_{3,k}$ = 0.88; 95% CI = 0.45 – 0.97), SIB ($ICC_{3,k}$ = 0.74; 95% CI = 0.00 – 0.94), and CAR ($ICC_{3,k}$ = 0.79; 95% CI = 0.09 – 0.95). Though intra-rater reliability was not perfect, the ICCs are consistent with previously published studies examining these outcomes (Norte et al., 2015).

Data Processing and Reduction

Kinematic (sacral marker positional data) and kinetic (force plate) data from the single-leg hop assessment were examined and gap-filled, if necessary, using Qualisys Track Manager and exported to Visual 3D (C-Motion Inc., Germantown, MD) for processing. The kinematic data were interpolated to match kinetic data using a cubic spline, and then both kinematic and kinetic data were filtered using a 4^{th} order, low-pass Butterworth filter with a 10Hz cutoff frequency (Blackburn, Norcross, Cannon, & Zinder, 2013; Lynall et al., 2018). Joint angles (°), internal moments (Nm/bw), vertical ground reaction force (N/bw), and the dynamic postural stability index were calculated within Visual 3D. Time-series motion capture data were then imported to MATLAB and analyzed to calculate reaction time across all trials. Gait and single-leg hop reaction time was calculated as the time (s) between audible or visual stimulus and the participant's center of pressure or sacral marker moving > 3cm in either the frontal or sagittal plane from its mean position 0.5s prior to stimulus, respectively (Lempke, Johnson, et al., 2020). The Dynamic Postural Stability Index was calculated as previously described during the single-leg hop task from initial contact to 3s after, with a higher composite score indicating greater balance variability (Wikstrom, Tillman, et al., 2010; Wikstrom et al., 2005). Peak ground reaction force was calculated as the highest force (N) value occurring during the single-leg hop and was normalized to body weight (N/bw).

Prior to statistical analysis, single-leg hop limb kinematic and kinetic outcome comparisons were made via dependent t-tests, with the majority indicating statistical differences. Limb kinematic and kinetic differences are well-established among healthy and pathological cohorts (Johnston, McClelland, & Webster, 2018; Lempke, Oh, Johnson, Schmidt, & Lynall, 2020; Pappas & Carpes, 2012). Further, traditional balance assessments analyze only the non-dominant limb (Guskiewicz et al., 2001; Ross & Guskiewicz, 2004), and a previous single-leg hop study indicated only non-dominant limb differences between concussion history and healthy cohorts (Lynall et al., 2020). For these reasons, we decided *a priori* to only examine the non-dominant limb single-leg hop trials to target our analyses while minimizing Type I error.

The passive joint repositioning trials were calculated as the absolute error (difference between target joint angle and participants indicated joint angle) and were averaged across trials within each of the three positions, resulting in three passive joint repositioning outcomes for each position. The touch sensation threshold via Semmes-Weinstein monofilament diameter was the final monofilament (gm) applied from the single stepping protocol. The pressure-pain threshold via algometry (lbf/cm^2) was calculated as the average of the three trials.

Torque produced during the MVIC is deemed their voluntary torque output and was derived from the average MVIC during the 0.5s period prior to electrical stimulation. The additional torque produced during their MVIC coupled with supramaximal electrical stimulus was their SIB, and was calculated as peak additional torque produced during the 100ms electrical stimulation minus the predicted voluntary MVIC at that specific datapoint via linear regression to account for fluctuations (Cureton et al., 2007; Park et al., 2008). The CAR, the ratio of voluntary quadricep torque production relative to maximal potential quadricep torque, was calculated as the following:

$$CAR = \frac{MVIC}{MVIC + SIB} \times 100$$

Statistical Analysis

Independent t-tests were conducted on all demographic (age, height, mass) and survey assessments (PCSS, TSK-11, Tegner activity scale), and a chi-square on concussion history, to examine for group differences. Frequencies and proportions were provided for the musculoskeletal injury history form outcomes. All outcomes from the functional movement and somatosensory assessments were examined using 2 (group) x 2 (time) mixed-model ANOVAs with $\alpha = 0.05$ *a priori* (Table 3.2). Single- and dual-task single-leg hop and gait trials were modeled in separate mixed-model ANOVAs. Tukey honestly significant difference (HSD) t-tests were utilized if statistically significant interaction or main effects were observed from the mixed-model ANOVAs. The neuromuscular assessment outcomes (MVIC, SIB, CAR) were only examined at the asymptomatic timepoint, and therefore independent t-tests were utilized to examine for group differences. Mean differences with associated 95% confidence intervals (95% CI) and Hedges' g effect sizes were calculated for all comparisons to provide insights to the magnitude and clinical meaning (Hedges & Olkin, 1985). Effect sizes were interpreted according to traditional guidelines with ≤ 0.20, 0.21–0.79, and ≥ 0.80 used as thresholds for small, medium, and large effects, respectively (Cohen, 1988). All general linear model assumptions were assessed, and statistical analyses were performed using the R Project for Statistical Programming version 3.4.3 (R Core Team, 2018).

Table 3.2 Planned Statistical Analyses

Specific Aim	*Assessments*	*Variables*	*Statistical Model(s)*
1) To examine the differences in functional movement (single-leg hop, gait) under single- and dual-task conditions between concussed young adults and healthy matched-controls at two clinical time-points (acute [<7 days] and at asymptomatic [±72 hours]) post-concussion.	Single-leg hop and gait assessments	IV: *Group* (control vs concussed), *time* (acute vs asymptomatic). DV: *Single-Leg Hop*: reaction time (s), sagittal and frontal ankle and knee joint angles (°), sagittal and frontal ankle and knee internal moments (Nm/bw), peak ground reaction force (N/bw), dynamic postural stability index. *Gait*: reaction time (s), stride length and width (cm), gait velocity (m/s), center of pressure path efficiency.	Mixed-model 2(group) x 2(time) ANOVAs for all DVs. Models ran separate for single- and dual-task.
2) To examine the differences in somatosensory (pressure-pain threshold, touch sensation threshold, and passive joint repositioning) function between concussed young adults and healthy matched-controls at two clinical time-points (acute [<7 days] and at asymptomatic [±72 hours]) post-concussion.	Algometry, Semmes-Weinstein monofilaments, Dynamometer (Biodex)	IV: *Group* (control vs concussed) and *time* (acute vs asymptomatic) DV: *Algometry*: Pressure-pain threshold (lbf/cm^2), *Semmes-Weinstein monofilaments*: force (grams), *Dynamometer*: absolute joint angle (°)	Mixed-model 2(group) x 2(time) ANOVAs for all DVs.
3) To examine the differences in neuromuscular function between concussed young adults and healthy matched-controls when asymptomatic [±72 hours]) post-concussion.	Neuromuscular (superimposed burst technique)	IV: *Group* (control vs concussed) and *time* (acute vs asymptomatic) DV: *Maximal Voluntary Isometric Contraction (MVIC)*: voluntary torque (Nm) *Superimposed burst (SIB)*: supramaximal torque (Nm), *Central Activation Ratio (CAR):* Ratio of MVIC relative to MVIC plus SIB (%)	Independent t-test for each DV (only completed at second timepoint).

CHAPTER 4

FUNCTIONAL MOVEMENT THROUGHOUT CONCUSSION RECOVERY: A BIOMECHANICAL ASSESSMENT[1]

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[1] Lempke LB, Hoch MC, Call JA, Schmidt JD, Lynall RC. To be submitted to *Med. Sci. Sports Exerc*.

Abstract

Objective: Compare gait and single-leg hop functional movement outcomes under single- and dual-task conditions between concussed college-aged individuals and healthy matched-controls acutely (0-7 days) and when asymptomatic (±72 hours).

Methods: Concussed and matched-controls (n=16, 63% male; 19.4 ± 1.2yrs; 180.6 ± 11.3cm; 75.3 ± 14.4kg) randomly completed a gait and functional single-leg hop assessment under single- and dual-task conditions (subtracting by 6's or 7's) at both timepoints. Gait was assessed on a 4.9m long instrumented walkway where spatiotemporal outcomes (gait velocity, stride length and width), single- and double-limb support center of pressure (CoP) efficiency, and reaction time were recorded for four trials under single- and dual-task. Single-leg hop involved jumping forward from a 30cm-tall box set at 50% of the participant's height and performing a single, non-dominant-leg landing and balancing for 10s (four trials) in a motion capture space. Single-leg hop outcomes included kinematics (ankle and knee range of motion), kinetics (ankle and knee moments, peak vertical ground reaction force), dynamic postural stability index (DPSI), and reaction time. We used 2(group) x 2(time) mixed-model ANOVAs ($\alpha=0.05$) and Tukey post-hoc tests to compare gait and single-leg hop outcomes separately for single- and dual-task. Hedges' g effect sizes were calculated to examine group difference magnitudes.

Results: Single-task stride length and gait velocity, and dual-task stride width displayed significant interaction effects ($p \leq 0.049$; g-range: -1.56, 0.49) with concussed individuals walking shorter, slower, and wider than controls acutely, but were not significant following post-hoc testing ($p \geq 0.057$). Single-task stride width, dual-task stride length, gait velocity, and single- or dual-task single-limb or double-limb support CoP efficiency were not significantly different ($p \geq 0.052$; g-range: -1.02, 0.42). No significant between-group differences in range of motion were observed across timepoints or task-conditions ($p \geq 0.074$; g-range: -2.35, 0.44). Dual-task plantarflexion moments had a significant interaction effect ($p=0.019$), with concussed individuals acutely displaying 0.03Nm/BW greater plantarflexion torque during dual-task ($p=0.035$). No other joint moments were statistically significant ($p \geq 0.059$; g-range: -0.97, 1.96). Peak vertical ground reaction force ($p \geq 0.067$; g-range: 0.45, 1.27), DPSI ($p \geq 0.065$; g-range: 0.00, 0.63), and reaction time ($p \geq 0.091$; g-range: -0.25, 0.48) did not statistically differ across timepoints or task-conditions.

Conclusions: Minimal biomechanical outcomes were present and indicates similar group performance across time. Medium to large effect sizes however were observed for decreased stride lengths, widths, and velocities, and decreased joint range of motion, and altered torque post-concussion and at symptom resolution. Our findings may indicate subtle, but important differences for future research to monitor after concussion during both every day and sport-like movement.

Keywords: Mild Traumatic Brain Injury; Biomechanics; Human Movement; Injury Prevention

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Introduction

Concussion is a complex neuropathology with high prevalence among athletic and general populations (Cancelliere et al., 2017; Wasserman et al., 2016). Clinicians examine concussion acutely and determine return to play readiness using a multidimensional assessment battery containing at least symptom, balance, and neurocognitive assessments (Lempke, Schmidt, et al., 2020; McCrory et al., 2017). Using this multidimensional assessment battery provides the strongest diagnostic capabilities (Garcia et al., 2018; Resch et al., 2016), with athletes being deemed clinically recovered and returning to full sport participation around 14 days post-concussion (Garcia et al., 2018; O'Connor et al., 2017). Growing concerns have emerged; however, as aberrant movement during gait and functional jumping and cutting tasks have been frequently identified months to years beyond the typical concussion recovery window (Büttner et al., 2019; DuBose et al., 2017; Howell, Osternig, et al., 2018; Lynall et al., 2020). Altered movement months beyond concussion recovery may signify cumulative impairments linger and go undetected during the multidimensional assessment battery, and could have vital sport and musculoskeletal safety implications (Howell, Lynall, et al., 2018; Lynall et al., 2015; Lynall, Mauntel, et al., 2017; McPherson et al., 2018).

Gait assessment utilization has grown in recent years due to the daily functional nature, gross sensorimotor demands required, and increasing ease of access to objectively assessing gait (Fino et al., 2016; Howell, Buckley, et al., 2018; Howell et al., 2015). Specifically, gait assessments under dual-task (i.e. simultaneously completing a cognitive task while walking) have received attention due to reduced gait velocity, altered spatiotemporal parameters, and increased center of mass displacement for up to two-months after concussion (Catena et al., 2007b; Howell, Lynall, et al., 2018; Parker et al., 2008). Impairments on a daily activity like gait when combined with cognitive loading are concerning as they are relatively simplistic compared to the cognitive and functional movement demands of sport. It is possible a functional movement measure is missing from the multidimensional assessment battery when returning athletes back to sport.

The sensory, cognitive, and neuromuscular demands during sport activities likely exceed those required for gait due to the ever-changing sport environments and highly dynamic movement. Our previous work has identified that reaction time between clinical neurocognitive testing and gait, jumping, cutting, and hopping movements do not correlate among healthy participants, and that gait and the sport-related jumping, cutting, and hopping movements do not correlate either (Lempke, Johnson, et al., 2020). Furthermore, a two-fold musculoskeletal injury risk is well-established for up to two years after a concussion (Howell, Lynall, et al., 2018; Lynall et al., 2015; Lynall, Mauntel, et al., 2017; McPherson et al., 2018). These findings collectively suggest sport-like functional movement assessments may be a critical missing piece. Recent sport-specific functional movement assessments have been explored among individuals with a history of concussion to help address this concern (Avedesian et al., 2020; DuBose et al., 2017; Eagle, Kontos, Mi, et al., 2019; Lapointe et al., 2018; Lynall et al., 2018). But to date, no studies have examined functional movement at any point within the typical concussion recovery timeframe, which greatly limits our insights to true functional movement alterations post-concussion.

Cumulatively, individuals with concussion history have displayed greater trunk flexion (Lynall et al., 2018), increased hip stiffness with concurrent decreased knee stiffness (DuBose et al., 2017), increased knee valgus and internal rotation (Lapointe et al., 2018), less ankle dorsiflexion and knee flexion (Avedesian et al., 2020), quicker time to peak knee flexion (Eagle, Kontos, Mi, et al., 2019), and slower time to stabilization (Lynall et al., 2020), during jumping, landing, and cutting tasks. These studies examined individuals with a previous concussion anywhere from 2 months to 3 years after initial injury with unknown musculoskeletal injury history among participants, which may confound findings (DuBose et al., 2017; Lapointe et al., 2018; Lynall et al., 2018). Our understanding of dual-task concussion deficits remains limited to gait assessments (Büttner et al., 2019; Howell, Lynall, et al., 2018; Parker et al., 2006) and therefore it is unknown if dual-task deficits are present or are amplified when coupled with more complex, sport-like movements. Understanding kinematic and kinetic functional movement differences may provide critical insights for researchers and clinicians to better identify movement deficits, and ultimately utilize therapeutic rehabilitation techniques before returning athletes back to sport.

The purpose of our study was to compare single-leg hop and gait functional movement performance under single- and dual-task conditions between concussed college-aged individuals and yoked (i.e. time-matched), healthy matched-controls acutely (0-7 days) and when asymptomatic (±72 hours of symptom resolution). We hypothesized concussed individuals would display the following relative to healthy-matched controls: 1) slower reaction time, worse dynamic postural stability indices, and more rigid kinematics with greater kinetics during the single-task single-leg hop assessment acutely and when asymptomatic, 2) slower reaction time, slower or more variable spatiotemporal outcomes, and worse center of pressure path efficiency during the single-task gait assessment acutely, but not when asymptomatic, and 3) significantly worse dual-task single-leg hop and gait outcome performance both acutely and when asymptomatic.

Methods

We employed a prospective, longitudinal case-control study design between August 2019 and February 2021 to examine functional movement performance among a concussed cohort and healthy, matched-control cohort acutely (0-7 days post-injury) and asymptomatic (± 72 hours). A total of 8 concussed and 8 controls were enrolled in the study (Appendix L). Concussed participants were recruited through the University Health Center and were included if they experienced an independent physician consensus-guided (McCrory et al., 2017) concussion diagnosis, and were assessed by the research team within 7 days following concussion. Concussed participants were given academic and physical activity restrictions consistent with current guidelines at the discretion of their physician (McCrory et al., 2017). Control participants were recruited across the university and were included if they matched with a concussed participant on sex, age (± 1 year), height (± 10%), mass (± 5%), and concussion history (± 1 year) (Lynall et al., 2018, 2020).

Participants were excluded if any of the following were met: were a National Collegiate Athletic Association athlete, had a history of any neurologic, memory, anxiety, or depression disorder, history of a lower extremity musculoskeletal injury <6 months that resulted in >24 hours of time-loss from physical activity, or history of any lower extremity orthopedic surgery in the past year. Participants received honorarium at the acute timepoint and asymptomatic timepoints. All participants provided written informed consent prior to study participation, and this study was approved by the University of Georgia’s Institutional Review Board (PROJECT00000469).

Procedures and Instrumentation

All participants first completed survey assessments followed by the functional movements (gait and single-leg hop under single- and dual-task) with *a priori* functional movement and cognitive condition block-randomization to minimize potential learning effects. The functional movement order was identical between a participant's acute and asymptomatic timepoints, as well as between each concussed and matched-control pair. The asymptomatic timepoint assessment occurred for concussed participants once their symptoms normalized to pre-injury status as described below. Control participants were yoked to their concussed match for their asymptomatic timepoint.

Survey Assessments

Post-Concussion Symptom Scale (PCSS)

Participants completed the 22-item Post-Concussion Symptom Scale (PCSS; Appendix A) by rating their symptom presence (i.e. yes or no) and symptom severity via a 6-point Likert scale (0= "none", 6= "severe") at that current point in time (Echemendia et al., 2017). Concussed participants completed the PCSS prior to any assessments at each timepoint, and then after each functional assessment block to monitor symptom provocation. Concussed participants would discontinue the protocol if symptom severity increased by ≥7, but no cases occurred.

Concussed participants also completed the PCSS with modified instructions (Appendix B) where they rated their symptoms "typically experienced (>3 times per week)", to establish a retrospective signs and symptoms pre-injury proxy (Hoffman et al., 2018; Lempke, Lynall, Hoffman, Devos, & Schmidt, 2020; Schmidt et al., 2017). Lastly, concussed participants completed daily PCSS via online survey (Qualtrics, Provo, UT) to allow the research team to determine when participants were asymptomatic (Hoffman et al., 2018; Lempke, Lynall, et al., 2020; Schmidt et al., 2017). Daily PCSS survey compliance was strong, with all concussed participants completing ≥81.2% (mean=96.3%) of daily surveys. Concussed participants' asymptomatic status was determined when their pre-injury proxy was within the PCSS symptom severity reliable change score (± 3 symptom severity score) of their daily PCSS (Chin et al., 2016).

Musculoskeletal Injury History Form

A musculoskeletal injury history form (Appendix E) was modified and implemented based off previously published forms for descriptive purposes (Houston et al., 2018, 2017). The survey asked participants whether they had ever sustained any musculoskeletal injuries (i.e., sprains, strains, fractures, dislocations, and surgery) to the lower extremity or back/torso in the past five years. If participants reported "yes" to any musculoskeletal injury, a brief description of the injury type (e.g., ankle sprain – lateral ankle sprain), how long ago it occurred, and how many times it happened were recorded.

Functional Movement Assessments

Both the gait and single-leg hop assessments were completed under single-task (walking at normal, comfortable pace for gait, and completing the movement as quickly and stable as possible for single-leg hop) and dual-task (i.e., subtract as quickly and accurately as possible while concurrently completing the movement task) conditions (Lempke, Johnson, et al., 2020). Participants performed a minimum of 1 practice gait and single-leg hop task prior to any data collection to ensure familiarity with each component, but were allowed more until they understood the task and self-reported feeling comfortable. Due to the potential for symptom provocation among concussed individuals completing the single-leg hop assessment, participants were allowed the opportunity to opt-in or -out of this assessment.

The dual-task paradigm used was standard across all assessments, with participants subtracting from a random number between 90 and 150 by either 6's or 7's during functional movements while instructed to do so “as quickly and accurately as possible” while audio recorded (Fino et al., 2016; Lempke, Johnson, et al., 2020; Lempke, Oh, et al., 2020). We employed the subtraction-based dual-task due to it being an unpracticed skill that provides high response frequency and is well-established in the dual-task literature (Fino et al., 2016; Howell, Lynall, et al., 2018; Howell et al., 2014; Lempke, Johnson, et al., 2020). Participants subtracted prior to initiating the functional movement and kept subtracting during the entire functional movement (Fino et al., 2016; Lempke, Johnson, et al., 2020; Lempke, Oh, et al., 2020). Trials were repeated if participants stopped reciting numbers or did not initiate the movement when cued.

Gait

Gait was assessed using a reliable and valid (Lynall, Zukowski, et al., 2017) 4.9m long by 0.6m wide pressure sensor-embedded walkway (Zeno Walkway, ProtoKinetics, Havertown, PA) sampling center of pressure at 120Hz (Appendix F). All participants started the assessment at a fixed location on the walkway and were instructed to walk at their normal, comfortable pace until completely off the walkway (Lempke, Johnson, et al., 2020). Participants performed all assessments with their athletic shoes on. Participants were instructed to “get set” when at the starting position and to initiate walking at their preferred pace immediately following an audible beep. The audible stimulus was randomly activated 2-5s after the participant was told to “get set”. Five gait trials under single- and dual-task (10 trials total per timepoint) were recorded and averaged under each condition.

Single-Leg Hop

The single-leg hop assessment occurred in an 8-camera 3D motion capture space (MIQUIS, Qualisys Systems, Göteborg, Sweden) recording at 240Hz with two synchronized piezoelectric ground-embedded force plates (BERTEC, Columbus, OH, USA) sampling at 1,200Hz (Appendix G). Participants stood on a 30cm-tall box placed 50% of their height behind the two force plates within the 3D motion capture space at the start of each trial (Lempke, Johnson, et al., 2020; Lempke, Oh, et al., 2020; Lynall et al., 2020). Participants were fitted with 47, 14mm retroreflective markers for static calibration and 24 clustered markers to track single-leg hop motion as described in detail elsewhere (Lempke, Oh, et al., 2020). Lab coordinates were defined with positive values indicating flexion, adduction, and internal rotation for sagittal (y-axis), frontal (x-axis), and transverse (z-axis) plane motion, respectively. Participants were instructed to take an athletic stance after being told to “get set”. Once participants were set, a green light-emitting diode was activated randomly between 2 and 5s. Participants were told to move as quickly as possible after seeing the visual stimulus (Lempke, Johnson, et al., 2020; Lynall et al., 2018).

Participants jumped off the box with both feet and landed on a single-leg. Participants were instructed to maintain the standardized static landing position (hands on hips, maintain single-leg balance, contralateral leg bent with slight hip and knee flexion and not resting on the ipsilateral limb) immediately upon foot contact on the force plate for 10s (Lempke, Johnson, et al., 2020; Ross & Guskiewicz, 2004; Ross et al., 2008). Trials were discarded and repeated if the participant’s contralateral foot made ground contact for any reason or any portion of the ipsilateral foot was off the force plate at ground contact. Four trials were completed for both dominant and non-dominant limbs under single- and dual-task conditions (12 trials total per timepoint) to provide strong test-retest reliability while minimizing potential fatigue with collecting more trials (James, Herman, Dufek, & Bates, 2007). The dominant limb was defined as the leg participants self-reported preferred to kick a ball with.

Data Processing and Reduction

Gait center of pressure data were filtered within the manufacturer software using a 5-pole, low-pass, Butterworth filter with a 10Hz cutoff frequency. The initial standing stance and first step from the center of pressure mat were removed from analyses to capture clean gait cycles. Spatiotemporal outcomes of stride length and width, gait velocity, and center of pressure path efficiency for double- and single-limb support gait phases were calculated within the manufacturer software from the center of pressure data throughout each entire trial (Lynall, Zukowski, et al., 2017). Center of pressure (CoP) path efficiency was calculated as the percentage ratio of sagittal center of pressure displacement divided by center of pressure distance for the respective gait phase (for single-limb and double-limb support), with a higher percentage indicating better movement efficiency. The CoP path efficiency was examined to quantify an individual's CoP displacement over time to potentially detect group differences and be used as a future post-concussion metric.

All single-leg hop kinematic data were examined and relational gap-filled, if necessary, using Qualisys Track Manager and then exported to Visual 3D (C-Motion Inc., Germantown, MD) for processing. Kinematic data for every individual trial were analyzed for erroneous movement artifact at a set threshold of ≥0.5cm prior to processing (Lempke, Oh, et al., 2020). Any trials exceeding the artifact threshold were reexamined and reprocessed prior to data analysis. Kinematic data were interpolated via cubic spline to match kinetic data sampling frequency, and then both kinematic and kinetic data were filtered using a 4th order, low-pass, Butterworth filter with a 10Hz cutoff frequency prior to calculating any outcomes (Blackburn et al., 2013; Lempke, Oh, et al., 2020; Lynall et al., 2018). All single-leg hop kinematic and kinetic outcomes were calculated from the initial contact (≥8N force plate) to 3s after initial contact timeframe.

Peak ground reaction force was calculated as the highest force (N) value occurring. Relative joint angles (°) were calculated from the filtered kinematic data using a flexion-extension first rotation, adduction-abduction second rotation, and internal-external rotation third rotation Cardan sequence (Kernozek, Torry, & Iwasaki, 2007). Joint range of motion (i.e. arc of motion between maximum and minimum relative joint angles) served as the primary kinematic outcome. Net internal joint moments and vertical ground reaction force were normalized to body weight (BW) (Kernozek et al., 2007). Normalized moments (Nm/BW) were derived from traditional inverse dynamics via kinematic, kinetic, and anthropometric data. The following Y-axis sagittal plane and X-axis frontal plane moments were assigned positive values for knee flexion and varus, and ankle plantarflexion and inversion. Only sagittal and frontal plane joint angles and moments for the ankle and knee were reported and analyzed due to previous work identifying concussion history deficits consistently at these joints and planes (Avedesian et al., 2020; DuBose et al., 2017; Eagle, Kontos, Mi, et al., 2019; Lapointe et al., 2018; Lynall et al., 2020), and to minimize type I error.

Time-series center of pressure (gait) and kinematic (single-leg hop) data were imported to MATLAB and analyzed to calculate reaction time across all trials. Gait and single-leg hop reaction time was calculated as the time (s) between audible stimulus and center of pressure (gait), or visual stimulus and sacral marker (single-leg hop), moving > 3cm in either the frontal or sagittal plane from its mean position 0.5s prior to stimulus, respectively (Lempke, Johnson, et al., 2020). The Dynamic Postural Stability Index was calculated as previously described (Wikstrom, Tillman, et al., 2010; Wikstrom et al., 2005) in Visual 3D during the single-leg hop task from initial contact to 3s after, with a higher composite score indicating greater balance variability (i.e., worse performance).

Prior to statistical analysis, single-leg hop limb comparisons for kinematic and kinetic outcomes were made via dependent t-tests, with the majority indicating statistically significant limb differences. Limb asymmetries are well-established among healthy and pathological cohorts (Johnston et al., 2018; Lempke, Oh, et al., 2020; Pappas & Carpes, 2012). Further, traditional balance assessments analyze only the non-dominant limb (Guskiewicz et al., 2001; Ross & Guskiewicz, 2004), and a previous single-leg hop study indicated only non-dominant limb differences between concussion history and healthy cohorts (Lynall et al., 2020). For these reasons, we decided *a priori* to only examine the non-dominant limb single-leg hop trials to target our analyses and minimize Type I error.

Statistical Analysis

Independent t-tests were conducted on age, height, mass, and sleep, and a Fisher's exact test on sex, concussion history, and limb dominance. Frequencies were calculated for the musculoskeletal injury history form outcomes. All PCSS, gait, and single-leg hop outcomes were examined using 2 (group) x 2 (time) mixed-model ANOVAs with $\alpha = 0.05$ *a priori* (Table 3.2). Single- and dual-task gait and single-leg hop trials were modeled in separate mixed-model ANOVAs as single- and dual-task differences are well-established within concussed and control groups (Büttner et al., 2019; Howell, Lynall, et al., 2018; Talarico et al., 2019, 2017) and to minimize ANOVA model overfitting. Tukey honestly significant difference (HSD) t-tests were utilized if statistically significant interaction or main effects were observed from the mixed-model ANOVAs. Mean differences with associated 95% confidence intervals (95% CI) and Hedges' g effect sizes were calculated for all comparisons to provide insights to the magnitude and clinical meaning, while accounting for small sample bias (Hedges & Olkin, 1985). Effect sizes were interpreted according to traditional guidelines with ≤ 0.20, 0.21–0.79, and ≥ 0.80 used as thresholds for small, medium, and large effects, respectively (Cohen, 1988). All statistical analyses were performed using the R Project for Statistical Programming version 3.4.3 (R Core Team, 2018).

Results

A total of 8 concussed and 8 controls completed the gait assessment at both acute and asymptomatic timepoints, with 6 concussed and 6 controls completing the single-leg hop assessment at both timepoints. No significant group differences were present for age, sex, height, mass, concussion history, hours of sleep, hand or leg dominance, or time between testing sessions ($p \geq 0.411$; Appendix L). Total PCSS symptom presence ($p<0.001$) and symptom severity ($p<0.001$) displayed significant group by time interactions, with post-hoc testing demonstrating significantly greater total symptom presence and severity acutely for concussed, but not once asymptomatic (Appendix L). The concussed cohort had a symptom total range of 6-22 (median=17) and severity range of 16-68 (median=36.5) acutely. A total of 3 concussed and 1 control had at least one musculoskeletal injury in the past 5-years, with three of the four being lateral ankle sprains (Appendix M).

Gait Assessment

All single-task and dual-task gait outcome descriptive statistics, between-group statistics (means, standard deviations, group mean differences with 95% CIs and Hedges' g effect sizes), and within-group statistics (means, standard deviations, timepoint change %, and Hedges' g effect sizes) are provided in Table 4.1. All mixed-model ANOVAs reported for gait outcomes had degrees of freedom of 1 and 14 for the numerator and denominator, respectively.

Table 4.1. Gait Outcomes Between Groups at Acute and Asymptomatic (n=16)

		Concussed				**Control**							
		Acute		*Asymptomatic*		*Acute*		*Asymptomatic*		*Acute*		*Asymptomatic*	
		Mean (SD)								Hedges' g			
		Hedges' g (timepoint change %)								*Group Mean Difference (95% CI)*			
Single-Task	Stride Length (cm)	142.53	(12.28)	149.13	(11.49)	153.53	(16.69)	152.57	(17.79)	-0.75		-0.23	
		0.56		*4.63%*		*-0.06*		*-0.63%*		*-11.00*	*(-26.73, 4.73)*	*-3.44*	*(-19.17, 12.29)*
	Stride Width (cm)	10.65	(2.27)	9.96	(2.05)	9.63	(2.56)	10.29	(3.20)	0.42		-0.12	
		-0.32		*-6.48%*		*0.23*		*6.85%*		*1.02*	*(-1.70, 3.72)*	*-0.33*	*(-3.04, 2.38)*
	Gait Velocity (cm/s)	122.70	(11.03)	132.51	(15.39)	143.71	(15.47)	141.29	(18.08)	-1.56		-0.52	
		0.73		*8.00%*		*-0.14*		*-1.68%*		*-21.01*	*(-36.99, -5.04)*	*-8.78*	*(-24.76, 7.19)*
	Single-Limb Support	98.31	(0.76)	98.18	(0.64)	98.38	(0.48)	98.32	(0.48)	-0.11		-0.25	
	CoP Efficiency (%)	*-0.19*		*-0.13%*		*-0.13*		*-0.06%*		*-0.07*	*(-0.70, 0.57)*	*-0.14*	*(-0.77, 0.49)*
	Double-Limb Support	99.99	(0.01)	99.99	(0.01)	99.99	(0.00)	99.99	(0.01)	0.00		0.00	
	CoP Efficiency (%)	*0.00*		*0.00%*		*0.00*		*0.00%*		*0.00*	*(-0.01, 0.00)*	*0.00*	*(-0.01, 0.01)*
	Reaction Time (s)	0.46	(0.26)	0.33	(0.14)	0.34	(0.14)	0.33	(0.10)	0.57		0.00	
		-0.62		*28.26%*		*-0.08*		*2.94%*		*0.12*	*(-0.06, 0.30)*	*0.00*	*(-0.18, 0.18)*
Dual-Task	Stride Length (cm)	131.99	(13.87)	146.16	(11.98)	141.81	(18.39)	146.85	(18.15)	-0.60		-0.04	
		1.09		*10.74%*		*0.28*		*3.55%*		*-9.82*	*(-26.60, 6.95)*	*-0.69*	*(-17.50, 16.08)*
	Stride Width (cm)	12.15	(3.68)	10.75	(2.59)	10.38	(3.48)	10.91	(3.20)	0.49		-0.05	
		-0.44		*-11.52%*		*0.16*		*5.11%*		*1.77*	*(-1.69, 5.23)*	*-0.16*	*(-3.63, 3.30)*
	Gait Velocity (m/s)	105.02	(20.06)	124.16	(15.30)	125.00	(18.95)	132.16	(18.94)	-1.02		-0.46	
		1.07		*18.23%*		*0.38*		*5.73%*		*-19.98*	*(-39.30, -0.63)*	*-8.00*	*(-27.40, 11.34)*
	Single-Limb Support	97.82	(1.75)	98.1	(0.93)	98.43	(0.55)	98.49	(0.62)	-0.47		-0.49	
	CoP Efficiency (%)	*0.20*		*0.29%*		*0.10*		*0.06%*		*-0.61*	*(-1.73, 0.51)*	*-0.39*	*(-1.52, 0.72)*
	Double-Limb Support	99.97	(0.02)	99.99	(0.01)	99.98	(0.02)	99.99	(0.01)	-0.50		0.00	
	CoP Efficiency (%)	*1.26*		*0.02%*		*0.63*		*0.01%*		*-0.01*	*(-0.02, 0.00)*	*0.00*	*(-0.02, 0.01)*
	Reaction Time (s)	0.53	(0.21)	0.36	(0.10)	0.40	(0.11)	0.40	(0.13)	0.78		-0.34	
		-1.03		*32.08%*		*0.00*		*0.00%*		*0.13*	*(-0.03, 0.27)*	*-0.04*	*(-0.19, 0.12)*

Hedges' g effect sizes are reported for between-group comparisons in the columns, and within-group comparisons in the rows. All mean difference and 95% CI are unadjusted

Single-Task Comparisons

Single-task stride length demonstrated a significant group by time effect (p=0.049), but not group (p=0.333) or time (p=0.130). Post-hoc examination showed the concussed group had a shorter stride length acutely relative to asymptomatic, and shorter acutely relative to acute controls (Table 4.1), but were not statistically significant after Tukey HSD t-tests (p≥0.078). A large effect for decreased concussed stride length magnitude was observed (g=-0.75), and a small effect at asymptomatic (g=-0.23). No significant group, time, or group by time effects for single-task stride width were observed (p≥0.078), with a medium effect for wider concussed stride width acutely (g=0.42), but small effect for narrower concussed stride width at asymptomatic (g=-0.12).

We observed a significant group by time (p=0.041) effect, but not group (p=0.194) or time (p=0.055), for single-task gait velocity. Post-hoc testing revealed the concussed group walked 21.01cm/s slower during single-task gait velocity than controls acutely, and approached controls at asymptomatic, but no statistical differences were observed following Tukey HSD t-tests (p≥0.057). Large acute and medium asymptomatic effects were observed for decreased concussion gait velocity relative to controls (g=-1.56 and -0.52, respectively). No significant group, time, or group by time effects for single-task single-limb support CoP efficiency (p≥0.360) or double-limb support CoP efficiency (p≥0.082) were observed along with negligible to small concussed deficit effects acutely (g=-0.11 and 0.00, respectively) and at asymptomatic (g=-0.25 and 0.00, respectively).

We observed significant group by time (p=0.037) and time (p=0.019) effects, but not group (p=0.481), for single-task gait reaction time. Post-hoc testing demonstrated only the concussed group having a time effect, with the acute timepoint having slower RT than asymptomatic (mean diff: 0.13, 95%CI: 0.02, 0.24; p=0.016), while no other comparisons were statistically significant following Tukey HSD t-tests (p≥0.518). A medium effect was observed for acute concussion reaction time deficits (g=0.57), but no effect for asymptomatic (g=0.00; Table 4.1).

Dual-Task Comparisons

A significant time effect (p=0.001), but not group by time (p=0.052) or group (p=0.502) for dual-task stride length. Post-hoc testing revealed the asymptomatic timepoint elicited 9.6cm more dual-task stride length than acute on average (95%CI: 5.0, 14.2). A medium effect was observed acutely for decreased dual-task stride length for concussed individuals (g=-0.60), but negligible effect once asymptomatic (g=-0.04).

A significant group by time (p=0.032) effect, but not group (p=0.620) or time (p=0.303) for dual-task stride width was observed. Post-hoc examination indicated concussed individuals displaying greater dual-task stride width acutely relative to acute controls that diminished by asymptomatic, but differences were not significant following Tukey t-tests (p>=0.114). A medium effect was observed acutely for increased dual-task stride width for concussed individuals (g=0.49), but negligible effect once asymptomatic (g=-0.05).

Dual-task gait velocity displayed a significant time effect (p=0.001), but not group by time (p=0.082) or group (p=0.127), with the asymptomatic timepoint resulting in 13.1cm/s greater dual-task velocity than acute (95% CI: 6.28, 20.00). A large effect was present for decreased gait velocity acutely for concussed individuals (g=-1.02), and a medium effect once asymptomatic (g=-0.46).

No significant group, time, or group by time effect was observed for dual-task single-limb support CoP efficiency (p≥0.316). Medium effects were observed for single-limb support

CoP efficiency post-concussion at acute (g=-0.47) and asymptomatic (g=-0.49). Double-limb support CoP efficiency elicited a significant time effect (p=0.032), but not group (p=0.372) or group x time (p=0.447), with the asymptomatic timepoint resulting in 0.01% greater dual-task double-limb CoP efficiency than acute (95% CI: 0.00, 0.02). A medium effect was observed for acute post-concussion deficits in double-limb support CoP efficiency (g=-0.50), but was non-existent at asymptomatic (g=-0.00).

We observed significant group by time (p=0.018) and time (p=0.010) effects, but not group (p=0.520), for dual-task gait reaction time. Post-hoc Tukey HSD t-tests demonstrated only the concussed group having a time effect, with the acute timepoint demonstrating slower reaction time than asymptomatic (mean difference: 0.17, 95%CI: 0.05, 0.29; p=0.006). A large post-concussion reaction time impairment magnitude effect was observed acutely (g=0.78), but a medium control group reaction time impairment magnitude effect emerged at asymptomatic (g=-0.34).

Single-Leg Hop Assessment

All single-task single-leg hop kinematic, kinetic, DPSI, and reaction time descriptive statistics, between-group statistics (means, standard deviations, group mean differences with 95% CIs and Hedges' g effect sizes), and within-group statistics (means, standard deviations, timepoint change %, and Hedges' g effect sizes) are provided in Table 4.2, and Table 4.3 provides the same outcomes for dual-task single-leg hop. All mixed-model ANOVAs reported for all single-leg hop had degrees of freedom of 1 and 10 for the numerator and denominator, respectively.

Table 4.2. Single-Task Single-Leg Hop Outcomes Between Groups at Acute and Asymptomatic (n=12)

	Concussed				**Control**							
	Acute		*Asymptomatic*		*Acute*		*Asymptomatic*		*Acute*		*Asymptomatic*	
	Mean (SD)								Hedges' g			
	Hedges' g (timepoint change %)								*Group Mean Difference (95% CI)*			
Sagittal Ankle ROM (°)	52.75	(6.38)	51.16	(10.55)	55.10	(6.50)	49.11	(6.44)	-0.36		0.23	
	-0.18		*-3.01%*		*-0.93*		*-10.87%*		*-2.35*	*(-11.71, 7.02)*	*2.05*	*(-7.31, 11.41)*
Frontal Ankle ROM (°)	25.40	(7.56)	23.10	(2.46)	28.17	(3.12)	28.59	(2.20)	-0.48		-2.35	
	-0.41		*-9.06%*		*0.16*		*1.49%*		*-2.77*	*(-8.12, 2.58)*	*-5.49*	*(-10.83, -0.14)*
Sagittal Knee ROM (°)	49.46	(5.96)	53.20	(5.59)	50.8	(7.88)	50.27	(7.68)	-0.19		0.44	
	0.65		*7.56%*		*-0.07*		*-1.04%*		*-1.34*	*(-9.95, 7.28)*	*2.93*	*(-5.69, 11.54)*
Frontal Knee ROM (°)	8.70	(2.44)	9.60	(4.51)	9.40	(2.04)	8.52	(2.00)	-0.31		0.31	
	0.25		*10.34%*		*-0.44*		*-9.36%*		*-0.7*	*(-4.29, 2.88)*	*1.08*	*(-2.50, 4.66)*
Ankle plantarflexion moment (Nm/BW)	0.17	(0.02)	0.14	(0.02)	0.12	(0.03)	0.14	(0.03)	1.96		0.00	
	-1.50		*-17.65%*		*0.67*		*16.67%*		*0.05*	*(0.02, 0.08)*	*0.00*	*(-0.02, 0.04)*
Ankle inversion moment (Nm/BW)	0.04	(0.02)	0.03	(0.01)	0.05	(0.04)	0.04	(0.03)	-0.32		-0.45	
	-0.63		*-25.00%*		*-0.28*		*-20.00%*		*-0.01*	*(-0.03, 0.04)*	*-0.01*	*(-0.02, 0.05)*
Knee extension moment (Nm/BW)	0.42	(0.07)	0.42	(0.07)	0.42	(0.09)	0.42	(0.05)	0.00		0.00	
	0.00		*0.00%*		*0.00*		*0.00%*		*0.00*	*(-0.09, 0.08)*	*0.00*	*(-0.08, 0.09)*
Knee valgus moment (Nm/BW)	0.14	(0.08)	0.09	(0.03)	0.12	(0.07)	0.14	(0.10)	0.27		-0.68	
	-0.83		*-35.71%*		*0.23*		*16.67%*		*0.02*	*(-0.07, 0.11)*	*-0.05*	*(-0.13, 0.04)*
Peak vertical ground reaction force (N/BW)	2.98	(0.16)	3.11	(0.16)	2.81	(0.19)	2.78	(0.33)	0.97		1.27	
	0.81		*4.36%*		*-0.11*		*-1.07%*		*0.17*	*(-0.11, 0.44)*	*0.33*	*(0.05, 0.61)*
Reaction Time (s)	0.62	(0.14)	0.56	(0.14)	0.56	(0.16)	0.56	(0.19)	0.40		0.00	
	-0.43		*9.68%*		*0.00*		*0.00%*		*0.06*	*(-0.14, 0.26)*	*0.00*	*(-0.20, 0.20)*
Dynamic Postural Stability Index (DSPI)	0.39	(0.03)	0.39	(0.03)	0.37	(0.05)	0.39	(0.07)	0.49		0.00	
	0.00		*0.00%*		*0.33*		*-5.41%*		*0.02*	*(-0.04, 0.08)*	*0.00*	*(-0.06, 0.06)*

Hedges' g effect sizes are reported for between-group comparisons (concussed vs controls) in the columns, and within-group comparisons (asymptomatic vs acute) in the rows. All mean difference and 95% CI are unadjusted calculations.

Single-Task Range of Motion

We did not observe any statistical group, time, or group by time effects in the mixed-model ANOVAs for single-task range of motion for frontal ($p \geq 0.074$) or sagittal ankle ($p \geq 0.136$), or frontal ($p \geq 0.333$) or sagittal knee ($p \geq 0.111$). Small to medium effects were observed for acute between-group range of motion differences (g range: -0.48, -0.19), indicating the concussed group had decreased range of motion acutely at the ankle and knee overall. Large, decreased frontal ankle range of motion magnitudes were present among concussed individuals along with medium sagittal ankle and frontal and sagittal knee range of motion magnitudes at asymptomatic (g range: -2.35, 0.44; Table 4.2).

Single-Task Moments

A significant group effect ($p=0.033$), but not group by time ($p=0.066$) or time ($p=0.355$), was observed for single-task plantarflexion moments with the concussed cohort producing significantly more normalized plantarflexion torque than controls overall (mean difference= 0.03; 95% CI: 0.01 - 0.05). No significant group, time, or group by time effects were observed for single-task inversion ankle moments ($p \geq 0.203$) or knee valgus ($p \geq 0.160$) or extension moments ($p \geq 0.837$). Small to large effects were observed for acute between-group moment differences, indicating the concussed group had increased plantarflexion and knee valgus and decreased ankle inversion moment magnitudes acutely (g range: -0.32, 1.96). Null to medium effects for asymptomatic between-group differences were identified, with the concussed group displaying decreased ankle inversion and knee valgus moment magnitudes at asymptomatic (g range: -0.68, 0.00; Table 4.2).

Single-Task Peak Vertical Ground Reaction Force, DPSI, and Reaction Time

No significant group, time, or group by time effects were observed for single-task normalized peak vertical ground reaction force ($p \geq 0.067$), reaction time ($p \geq 0.133$), or DPSI ($p \geq 0.516$). Medium to large effects were observed for acute between-group differences, indicating the concussed group had increased peak vertical ground reaction force, increased reaction time (i.e. slower), and increased DPSI (i.e. more unstable) magnitudes (g range: 0.40, 0.97). Asymptomatic effects indicated increased peak vertical ground reaction force and no reaction time or DPSI magnitudes (g range: 0.00, 1.27; Table 4.2).

Dual-Task Range of Motion

Table 4.3 provides summary statistics for both cohorts over time. A significant time effect was observed for dual-task sagittal knee range of motion ($p=0.020$), but no group ($p=0.612$) or group x time effect ($p=0.290$). Post-hoc testing revealed dual-task sagittal knee range of motion decreased from acute to asymptomatic timepoints for both cohort (mean difference: -2.32; 95% CI: -4.20 - -0.44). No significant group, time, or group by time effects were observed however for frontal ($p \geq 0.303$) or sagittal ankle ($p \geq 0.150$), or frontal knee range of motion ($p \geq 0.594$). Small to medium effects were observed for acute between-group range of motion differences, with the concussed group having decreased frontal ankle and sagittal and frontal knee range of motion magnitudes acutely (g range: -0.47, 0.36). Decreased concussed group effects were also observed for sagittal knee and sagittal and frontal ankle joint range of motion at asymptomatic (g range: -0.64, 0.29; Table 4.3).

Table 4.3. Dual-Task Single-Leg Hop Outcomes Between Groups at Acute and Asymptomatic (n=12)

	Concussed				**Control**							
	Acute		*Asymptomatic*		*Acute*		*Asymptomatic*		*Acute*		*Asymptomatic*	
	Mean (SD)								Hedges' g			
	Hedges' g (timepoint change %)								*Group Mean Difference (95% CI)*			
Sagittal Ankle ROM (°)	55.70	7.19	48.06	(13.32)	51.80	(13.59)	53.55	(3.80)	0.36		-0.56	
	-0.71		*-13.72%*		*0.18*		*3.38%*		*3.90*	*(-8.76, 16.55)*	*-5.49*	*(-18.14, 7.17)*
Frontal Ankle ROM (°)	28.05	9.48	26.68	(6.32)	29.01	(4.50)	29.94	(3.45)	-0.13		-0.64	
	-0.17		*-4.88%*		*0.23*		*3.21%*		*-0.96*	*(-8.97, 7.06)*	*-3.26*	*(-11.28, 4.75)*
Sagittal Knee ROM (°)	48.90	7.01	47.52	(8.65)	51.92	(5.79)	48.65	(6.24)	-0.47		-0.15	
	-0.18		*-2.82%*		*-0.54*		*-6.30%*		*-3.02*	*(-11.93, 5.90)*	*-1.13*	*(-10.05, 7.79)*
Frontal Knee ROM (°)	8.84	4.69	8.97	(3.34)	9.56	(5.37)	8.18	(1.95)	-0.14		0.29	
	0.03		*1.47%*		*-0.34*		*-14.44%*		*-0.72*	*(-5.64, 4.19)*	*0.79*	*(-4.12, 5.70)*
Ankle plantarflexion moment (Nm/BW)	0.16	0.02	0.14	(0.02)	0.13	(0.02)	0.15	(0.02)	1.50		-0.50	
	-1.00		*-12.50%*		*1.00*		*15.38%*		*0.03*	*(0.01, 0.05)*	*-0.01*	*(-0.03, 0.02)*
Ankle inversion moment (Nm/BW)	0.04	0.02	0.03	(0.01)	0.04	(0.05)	0.04	(0.03)	0.00		-0.45	
	-0.63		*-25.00%*		*0.00*		*0.00%*		*0.00*	*(-0.03, 0.04)*	*-0.01*	*(-0.02, 0.05)*
Knee extension moment (Nm/BW)	0.42	0.09	0.44	(0.08)	0.42	(0.08)	0.42	(0.05)	0.00		0.30	
	0.23		*4.76%*		*0.00*		*0.00%*		*0.00*	*(-0.10, 0.09)*	*0.02*	*(-0.08, 0.11)*
Knee valgus moment (Nm/BW)	0.13	0.05	0.09	(0.03)	0.11	(0.06)	0.13	(0.05)	0.36		-0.97	
	-0.97		*-30.77%*		*0.36*		*18.18%*		*0.02*	*(-0.04, 0.07)*	*-0.04*	*(-0.10, 0.02)*
Peak vertical ground reaction force (N/BW)	2.83	0.18	3.03	(0.21)	2.71	(0.33)	2.81	(0.25)	0.45		0.95	
	1.02		*7.07%*		*0.34*		*3.69%*		*0.12*	*(-0.19, 0.43)*	*0.22*	*(-0.09, 0.53)*
Reaction Time (s)	0.82	0.29	0.62	(0.14)	0.70	(0.20)	(0.67)	(0.25)	0.48		-0.25	
	-0.88		*24.39%*		*-0.13*		*4.29%*		*0.12*	*(-0.16, 0.40)*	*-0.05*	*(-0.33, 0.23)*
Dynamic Postural Stability Index (DSPI)	0.38	0.02	0.40	(0.04)	0.36	(0.04)	0.39	(0.05)	0.63		0.22	
	0.63		*-5.26%*		*0.66*		*-8.33%*		*0.02*	*(-0.03, 0.07)*	*0.01*	*(-0.03, 0.06)*

Hedges' g effect sizes are reported for between-group comparisons in the columns, and within-group comparisons in the rows. All mean difference and 95% CI are unadjusted calculations.

Dual-Task Moments

We observed a significant group by time effect (p=0.019), but not group (p=0.154) or time (p=0.835), for dual-task plantarflexion moments. Post-hoc testing revealed the concussed cohort had significantly greater plantarflexion torque than controls acutely (0.03 Nm/BW, 95% CI: 0.01 - 0.07, p=0.035), but no other group or time differences (p≥0.212). No other group, time, or group by time effects were observed for dual-task ankle inversion moments (p≥0.399), or knee extension (p≥0.554) or valgus moments (p≥0.059). None to large effects were observed for acute between-group moment differences (g range: 0.00, 1.50), indicating the concussed group had increased ankle plantarflexion and knee valgus joint moment magnitudes acutely. Medium to large effects for asymptomatic between-group differences were observed, with decreased ankle plantarflexion, knee extension, and knee valgus joint moment magnitudes (g range: -0.97, 0.30; Table 4.3).

Dual-Task Peak Vertical Ground Reaction Force, DPSI, and Reaction Time

We observed a significant time effect (p=0.024), but not group (p=0.22) or group by time (p=0.411), for dual-task normalized peak vertical ground reaction force. Overall greater vertical ground reaction force was produced at the asymptomatic timepoint relative to the acute (mean difference: 0.15N/BW; 95% CI: 0.03 – 0.28). A significant time effect (p=0.028), but not group (p=0.786) or group by time (p=0.091), was also observed for dual-task reaction time. The asymptomatic timepoint resulted in faster RT than acute among both cohorts (mean difference: -0.12, 95% CI: -0.22, -0.02). No significant group, time, or group by time effect was observed for dual-task DPSI (p≥0.062). Acute effect size interpretation indicated the concussed group had increased peak vertical ground reaction force, increased reaction time (i.e. slower), and increased DPSI (i.e. more unstable) magnitudes (g range: 0.45, 0.63), while asymptomatic effects indicated large increased peak vertical ground reaction force, small decreased reaction time, and small increased DPSI magnitudes (g range: -0.25, 0.95; Table 4.3).

Discussion

These findings provide novel insights into concerns about post-concussion movement impairments and indicate subtle, but potentially important, group differences during gait and a sport-like single-leg hop assessment acutely. Statistically, we observed minimal group differences, but found small to large effect size magnitudes for both the gait and single-leg hop assessments acutely that reduced in magnitude at asymptomatic. Collectively, these findings may indicate that gait and functional movement are inhibited acutely following a concussion, but improve once symptoms resolve.

Gait Group Differences

We observed decreased stride length and gait velocity, but not stride width, acutely that returned to control levels once asymptomatic during single-task (Table 4.3). Dual-task did not statistically demonstrate decreased stride length or gait velocity between cohorts at any timepoint, but stride width was wider acutely for concussed individuals. We however observed medium to large effect magnitudes for both single- and dual-task gait velocity, stride length, and stride width acutely, and notably a moderate effect magnitude for single- and dual-task gait velocity at asymptomatic consistent with aberrant post-concussion gait (Table 4.3). Single- and dual-task gait has been thoroughly examined from acutely to 2-months post-concussion in the literature (Büttner et al., 2019; Howell, Buckley, et al., 2018; Howell et al., 2014), and our present findings overall are in line with the existing literature which indicate slowed gait velocity, shorter stride length, and greater stride width acutely with larger deficits when performed under dual-task.

Single-Leg Hop Group Differences

Previous research has examined functional, sport-like movement after concussion, but have been limited to assessing individuals two-months to three-years after their concussion (Avedesian et al., 2020; DuBose et al., 2017; Eagle, Kontos, Mi, et al., 2019; Lapointe et al., 2018; Lynall et al., 2018), with the earliest examination occurring approximately 16 days after full medical clearance (Lee, Blueitt, Hannon, Goto, & Garrison, 2021). Our findings provide insights to acute and asymptomatic post-concussion movement deficits, as well as if these deficits are augmented by incorporating a dual-task paradigm. Overall we observed a small quantity of statistically different outcomes between cohorts over time during both single- and dual-task, a similar finding to previously published functional movement data on concussion history individuals (Avedesian et al., 2020; DuBose et al., 2017; Eagle, Kontos, Mi, et al., 2019; Lapointe et al., 2018; Lynall et al., 2018).

Though we did not observe statistically different single- or dual-task lower extremity kinematics between groups at any timepoint during the single-leg hop assessment, we did observe medium to large effect sizes overall (Table 4.1 and 4.2). Medium to large effects in the absence of statistical significance may indicate important group differences that were not identified due to the relatively small sample size and associated greater outcome variability observed (Cohen, 1988; Hedges & Olkin, 1985). These effect sizes collectively can be interpreted as decreased single-task range of motion acutely that are relatively normalized or improved at asymptomatic for concussed individuals, while dual-task elicited decreased range of motion magnitudes at asymptomatic. Slightly decreased lower extremity range of motion for concussed individuals is consistent with previous concussion history research (Avedesian et al., 2020; Lapointe et al., 2018), and may indicate altered movement consistent with conservative, stiff motion is occurring (DuBose et al., 2017). Dual-task assessment following concussion has been limited to gait and balance assessments (Howell, Lynall, et al., 2018). We are the first to provide preliminary insights to dual-task functional movement outcomes post-concussion. Our findings indicate a similar trend to previous research demonstrating that dual-task assessments can elicit a greater aberrant movement response than single-task alone during gait (Büttner et al., 2019), and may be an important factor for maximizing post-concussion assessment sensitivity.

Kinetic outcomes have only been examined in a few previous concussion history studies which collectively did not observe any differences between concussion history and healthy cohorts during double-leg and single-leg jump landings (Avedesian et al., 2020; DuBose et al., 2017). We examined peak ground reaction force and joint moments throughout the study and observed minimal statistically different outcomes. We observed greater normalized plantarflexion torque in the concussed cohort relative to controls at both timepoints during single-task, and greater plantarflexion torque only acutely during dual-task (Table 4.1 and 4.2). No other ankle or knee moments were statistically significant among the mixed-model ANOVAs. In the absence of statistically significant findings, medium effect size magnitudes were observed for increased vertical ground reaction force, increased knee valgus torque, and decreased ankle inversion torque acutely during single-task for concussed individuals, and increased vertical ground reaction force, decreased knee valgus, and decreased ankle inversion torque at asymptomatic. Dual-task similarly resulted in increased vertical ground reaction force and increased knee valgus torque effect size magnitudes acutely, and increased vertical ground reaction force and decreased knee valgus torque at asymptomatic.

Our collective kinetic findings suggest ankle plantarflexion and potentially vertical ground reaction force and knee valgus moments are heightened acutely following concussion, and all but vertical ground reaction force return to or drop below control group levels once asymptomatic under both single- and dual-task. Given the relationship between increased joint angles, forces, and moments and potential lower extremity musculoskeletal injury (Hewett et al., 2005), it is critical future work examines and monitors a larger concussed sample longitudinally to ensure the biomechanical recovery of joint moments at asymptomatic is not potentially attributed to an undetected learning and/or motivation effect, and to further understand why greater peak vertical ground reaction force is present throughout concussion recovery.

We examined DPSI (a metric for whole-body stabilization when transferring from a dynamic to static posture) to understand how functional stability may be altered after concussion. Overall, we did not observe any statistical group differences for DPSI at any timepoint or for either single- or dual-task conditions. The DPSI outcome demonstrated medium effect magnitudes for greater DPSI among concussed individuals acutely under single- and dual-task that diminished by asymptomatic. Therefore, it is likely reaction time and DPSI impairments during the single-leg hop exist but were not detected due to the relatively small sample size employed.

Reaction Time Differences

Reaction time deficits are common acutely following concussion on computerized neurocognitive testing assessments (Lempke, Howell, et al., 2020), however, it was not known whether reaction time impairments would remain or even increase in magnitude or time when examined via gait or single-leg hop. We observed slowed gait reaction time among concussed individuals with a medium effect size acutely that normalized at asymptomatic during single-task performance, but surprisingly did not observe any statistical group differences for single-leg hop reaction time. Dual-task gait reaction time interestingly produced similar statistically decreased reaction time, but elicited a larger acute effect size. Slower reaction time during dual-task relative to single-task has been established for gait among healthy individuals (Lempke, Johnson, et al., 2020). Our findings collectively show a similar, but larger, dual-task effect occurs among concussed individuals.

A lack of single-leg hop reaction time deficits is abnormal acutely following concussion (Covassin, Moran, & Wilhelm, 2013; Lempke, Howell, Eckner, & Lynall, 2020; Lempke, Lynall, et al., 2020), but is potentially due to the elevated reaction time variability observed (Table 4.1 and 4.2) and established during this single-leg hop assessment relative to clinical reaction time measures (Lempke, Johnson, et al., 2020). Future research should aim to examine the added utility of dual-task assessments in aiding in concussion assessment, return to play, and potential lingering deficits in order to ensure optimal patient safety.

Limitations

Our study had several noteworthy limitations. We examined a relatively small sample size and is a critical factor when interpreting statistical significance from analytical models. Numerous single-leg hop and gait biomechanics outcomes were examined among this cohort, and leads to greater likelihoods for type I errors. For this reason, we implemented effect sizes, group mean differences, and timepoint change scores to augment statistical comparisons and provide complimentary insights. Our findings also may not be generalizable to other populations such as athletic populations or younger or older cohorts due to examining college-aged individuals within the university system. The single-leg hop task employed does not allow for direct comparisons to previous post-concussion movement studies, but our findings do provide novel insights to functional stability capabilities for future research to build upon. Lastly, motivational factors were not assessed between the concussed and control groups and alter their outcomes, although individuals were given verbal encouragement prior to each movement block. Future research should examine early post-concussion functional movement with a larger, athletic-based sample to provide independent validation and more direct implications of our findings.

Conclusion

Altered spatiotemporal gait outcomes were observed acutely, with dual-task gait potentially providing greater sensitivity to post-concussion deficits. Single- and double-limb CoP efficiency did not demonstrate meaningful group differences and likely does not have utility for post-concussion assessment. Slowed gait velocity was the most robust gait alteration after concussion and should be an outcome of interest as researchers aim to translate assessments from the lab to clinical practice. Minimal statistically significant single-hop biomechanics group differences were observed, but numerous medium to large effect sizes indicating potentially meaningful decreases in lower extremity joint range of motion and altered joint torque occurred among acutely concussed individuals. Single-leg hop group differences overall dissipated once asymptomatic, but medium effect size magnitudes, such as greater concussed knee valgus torque, may indicate critical focal points for future research to monitor long-term and understand how biomechanical changes relate to post-concussion musculoskeletal injury risk.

CHAPTER 5

LOWER EXTREMITY SOMATOSENSORY FUNCTION THROUGHOUT CONCUSSION RECOVERY[1]

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[1] Lempke LB, Hoch MC, Call JA, Schmidt JD, Lynall RC. To be submitted to *J Ath Train*.

Abstract

Objective: To examine somatosensory function between concussed young adults and healthy matched-controls acutely (0-7 days) and when asymptomatic (±72hours).

Methods: Concussed and matched-control participants (n=16; 63% male, age:19.4±1.2yrs, mass:75.3±14.4kg, height:180.6±11.3cm, concussion history:0.1±0.3) completed somatosensory assessments acutely (3.6±1.7days post-injury) and when asymptomatic (25.8±21.3days post-injury) on their dominant limb. Somatosensory assessments included: 1) plantar touch-sensation threshold via Semmes-Weinstein monofilaments, 2) plantar pain-pressure threshold via algometry, and 3) knee absolute joint repositioning error via Biodex joint across 3 testing arcs of motion (105°-75°, 30°-60°, 90°-45° knee-flexion). We used mixed-model ANOVAs, post-hoc Tukey HSD t-tests with mean difference 95% confidence intervals (95% CI), and Hedges' g effect sizes to examine and interpret differences (α=0.05).

Results: Touch sensation had a group effect with concussed participants needing 1.31grm-f more relative to controls (95% CI: 0.03, 2.58; p=0.048). Concussed individuals required 1.18grm-f (95%CI: -0.17, 2.76; g=0.98) and 1.15grm-f (95%CI: -0.14, 1.90; g=0.97) more force for touch sensation relative to controls acutely and at asymptomatic, respectively. No plantar pressure-pain threshold effects were observed (p≥0.698), but slightly more pressure acutely (0.80lbf/cm^2; 95%CI: -1.88, 2.56; g=0.36) and at asymptomatic (0.44lbf/cm^2; 95%CI: -1.77, 2.67; g=0.20) was needed for concussed individuals. The 30°-60° joint repositioning trials had a time effect, with asymptomatic having 4.12° better accuracy (95% CI: 1.69- 6.56; p=0.002). Concussed individuals had small mean differences and effect sizes relative to controls for joint repositioning during 105°-75° (0.79°; g=0.25) and 90°-45° trials (0.96°; g=0.16), but not 30°-60° trials (-1.75°; g=-0.45) acutely.

Conclusions: Concussed individuals exhibited diminished plantar touch-sensation compared to controls which may relate to the musculoskeletal injury risk post-concussion phenomenon. Pressure-pain sensation displayed small to medium effect sizes which may indicate subtly altered somatosensory neurotransmission after concussion. Negligible joint repositioning differences may indicate joint position sense and/or somatosensory function at the knee are not altered post-concussion. Further research pre- and post-concussion is warranted to enhance the clinical interpretation of these findings.

Keywords: Proprioception; Sensorimotor; Mild Traumatic Brain Injury

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Introduction

Concussion is a widespread pathology affecting millions of athletes, military service members, and the general population annually (Cancelliere et al., 2017; Harman et al., 2005; Wasserman et al., 2016). A complex neurometabolic cascade occurs in the brain immediately following concussion that results in altered sensorimotor and cognitive clinical manifestations (Broglio & Puetz, 2008; Giza & Hovda, 2014). Current best evidence and clinical practices employ a multidimensional assessment to evaluate at least symptoms, postural stability, and neurocognitive status post-concussion to provide strong diagnostic accuracy and guide clinical recovery decision-making (Garcia et al., 2018; Lempke, Schmidt, et al., 2020; McCrory et al., 2017; Resch et al., 2016). Clinical recovery occurs for the vast majority of college-aged athletes around 14 days (Garcia et al., 2018; Wasserman et al., 2016), however, growing research has consistently identified lingering dual-task (i.e., completing a motor and cognitive task simultaneously) movement impairments months beyond clinical recovery (Büttner et al., 2019; Howell, Lynall, et al., 2018; Parker et al., 2006). Numerous neural inputs and outputs between the brain, spinal cord, and periphery contribute to human movement, and examining movement like gait or postural stability may only provide collective insights to an individual's global sensorimotor function rather than subsystem function. Further investigation targeting specific sensorimotor pathways is warranted to gain a deeper understanding of the underlying deficits.

The sensorimotor system is comprised of multifactorial afferent (somatosensory, vestibular, visual) and efferent (intrafusal and extrafusal muscle fibers) receptors which contribute to collective sensory integration (Riemann & Lephart, 2002). The somatosensory system specifically is comprised of four subcomponents: pain, temperature, tactile, and proprioception, with proprioception being segmented into kinesthesia, joint position sense, and sense of force (Riemann & Lephart, 2002). Each somatosensory subcomponent serves a unique and vital role to human movement. Though all subcomponents of the somatosensory system contribute to movement performance, subtle subcomponent changes may be partially masked via sensory reweighting when being assessed through global movement like gait or postural stability (Assländer & Peterka, 2014). For this reason, researchers have developed methods for isolating somatosensory subcomponents to truly understand their independent function (Edwards, Talelli, & Rothwell, 2008; Palmieri et al., 2004; Riemann et al., 2002; Rolke et al., 2005). Pain, tactile, and joint position sense have been extensively studied across a variety of musculoskeletal injuries to understand somatosensory function post-injury and understand if impairment predisposes someone to subsequent injury (Konradsen & Magnusson, 2000; Medina McKeon & Hoch, 2019; N. Relph, Herrington, & Tyson, 2014; Walton et al., 2011; Wikstrom, Naik, et al., 2010). No existing research has isolated somatosensory function following concussion, leaving a gap for clinicians and researchers trying to identify and implement post-concussion rehabilitative strategies.

Indirect measures of gait and dynamic balance suggest somatosensory deficits may exist well beyond clinical recovery (Howell, Lynall, et al., 2018; Lynall et al., 2020; Parker et al., 2006), but somatosensory subcomponents have never been directly studied in concussed individuals. Impairments beyond clinical recovery are concerning as clinical measures may provide a false positive to when safe recovery has occurred, and may partially explain why concussed individuals have a two-fold increase in musculoskeletal injury risk (Howell, Lynall, et al., 2018; Lynall et al., 2015; Lynall, Mauntel, et al., 2017; McPherson et al., 2018). Identifying if specific somatosensory impairments exist following concussion is critical to prevent long-term health consequences from both concussions and subsequent musculoskeletal injury.

Therefore, the purpose of this study was to examine differences in somatosensory (pressure-pain threshold, touch sensation threshold, and passive joint repositioning) function between concussed young adults and yoked, healthy matched-controls at acute (<7 days) and asymptomatic (±72 hours) post-concussion clinical timepoints. We hypothesized 1) concussed individuals would display decreased somatosensory function (i.e., lower pressure-pain thresholds, lower touch sensation thresholds, and greater passive joint repositioning error) compared to healthy matched-controls acutely and when asymptomatic, and 2) concussed individuals would not demonstrate significant somatosensory improvement at asymptomatic compared to acute.

Methods

We employed a prospective, longitudinal case-control study design to examine somatosensory function among a concussed cohort acutely (0-7 days post-injury) and asymptomatic (± 72 hours), and a healthy, yoked, matched-control cohort. A total of 8 concussed and 8 controls were enrolled in the study (Appendix L). Concussed participants were recruited through concussion clinic referral from the University Health Center, and control participants were recruited from the student body at the University of Georgia between August 2019 and February 2021. Concussed participants were included if they experienced an independent physician concussion diagnosis consistent with current consensus guidelines (McCrory et al., 2017) and were assessed by the research team within 7 days post-injury. Concussed participants were given academic and physical activity restrictions consistent with current guidelines at the discretion of their physician (McCrory et al., 2017). Control participants were included if they matched with a concussed participant on sex, age (± 1 year), height (± 10%), mass (± 5%), and concussion history (± 1 year) (Lynall et al., 2018, 2020).

Participants were excluded if any of the following were met: National Collegiate Athletic Association athlete, history of any neurologic, memory, anxiety, or depression disorder, history of a lower extremity musculoskeletal injury <6 months that resulted in >24 hours of time-loss from physical activity, history of any lower extremity orthopedic surgery in the past year. Participants received honorarium at the acute timepoint and asymptomatic timepoints to minimize attrition. All participants provided written informed consent prior to study participation, and this study was approved by the University of Georgia's Institutional Review Board (PROJECT00000469).

Procedures and Instrumentation

All participants first completed the survey assessments and then the somatosensory assessment battery with *a priori* somatosensory assessment randomization. The somatosensory assessment order was identical between a participant's acute and asymptomatic timepoints, as well as between each concussed and matched-control pair. The asymptomatic timepoint assessment occurred for concussed participants once their signs and symptoms normalized to pre-injury status as described below. Control participants completed testing at the asymptomatic timepoint based upon the number of days between the two timepoints of their matched concussed counterpart.

Survey Assessments

Post-Concussion Symptom Scale (PCSS)

The 22-item Post-Concussion Symptom Scale (PCSS; Appendix A) was employed where participants rated their symptom presence (i.e. yes or no for each symptom) and symptom severity via a 6-point Likert scale, with 0= "none" and 6= "severe", at that current point in time

(Echemendia et al., 2017). Both concussed and control participants completed the PCSS at the start of both timepoints prior to any assessments, and then after each somatosensory assessment to examine for symptom provocation. Concussed participants were discontinued from completing the testing session if symptom severity increased by ≥7, but no cases occurred.

Concussed participants also completed the PCSS with modified instructions (Appendix B) where they rated their symptoms “typically experienced (>3 times per week)”, to establish a retrospective signs and symptoms pre-injury proxy (Hoffman et al., 2018; Lempke, Lynall, et al., 2020; Schmidt et al., 2017). Lastly, concussed participants completed daily PCSS via online survey (Qualtrics, Provo, UT) to allow the research team to determine when the participant was asymptomatic (Hoffman et al., 2018; Lempke, Lynall, et al., 2020; Schmidt et al., 2017). Daily PCSS survey compliance was strong, with concussed participants completing ≥81.2% (mean=96.3%) of daily surveys. Concussed participants’ asymptomatic status was determined when their pre-injury proxy was within the PCSS symptom severity reliable change score (± 3 symptom severity score) of their daily PCSS (Chin et al., 2016).

Musculoskeletal Injury History Form

A musculoskeletal injury history form (Appendix E) was modified and implemented based off previously published forms for descriptive purposes (Houston et al., 2018, 2017). The survey asked participants whether they had ever sustained any musculoskeletal injuries (i.e., sprains, strains, fractures, dislocations, and surgery) in the lower extremity or trunk in the past five years. If participants reported “yes” to any musculoskeletal injury, a brief description of the injury type (e.g., ankle sprain – lateral ankle sprain), how long ago it occurred, and how many times it has happened were recorded.

Somatosensory Assessments

The somatosensory assessments consisted of a touch sensation threshold to assess tactile sensation, pressure-pain threshold to assess pain sensation, and passive joint repositioning to assess joint position sense. All somatosensory assessments were completed on the participant's self-reported dominant leg (i.e., the leg they would kick a ball the farthest with) in a randomized order.

Touch Sensation Threshold

The touch sensation threshold was assessed using Semmes-Weinstein monofilaments (Baseline® Tactile sensory evaluators, Fabrication Enterprises Inc., White Plains, NY) to assess tactile sensation (Appendix I). Semmes-Weinstein monofilaments are calibrated to flex at specific grams of force (grm-f), providing a reliable touch sensation threshold assessment (Snyder et al., 2016). Participants laid prone with their head facing down on a treatment table while the monofilaments were applied over the participant's plantar surface of their first metatarsal head of their dominant foot until a "C" shaped bend occurred, and was held for 1s (Appendix I). Participants indicated they felt monofilament application by stating "yes", and if nothing was felt, remained quiet. The same researcher (LBL) assessed all participants. The first metatarsal head was marked with a pen to ensure accurate application location. Semmes-Weinstein monofilaments were applied using a standard "4-2-1" stepping protocol (Snyder et al., 2016). For example, the examiner applied a 6.0grm-f monofilament and the choice to apply a thinner (1.0grm-f) or thicker (26.0grm-f) diameter monofilament "4 steps" away from the initial 6.0grm-f was determined by the participant's positive (thinner monofilaments applied) or negative (thicker monofilament applied) detection of the monofilaments. The Semmes-Weinstein monofilaments were applied in steps of 4 until 3 reversals were detected (i.e., negative response followed by a positive response), indicating a range of sensory detection. The researcher then followed the same process outlined above for the “4 step” process but continued using a “2 step” process until 3 reversals, then again for “1 step”. The final Semmes-Weinstein monofilament grm-f applied was the main outcome measure, with one stepping protocol being completed each timepoint (Snyder et al., 2016).

Pressure-pain Threshold

The pressure-pain threshold was used to measure perceived pain sensation. Pressure-pain threshold was assessed using a digital algometer (Wagner FPX50, Wagner Instruments, Greenwich, CT, USA) with a $1cm^2$ applicator applied to the participant’s dominant foot over the area where the medial longitudinal arch surface and navicular tuberosity intersected (Rolke et al., 2005). The location was selected as it is a reliable and pressure-sensitive location (Rolke et al., 2005). Participants sat upright with their leg passively extended on a treatment table while the algometer was applied at approximately 1lbf/s until the pressure was perceived as a painful stimulus (Appendix J). Participants were instructed to say “stop” as soon as the pressure was perceived as the initiation of a painful stimulus, and the researcher (LBL) removed the algometer and recorded the pressure at that time. The applicator was moved slightly proximal or distal for each trial to avoid tissue sensitivity and/or bruising. Three trials were completed at each timepoint, and pressure (lbf/cm^2) was the main outcome.

Passive Joint Repositioning

Passive joint repositioning was assessed using a Biodex System 4 dynamometer (Biodex Medical Systems, Shirley, NY, USA). All participants completed trials with their dominant leg while blindfolded to remove any joint position visual cues (Nagai et al., 2012). One practice trial was completed unblinded to ensure participants understood the instructions and felt comfortable with the assessment prior to recording trials. Participants were placed in a standardized sitting position of 90° hip flexion with the trunk perpendicular to the ground, the dynamometer and participant knee joint axes aligned, and the dynamometer movement arm attached proximal to the participant's superior malleoli surface (Appendix H). The lower leg was placed in a starting joint angle position and participants were told that this was their "start position". The lower leg was then passively moved from a starting position to a target position where the dynamometer locked in place for 10s and participants were instructed to "remember this position". The dynamometer then returned to the original starting position, and the assessment was initiated. The dynamometer passively moved the participant's lower leg 1°/s and participants pressed a trigger that locked the moment arm when they believed their leg was at the target position (Appendix H), with the difference between target and participant indicated angle recorded (i.e., absolute joint repositioning error). Three combinations of starting and target knee flexion angle positions (105° to 75°, 30° to 60°, and 90° to 45°) were completed for three trials each (9 total trials each timepoint). These position combinations were utilized because joint and muscle mechanoreceptors overlap in function, but can differ in their sensitivity throughout joint range of motion (Clark et al., 1989; Riemann & Lephart, 2002).

Somatosensory Intra-Rater Reliability

Though the employed assessments have been deemed reliable and valid, they are all subject to examiner error. Therefore, an additional sample of healthy participants (n=10) independent from the described healthy, matched-control cohort completed the somatosensory assessments at two timepoints within 14 days to determine intra-rater reliability. Intraclass correlation coefficients (ICC) models with 95% confidence intervals (95% CI) were calculated in accordance to Shrout and Fleiss guidelines (Shrout & Fleiss, 1979). Touch sensation ($ICC_{3,1}$ = 1.00; 95% CI = 0.98 – 1.00) and pressure-pain thresholds ($ICC_{3,k}$ = 0.98; 95% CI = 0.92 – 1.00) demonstrated perfect and strong reliability, respectively. The three joint repositioning angles of 105° to 70°, 30° to 60°, and 90° to 45° were demonstrated to be reliable ($ICC_{3,k}$ = 0.56, 0.82, 0.85; 95% CI = 0.00 – 1.00, 0.20 – 0.96, 0.35 – 0.97, respectively).

Data Processing

The touch sensation threshold via Semmes-Weinstein monofilament diameter was the final monofilament (gm) applied from the single stepping protocol. The pressure-pain threshold via algometry (lbf/cm^2) was calculated as the average of the three trials. The passive joint repositioning trials were calculated as the absolute error (difference between target joint angle and participants indicated joint angle) and were averaged across trials within each of the three positions, resulting in three passive joint repositioning outcomes for each position.

Statistical Analysis

Independent t-tests were conducted on age, height, mass, and sleep (total hours night before), and a Fisher's exact test on sex, concussion history, and limb dominance. Frequencies were calculated for the musculoskeletal injury history form outcomes. All outcomes from PCSS and somatosensory assessments were examined using 2 (group) x 2 (time) mixed-model ANOVAs with $\alpha = 0.05$ *a priori*. Tukey honestly significant difference (HSD) t-tests were utilized if statistically significant interaction or main effects were observed from the mixed-model ANOVAs. Mean differences with associated 95% CI and Hedges' g effect sizes were calculated for all comparisons to provide insights to the magnitude and clinical meaning (Hedges & Olkin, 1985). Effect sizes were interpreted according to traditional guidelines with ≤ 0.20, 0.21–0.79, and ≥ 0.80 used as thresholds for small, medium, and large effects, respectively (Cohen, 1988). All general linear model assumptions were assessed, and statistical analyses were performed using the R Foundation for Statistical Computing (version 3.4.3; Vienna, Austria) (R

Core Team, 2018).

Results

A total of 8 concussed and 8 controls completed all somatosensory assessments at both timepoints. No significant group differences were present for age, sex, height, mass, concussion history, hours of sleep, hand or leg dominance, or time between testing sessions ($p \geq 0.411$; Appendix L). Total PCSS symptom presence ($p<0.001$) and symptom severity ($p<0.001$) displayed significant group by time interactions, with post-hoc testing demonstrating significantly greater total symptom presence and severity acutely for concussed, but not once asymptomatic (Appendix L). The concussed cohort had a symptom total range of 6-22 (median=17) and severity range of 16-68 (median=36.5) acutely. A total of 3 concussed and 1 control had at least one musculoskeletal injury in the past 5-years, with three of the four being lateral ankle sprains (Appendix M).

All mixed-model ANOVAs degrees of freedom are 1 and 14 for the numerator and denominator, respectively. Touch sensation via Semmes-Weinstein monofilaments resulted in significant group ($p=0.048$) and time effect ($p=0.042$), but not a group by time interaction effect ($p=0.273$). Post-hoc testing indicated the concussed cohort required 1.31grm-f (95% CI: 0.03 – 2.58) more than the control cohort regardless of timepoint. At the asymptomatic timepoint, the concussed group demonstrated less force needed to elicit touch sensation than the acute timepoint (-0.30grm-f; 95% CI: -0.58, -0.01). A large effect size with 1.18grm-f more force needed for concussed individuals was present acutely ($g=0.98$). A similar effect ($g=0.97$) and 1.15grm-f more force was present at asymptomatic for the concussed group needing more force to detect touch sensation (Table 5.1). Concussed individuals displayed a 6.90% increase in touch sensation performance (i.e., less grm-f needed), while control individuals displayed a 16.07% increase.

Table 5.1 Somatosensory Function Between Groups at Acute and Asymptomatic (n=16)

	Concussed				**Control**							
	Acute		*Asymptomatic*		*Acute*		*Asymptomatic*		*Acute*		*Asymptomatic*	
	Mean (SD)								Hedges' g			
	Hedges' g (timepoint change %)								*Group Mean Difference (95% CI)*			
JPT: 105°-75° Joint Error	8.12	(2.84)	6.08	(3.33)	7.33	(2.95)	5.83	(2.97)	0.25		0.08	
	-0.28		*25.12%*		*-0.51*		*20.46%*		*0.79*	*(-2.32, 3.90)*	*0.25*	*(-2.86, 3.36)*
JPT: 30°-60° Joint Error	10.6	(4.48)	7.25	(3.39)	12.33	(4.32)	7.42	(3.83)	-0.45		-0.05	
	-0.37		*31.47%*		*-1.20*		*39.82%*		*-1.75*	*(-5.90, 2.40)*	*-0.17*	*(-4.32, 3.98)*
JPT: 90°-45° Joint Error	8.25	(3.69)	8.96	(7.09)	7.29	(4.36)	7.79	(4.75)	0.16		0.19	
	0.08		*-8.61%*		*0.11*		*-6.86%*		*0.96*	*(-4.30, 6.22)*	*1.17*	*(-4.09, 6.43)*
Algometry (lbf/cm^2)	5.62	(2.43)	4.97	(2.57)	4.82	(1.75)	4.53	(1.87)	0.36		0.20	
	-0.12		*11.57%*		*-0.16*		*6.02%*		*0.80*	*(-1.88, 2.56)*	*0.44*	*(-1.77, 2.67)*
Semmes-Weinstein Monofilament (grm)	1.74	(1.58)	1.62	(1.55)	0.56	(0.70)	0.47	(0.65)	0.98		0.97	
	-0.07		*6.90%*		*-0.13*		*16.07%*		*1.18*	*(-0.17, 2.76)*	*1.15*	*(-0.14, 1.90)*

Hedges' g effect sizes are reported for between-group comparisons in the columns, and within-group comparisons in the outcome rows. All mean difference and 95% CI are unadjusted calculations.

The pressure-pain sensation assessment did not demonstrate significant group (p=0.698), time (p=0.955), or group by time effects (p=0.880). A medium effect size (g=0.36) with a 0.80lbf/cm^2 mean difference was observed acutely and a small effect size (g=0.20) and 0.44lbf/cm^2 mean difference at asymptomatic for more pressure needed to elicit pain initiation for concussed participants (Table 5.1). Both concussed (11.57% change) and controls (6.02% change) demonstrated less pressure needed to elicit pain initiation at the asymptomatic timepoint.

Joint repositioning error for the 105-to-75-degree trials did not demonstrate statistically significant group (p=0.670), time (p=0.077), or group by time effects (p=0.775; Table 5.1). A small effect (g=0.25) and mean difference of 0.79 degrees was present for worse performance among concussed individuals acutely, but did not exist at asymptomatic (g=0.08). Both concussed and controls demonstrated medium effect magnitudes for improved 105-to-75-degree joint repositioning at the asymptomatic timepoint, with concussed improving by 25.12% and controls by 20.46% (Table 5.1).

The 30-to-60-degree trials demonstrated a significant time effect (p=0.002), with the asymptomatic timepoint resulting in better accuracy by 4.12 degrees (95% CI: 1.69- 6.56). No group by time (p=0.497) or group effects (p=0.573) were observed for 30-to-60-degree trials. A medium effect (g=-0.45) and mean difference of 1.75 degrees was present acutely for better performance among concussed individuals, but no real effect once asymptomatic (g=-0.05). Both groups displayed improved performance from acute to asymptomatic, with concussed improving by 31.47% and controls by 39.82% (Table 5.1).

The 90-to-45-degree trials did not elicit significant group (p=0.583), time (p=0.733), or group by time effects (p=0.953). A small effect (g=0.16) with a mean difference of 0.96 degrees was observed acutely for worse joint repositioning accuracy for concussed individuals that was also present at asymptomatic (g=0.19; Table 5.1). The concussed group demonstrated -8.61% worse repositioning accuracy at asymptomatic while controls worsened by 6.86%.

Discussion

We examined somatosensory function via touch and pressure-pain sensation on the plantar surface of the foot and joint position sense at the knee among concussed individuals acutely and once asymptomatic relative to matched-controls. Overall, we observed significant differences for decreased touch sensation among concussed individuals throughout study timepoints. Statistically different pressure-pain sensation and joint position sense was not observed between cohorts, but subtle group differences with potentially meaningful effect sizes were observed and may indicate diminished sensation for concussed individuals.

Diminished touch sensation on the plantar surface of the feet has been examined among other pathological populations due to its critical role in maintaining postural stability (McKeon & Hertel, 2007; Meyer, Oddsson, & De Luca, 2004). Our study provides novel insights to touch sensation following concussion, and indicates reduced tactile mechanoreception may be present both acutely and when asymptomatic. Specifically, we observed 1.18grm-f and 1.15grm-f more force needed at the first metatarsal head among concussed individuals with large effect sizes to detect touch sensation than the healthy matched-controls acutely and at asymptomatic, respectively. Chronic ankle instability research (Medina McKeon & Hoch, 2019) has thoroughly examined touch-sensation via Semmes-Weinstein monofilaments and allows for indirect comparisons to the differences in touch-sensation we observed. Previous research (Powell, Powden, Houston, & Hoch, 2014) has indicated individuals with chronic ankle instability required 0.6grm-f more than healthy individuals to detect touch-sensation, only half the mean group difference we observed.

Though 1.15-1.18grm-f may seem insignificant, Semmes-Weinstein monofilament clinical interpretation guidelines would classify the concussed cohort acutely and at asymptomatic as “diminished touch sensation” (0.6-2.0grm-f), while controls were near normal (≤0.4grm) (Powell et al., 2014). Importantly, greater touch-sensation is required during simultaneous cognitive activity (Burcal & Wikstrom, 2016). Given we observed worse tactile mechanoreception among concussed individuals and worse tactile detection occurs during cognitive activity, it is likely these factors interact and impact concussed individuals returning to sport where high-cognitive processing and rapid-decision making are required. Touch sensation may be one of numerous factors contributing to heightened musculoskeletal injury risk following concussion (Howell, Lynall, et al., 2018; Lynall et al., 2015; Lynall, Mauntel, et al., 2017; McPherson et al., 2018), and therefore future research should monitor pre- and post-concussion touch sensation to understand the clinical relevance.

Group differences were not observed for pressure-pain sensation, but importantly, potentially meaningful pressure differences and medium effect sizes were, indicating more force was needed among concussed acutely to illicit initial pain. Reduced pressure-pain thresholds may indicate subtle, but altered neurotransmission and/or cortical processing of the afferent Aδ nociceptor fiber signal (Kandel, Schwartz, Jessell, Siegelbaum, & Hudspeth, 2013) as a result of a concussion imparting dysfunctional neurotransmitter release (Giza & Hovda, 2014). The clinical implications for potentially reduced pressure-pain sensation post-concussion are unknown at this time. If altered pain sensation is affected at the foot plantar surface or even more globally among concussed individuals, it is possible they may not detect nociception as quickly due to the higher threshold required, which could theoretically be a risk factor for more severe injury. However, we did not examine pre-injury pressure-pain thresholds in the present study, and therefore the potential differences may be attributed to pre-existing perceptions of pain. Additional research is warranted to understand the mechanistic onset for potentially reduced pressure-pain sensation following concussion and the associated implications.

Joint position sense was assessed at the knee and did not elicit any statistically significant differences between groups acutely or at asymptomatic, along with heterogeneous effect sizes that suggest better performance among concussed individuals (Table 5.1). Differences between the employed somatosensory outcomes and their effect directions in our study are somewhat expected given we examined somatosensory measures at different lower extremity segments (e.g., pain and touch sensation at the foot, joint position sense at the knee). One reason for this can be attributed to the unique mechanoreceptor or nociceptor pathways being examined via touch sensation, pressure-pain sensation, and joint position sense. For example, the plantar surface touch sensation ascending pathway is not identical to the plantar surface pressure-pain sensation due to subcomponents of the spinal cord, thalamus, and somatosensory cortex uniquely being in charge of processing the signals (Kandel et al., 2013). Furthermore, these specific sensory paths are different throughout sections of the human body (e.g., plantar surface pathway is different from knee pathway). Thus, it is possible we observed subtle deficits for plantar touch sensation and possibly pressure-pain sensation, but not knee joint position sense, because the unique pathway and/or somatosensory region being targeted. Our findings may cumulatively suggest that future research aiming to better understand somatosensory alterations and/or musculoskeletal injury risk post-concussion may benefit from isolating somatosensory assessments at the foot and ankle. Regardless, further research is warranted to thoroughly explore somatosensory function to ultimately ensure long-term patient safety.

Limitations

We examined a relatively small sample size of college-aged individuals within the university system, and therefore our findings may not be generalizable to other populations. We also only examined the concussed cohort after injury making it challenging to determine whether somatosensory changes occurred. Future research should aim to examine somatosensory measures pre- and post-injury to provide better insights and validity. One author (LBL) completed all assessments and was not blinded to group assignment, potentially leading to bias during the assessments. Lastly, only the dominant limb and select somatosensory assessments at lower extremity locations were examined in the present study. It is possible our findings may differ if examined on the non-dominant limb or if other somatosensory functions, such as temperature or vibration sensation, were examined.

Conclusion

Worse plantar touch-sensation among concussed individuals compared to controls may indicate diminished cutaneous mechanoreception after concussion, and may partially contribute to the established musculoskeletal injury risk post-concussion phenomenon (Howell, Lynall, et al., 2018; Lynall et al., 2015; Lynall, Mauntel, et al., 2017; McPherson et al., 2018). Though not statistically significant, pressure-pain sensation displayed small to medium effect sizes which may indicate altered pain neurotransmission or perception after concussion. Joint repositioning did not demonstrate any group differences along with small to negligible effect sizes, and may indicate joint position sense and/or somatosensory function at the knee is not altered post-concussion. Further research pre- and post-concussion is needed to understand if somatosensory is altered, and the role it plays for heightened musculoskeletal injury risk.

CHAPTER 6

LOWER EXTREMITY NEUROMUSCULAR FUNCTION FOLLOWING CONCUSSION: A PRELIMINARY EXAMINATION[1]

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[1] Lempke LB, Call JA, Hoch MC, Schmidt JD, Lynall RC. To be submitted to *Muscle & Nerve.*

Abstract

Objective: To compare neuromuscular function between college-aged concussed individuals when asymptomatic (±72 hours) following concussion and healthy matched-controls.

Methods: Concussed and matched-control participants (n=16; 63% male, age:19.4±1.2yrs, mass:75.3±14.4kg, height:180.6±11.3cm, concussion history:0.1±0.3) completed the neuromuscular assessment when asymptomatic (20.6±20.4days post-injury) on their dominant limb. The neuromuscular assessment utilized the superimposed burst technique to assess bodyweight-normalized quadriceps maximal voluntary isometric contraction (MVIC) torque, bodyweight-normalized superimposed burst (SIB) torque, pain (numeric 1-10) during SIB, and the central activation ratio (CAR). We used parametric and non-parametric statistical models, 95% confidence intervals (95% CI), and Hedges' g (parametric) and Spearman ρ (non-parametric) effect sizes to compare neuromuscular outcomes between groups ($\alpha=0.05$).

Results: The MVIC torque (concussed: 0.96Nm_{BW}±0.38, control: 0.79Nm_{BW}±0.21; 95% CI: -0.17, 0.51; p=0.28; g=0.55), SIB torque (concussed: 0.36Nm_{BW}±0.23, control: 0.34Nm_{BW}±0.17; 95% CI: -0.20, 0.23; p=0.879; g=0.10), and CAR (concussed: 72.40%±17.92, control: 71.25%±9.79; 95% CI: -14.77, 17.08; p=0.875; g=0.08) did not differ between groups. Pain during SIB was significantly greater for concussed (median=6, interquartile range=0.25) relative to controls (median=4.8, interquartile range=1.13; p=0.046, ρ=-0.53).

Conclusions: Our findings indicate concussed individuals do not have altered voluntary or involuntary quadricep neuromuscular function. Therefore, the heightened musculoskeletal injury risk following concussion might not be attributed to lower extremity neuromuscular function. Future research among other muscle groups pre- and post-injury is warranted before ruling out the presence of neuromuscular alterations following concussion.

Keywords: Mild Traumatic Brain Injury; Strength Training; Sensorimotor; Muscle Potentiation.

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Introduction

Concussion is a prevalent pathology across all populations resulting in transient symptom presentation, impaired postural stability, and/or diminished neurocognitive function (Cancelliere et al., 2017; Langlois et al., 2006; McCrory et al., 2017). Post-concussion impairments on standard clinical assessments of signs and symptoms, postural stability, and neurocognitive performance resolve around 14 days for the majority of individuals in athletics (Garcia et al., 2018; Kerr, Zuckerman, et al., 2016; Wasserman et al., 2016), however, emerging research indicates lingering movement deficits (Howell, Lynall, et al., 2018; Parker et al., 2006) theorized to stem from altered neuromuscular control that could have vital implications for patient outcomes (Chmielewski et al., 2020; Eagle, Kontos, Pepping, et al., 2019; Wilkerson et al., 2017).

Growing studies have examined gait spatiotemporal outcomes following concussion and have identified gross impairments (Büttner et al., 2019; Fino et al., 2016; Howell, Buckley, et al., 2018; Howell et al., 2015). Similarly, individuals with a concussion history have displayed altered movement and landing biomechanics during jumping and cutting tasks (Avedesian et al., 2020; DuBose et al., 2017; Lapointe et al., 2018; Lynall et al., 2018). This cumulative body of movement deficits suggests underlying neurophysiological deficits during functional tasks that may stem from neuromuscular impairment (Chmielewski et al., 2020), and may be a critical missing piece for understanding increased musculoskeletal injury risk following concussion (Kardouni et al., 2018; Lynall et al., 2015; Lynall, Mauntel, et al., 2017; McPherson et al., 2018).

Few studies to date have directly assessed neuromuscular function following concussion. Post-concussion patients have demonstrated weaker hand grip strength and decreased jump distance when symptomatic, but not after symptom resolution (Reed et al., 2016; Toong et al., 2021). Similarly, individuals with concussion history relative to a matched control group did not display knee extension or flexion isokinetic strength deficits (Eagle, Kontos, Mi, et al., 2019). One concern with this existing body of research is the neuromuscular outcomes are strictly measuring voluntary neuromuscular *output* rather than maximal neuromuscular *capability*.

Numerous factors can influence the neuromuscular output sent from the primary motor cortex such as altered inter- and intra-cortical connections, spinal cord interneuron transmission, or muscle excitation-contraction coupling (Rozand et al., 2015). As a result, an individual's ability to voluntarily activate a muscle could be inhibited if there is altered neuronal signaling anywhere along the pathway. For this reason, researchers have developed neuromuscular assessments, such as transcranial magnetic stimulation for the supraspinal level, Hoffmann reflex for the spinal level, and the superimposed burst technique for the muscular level (Hart, Weltman, et al., 2010; Livingston et al., 2010; Palmieri et al., 2004; Rozand et al., 2015). The superimposed burst specifically may provide early insights into neuromuscular impairment after concussion and warrants exploration before devoting large-study time and resources.

Superimposed burst assesses an individual's maximal voluntary muscle output relative to their maximal capability by using electrical stimulation to recruit all motor units in a muscle group (Shield & Zhou, 2004). This technique has been widely employed in sports medicine and clinical science settings (Hart, Pietrosimone, et al., 2010). Research using superimposed burst has identified decreased voluntary quadricep muscle activation in individuals long after recovery from anterior cruciate ligament repair in both affected and unaffected limbs (Hart, Pietrosimone, et al., 2010; Lepley et al., 2015), as well as pathologies not directly linked to the quadriceps such as patellofemoral pain syndrome (Norte et al., 2015), chronic ankle instability (Sedory et al., 2007), and low back pain (Hart, Weltman, et al., 2010). Growing research has also observed similarly altered primary motor cortex activity following musculoskeletal injuries (Diekfuss et al., 2019) and concussion (De Beaumont et al., 2011; Wang et al., 2016). It is possible that concussions alter neuromuscular function similar to musculoskeletal injuries, especially considering the brain has direct control over neuromuscular function. Due to numerous pathologies demonstrating altered quadricep central activation and the unknown neuromuscular consequences post-concussion, further research is warranted.

The purpose of this study was to compare neuromuscular function between a cohort of college-aged individuals once asymptomatic (±72 hours symptom resolution) following concussion and healthy matched-controls. We hypothesized concussed individuals would display decreased maximal voluntary isometric contraction (MVIC) torque, no differences in superimposed burst torque (SIB), and decreased central activation ratio (CAR) compared to healthy matched-controls.

Methods

This study was part of a prospective, longitudinal case-control study, but this research question examined voluntary and maximal potential neuromuscular function among a concussed cohort and healthy, matched-control cohort only at the asymptomatic timepoint (± 72 hours of symptom resolution). A total of 8 concussed and 8 controls were enrolled in the study (Appendix L). All participants were recruited through the University Health Center (concussed participants) or from the student body at the University of Georgia (control participants) between August 2019 and February 2021. Concussed participants were included if they experienced an independent physician concussion diagnosis under best-evidence guidelines (McCrory et al., 2017) and were initially assessed and recruited by the research team within 7 days post-concussion. Concussed participants were given academic and physical activity restrictions consistent with current guidelines at the discretion of their physician (McCrory et al., 2017). Control participants were recruited across the university and were included if they matched with a concussed participant on sex, age (± 1 year), height (± 10%), mass (± 5%), and concussion history (± 1 year) (Lynall et al., 2018, 2020). All participants were excluded if any of the following were met: were a National Collegiate Athletic Association athlete, had a history of any neurologic, memory, anxiety, or depression disorder, history of a lower extremity musculoskeletal injury <6 months that resulted in >24 hours of time-loss from physical activity, history of any lower extremity orthopedic surgery in the past year, and any contraindications to electrical stimulation (i.e. open wounds, deep vein thrombosis, potential pregnancy, malignancy, learning disability, cardiopulmonary history, infection, implanted electronic devices, and impaired sensation in the lower extremity). Participants received honorarium for participating in the study. The asymptomatic timepoint assessment occurred for concussed participants once their signs and symptoms normalized to pre-injury status as described below, and control participants were yoked to their matched concussed counterpart. All participants provided written informed consent prior to study participation, and this study was approved by the University of Georgia’s Institutional Review Board (PROJECT00000469).

Survey Assessments

Post-Concussion Symptom Scale (PCSS)

We used the 22-item Post-Concussion Symptom Scale (PCSS; Appendix A) where participants rated their symptom presence (yes or no) and symptom severity via a 6-point Likert scale (0= “none”, 6= “severe”) at that current moment in time (Echemendia et al., 2017). Concussed participants initially completed the PCSS with modified, previously established instructions (Appendix B) where they rated their symptoms “typically experienced (>3 times per week)” to establish a retrospective signs and symptoms pre-injury proxy when first seen by the research team for clinical evaluation (Hoffman et al., 2018; Lempke, Lynall, et al., 2020; Schmidt et al., 2017). Asymptomatic status for this study occurred when a participants pre-injury PCSS proxy was within the PCSS symptom severity reliable change score (± 3 symptom severity score) of their daily PCSS (Chin et al., 2016). Concussed participants then completed daily PCSS via online survey (Qualtrics, Provo, UT) so the research team could determine when asymptomatic status was reached (Hoffman et al., 2018; Lempke, Lynall, et al., 2020; Schmidt et al., 2017). Daily PCSS survey compliance was strong, with concussed participants completing ≥81.2% (mean=96.3%) of daily surveys. Asymptomatic status for this study occurred when a participants pre-injury PCSS proxy was within the PCSS symptom severity reliable change score (± 3 symptom severity score) of their daily PCSS (Chin et al., 2016). Lastly, concussed participants completed the PCSS at the start of the asymptomatic testing session before any assessments, and then after the neuromuscular assessment to examine for symptom provocation. Concussed participants were discontinued from completing the testing session if symptom severity increased by ≥7, but no cases occurred.

Tegner Activity Scale

The Tegner activity scale (Appendix D) is a reliable and valid scale where participants self-rate their before injury and current physical activity level using defined scores ranging from 0-10, with higher being greater physical activity levels (Briggs et al., 2009; Tegner & Lysholm, 1985). The Tegner activity scale was administered to control for pre-injury and current differences in physical activity between concussed and control participants. The Tegner activity scales level 0 (originally “sick leave or disability pension because of knee problems) was modified to "sick leave or disability pension" to be more applicable to our study sample.

Tampa Scale of Kinesiophobia – 11 Item

The TSK-11 was administered at asymptomatic to account for movement fear that may have confounded outcomes. The 11-item version of the Tampa Scale of Kinesiophobia (TSK-11; Appendix C) is a reliable and valid survey designed to assess the fear of movement (Woby et al., 2005). The TSK-11 asked participants to indicate their level of agreement on a 4-point Likert scale (1=strongly disagree, 4=strongly agree) for all 11-items. The TSK-11 was modified as previously established (Anderson et al., 2019) to be more applicable to our study. Specifically, the original word "injury" was changed to "concussion" for the concussed cohort and "general beliefs" for the control cohort. The TSK-11 items were totaled and ranged from 11-44, with a higher score indicating greater fear of movement.

Musculoskeletal Injury History Form

A musculoskeletal injury history form (Appendix E) was modified and implemented based off previously published forms for descriptive purposes (Houston et al., 2018, 2017). The survey asked participants whether they had ever sustained any musculoskeletal injuries (i.e., sprains, strains, fractures, dislocations, and surgery) to the lower extremity or back/torso in the past five years. Participants reporting "yes" to any musculoskeletal injury, they provided a brief description of the injury type (e.g., ankle sprain – lateral ankle sprain), how long ago it occurred, and how many times it had happened.

Neuromuscular Assessment

The neuromuscular assessment (Appendix K) was completed at a single timepoint (asymptomatic) to avoid any potential symptom provocation among concussed participants during recovery. The neuromuscular assessment was performed on a previously established, custom fabricated isometric leg extension machine affixed with a force transducer (model SBO-300-T, Transducer Techniques, Temecula, CA) and computer-synchronized electrical stimulation system (Cureton et al., 2007; Park et al., 2008). Electrical stimulation parameters and administration were controlled by a computer system consisting of an electrical stimulator (Digitimer model DS7AH, Hertfordshire, England, UK), analog-digital board sampling at 5000Hz (Keithley Instruments model KPCI-3108, Cleveland, OH, USA), and custom TestPoint software V6.0 (Capital Equipment Co., Billerica, MA, USA) (Cureton et al., 2007; Park et al., 2008). Participants were seated on the isometric leg extension machine and secured to the machine via chest, waist, and lower leg harnessing to isolate the quadriceps. The isometric leg extension machine was set so that hip and knee joint angles were 80° and 70°, but some variance occurred between participants due to the fixed moment arm length of the isometric machine. Back support was added or removed to help minimize difference in limb moment arms, and matched controls were of similar height and mass to their concussed pair. Two, 7.6cm x 12.7cm self-adhesive electrodes (ValuTrodes, Axelgaard Manufacturing Co., Ltd, Fallbrook, CA, USA) were placed in standardized locations to ensure reliable and maximal tetanic quadricep recruitment (Pietrosimone et al., 2011). The center of the proximal electrode’s superior edge was placed at the cross-section between the participant’s greater trochanter and anterior superior iliac spine. The center of the distal electrode’s inferior edge was placed 3cm superior and midline to the patella.

The neuromuscular assessment was similar to previously established superimposed burst technique for determining a participants CAR (Grindstaff & Threlkeld, 2014; Hart, Pietrosimone, et al., 2010; Pietrosimone et al., 2011). Participants completed warm-up maximal voluntary isometric contraction (MVIC) trials at 25%, 50%, 75%, and 100% of their perceived MVIC before assessing CAR to ensure stable, plateaued torque output and proper assessment understanding. The computer automated superimposed burst (SIB) assessment consisted of a 2.5s MVIC followed immediately by a MVIC coupled with supramaximal electrical stimulation to recruit all quadricep motor units. The electrical stimulation was a 10-train, 100ms long signal with a 200μs pulse duration at 500mA and 200V (Grindstaff & Threlkeld, 2014). Our intra-rater sample (n=10) demonstrated acceptable reliability for the MVIC ($ICC_{3,k}$ = 0.88; 95% CI = 0.45 – 0.97), SIB ($ICC_{3,k}$ = 0.74; 95% CI = 0.00 – 0.94), and CAR ($ICC_{3,k}$ = 0.79; 95% CI = 0.09 – 0.95). Though intra-rater reliability demonstrated wide 95% CIs, our reliability was consistent with previously published work examining these outcomes (Norte et al., 2015). The neuromuscular assessment was completed for up to three trials, with a minimum of two trials needed to be included for analysis.

Torque produced during the MVIC was deemed participant voluntary output and was the average MVIC torque during the 0.5s period prior to electrical stimulation. The additional torque produced during the MVIC coupled with supramaximal electrical stimulus was the participant's SIB torque (i.e. maximal quadricep torque capability), and was calculated as peak additional torque produced during the 100ms electrical stimulation minus the predicted voluntary MVIC at that specific timepoint via linear regression to account for MVIC fluctuations (Cureton et al., 2007; Park et al., 2008). Pain (0-10 numeric scale) was rated immediately following the SIB torque was recorded and averaged for each trial. Both MVIC and SIB were examined in their raw form (Nm), as well as after being normalized the participant's bodyweight (Nm_{BW}) to account for within-group bodyweight differences that can result in considerable outcome variance. The CAR, the ratio of voluntary relative to maximal potential quadricep torque, was calculated as the following (Grindstaff & Threlkeld, 2014; Pietrosimone et al., 2011):

$$CAR = \frac{MVIC}{MVIC + \ SIB} \times 100$$

Statistical Analysis

Independent t-tests were conducted on all demographic outcomes (age, height, mass), and a chi-square on concussion history to examine for group differences. Frequencies were calculated for the musculoskeletal injury history form outcomes. The Tegner activity scale for before and current level outcomes and pain during the SIB were ordinal data, and therefore examined using Mann-Whitney U-tests. An Independent t-test was performed on the TSK-11 due to the pseudo-continuous data nature (e.g., sum of ordinal Likert items) and normality being met. Independent t-tests were employed for MVIC, SIB, and CAR to examine for group differences. Mean differences with associated 95% CI and Hedges' g effect sizes were calculated for all continuous data comparisons, and median differences with 95% CI and Spearman ρ effect sizes for ordinal data, to provide insights to the potential clinical meaning and magnitude (Hedges & Olkin, 1985). Effect sizes were interpreted according to traditional guidelines with ≤ 0.20, 0.21–0.79, and ≥ 0.80 used as thresholds for small, medium, and large effects, respectively (Cohen, 1988). All general linear model assumptions were assessed, and statistical analyses were performed using the R Project for Statistical Programming version 3.4.3 (R Core Team, 2018).

Results

A total of 8 concussed and 8 control participants completed the neuromuscular assessment. No significant group differences were present for age, sex, height, mass, concussion history, hours of sleep, hand or leg dominance, or time between testing sessions ($p \geq 0.411$; Appendix L). Total PCSS symptom presence ($p<0.001$) and symptom severity ($p<0.001$) displayed significant group by time interactions, with post-hoc testing demonstrating significantly greater total symptom presence and severity acutely for concussed, but not once asymptomatic (Appendix L). The concussed cohort had a symptom total range of 6-22 (median=17) and severity range of 16-68 (median=36.5) acutely. A total of 3 concussed and 1 control had at least one musculoskeletal injury in the past 5-years, with three of the four injuries being lateral ankle sprains (Appendix M).

Tegner activity scale levels before injury (p=0.092; ρ=-0.45) and at time of testing (p=0.550; ρ=-0.17) were not statistically different between groups, with the Spearman effect sizes indicating the concussed group had moderate and small associations with greater physical activity levels, respectively (Table 6.1). Concussed individuals displayed significantly lower TSK-11 total scores (i.e. less fear of movement) than controls when asymptomatic with a large effect size (t_{14}=-2.48, p=0.026; mean difference: -2.5, Hedges' g=-1.24).

No significant differences were observed between raw (t_{14}=0.74, p=0.472, g=0.37) or bodyweight-normalized MVIC torque (t_{14}=1.12, p=0.283, g=0.55) between concussed or control groups, with medium effect sizes for greater concussed group torque (Table 6.1). The SIB torque did not demonstrate statistical differences between concussed or control groups regardless of raw (t_{14}=0.16, p=0.879, g=0.08) or bodyweight-normalized status (t_{14}=0.15, p=0.879, g=0.10), with negligible effect sizes observed. The CAR was not statistically different between concussed and control groups and produced a negligible effect size (t_{14}=0.16, p=0.875, g=0.08). Pain during the SIB electrical stimulation was significantly greater among concussed individuals than controls on the 0-10 pain scale (U=51, p=0.046), with the concussed group having a 1.33 (95% CI: 0.01-2.50) median difference and medium association for greater pain (ρ=-0.53).

Table 6.1 Neuromuscular Function Between Groups (n=16)

	Concussed	**Control**		
	Mean	Mean	p-value	Group Mean Difference
	(SD)	*(SD)*	*(Hedges' g)*	*(95% CI)*
Tampa Scale of Kinesiophobia (11-item)	14.88	17.38	0.026	-2.50
	(1.96)	*(2.07)*	*(-1.24)*	*(-4.66, -0.34)*
Maximal Voluntary Isometric Contraction Torque (Nm)	688.44	595.23	0.473	93.21
	(286.17)	*(212.30)*	*(0.37)*	*(-179.14, 365.55)*
Normalized Maximal Voluntary Isometric Contraction Torque (Nm*BW)	*0.96*	*0.79*	*0.288*	0.17
	(0.38)	*(0.21)*	*(0.55)*	*(-0.17, 0.51)*
Superimposed Burst Torque (Nm)	282.71	267.21	0.879	15.5
	(235.26)	*(156.02)*	*(0.08)*	*(-201.64, 232.64)*
Normalized Superimposed Burst Torque (Nm*BW)	*0.36*	*0.34*	*0.879*	0.02
	(0.23)	*(0.17)*	*(0.10)*	*(-0.20, 0.23)*
Central Activation Ratio (%)	72.40%	71.25%	0.876	1.15%
	(17.92%)	*(9.79%)*	*(0.08)*	*(-14.77%, 17.08%)*
	Median	Median	p-value	Median Difference
	(IQR)	*(IQR)*	*(Spearman ρ)*	*(95% CI)*
Tegner Activity Scale (Before)	7	6	0.092	1.00
	(1.5)	*(1.3)*	*(-0.45)*	*(-0.01, 3.00)*
Tegner Activity Scale (Current)	6	6	0.550	0.00
	(2.25)	*(1.25)*	*(-0.17)*	*(-1.00, 2.00)*
Superimposed Burst Torque Pain (1-10 scale)	6	4.8	0.046	1.33
	(0.25)	*(1.13)*	*(-0.53)*	*(0.01, 2.50)*

Abbreviations: SD = standard deviation; 95% CI = 95% confidence interval; IQR = Interquartile range; Nm = Netwon-meter; NM*BW = bodyweight-normalized Nm.

Discussion

Our study provides early insights to neuromuscular function in the lower extremity following concussion. We did not observe any statistical or clinically meaningful deficits among the asymptomatic concussed cohort relative to controls for MVIC knee extension torque. Our MVIC findings are in line with previous research demonstrating no impairments on grip strength or jumping distance for symptom-free concussed individuals relative to controls (Reed et al., 2016; Toong et al., 2021). However, voluntary neuromuscular function in the lower extremity only examines the efferent cumulative motor-unit recruitment signal and does not account for a muscle group’s maximal potential (Hart, Pietrosimone, et al., 2010; Shield & Zhou, 2004). Our work builds upon existing research by also examining maximal neuromuscular potential via the superimposed burst technique, though we did not observe any group differences for SIB or CAR. From a clinical standpoint, our cumulative findings indicate concussed individuals 1) could voluntarily recruit similar peak knee extension torque (i.e., MVIC), 2) had similar supramaximal knee extension torque recruitment (i.e., SIB), and 3) had similar ratios of voluntary relative to maximal potential knee extension torque (i.e., CAR) relative to their healthy-matched control counterparts.

No group differences for any neuromuscular outcomes indicates the efferent signal from the primary motor cortex descending to the knee extensors goes unaltered in the context of maximal torque production. Given altered neuromotor transmission can occur from dysfunctional connections between and within cortices, spinal cord interneurons, and muscle excitation-contraction coupling (Kandel et al., 2013; Rozand et al., 2015), our findings indicate these are globally unaltered when concussed individuals are symptom free. A recent meta-analysis on post-concussion transcranial magnetic stimulation (Scott, Kidgell, Frazer, & Pearce, 2020), a technique to quantitatively assess the descending neuromotor pathway, similarly did not observe any significant effect sizes for motor threshold, motor-evoked potential latency or amplitude 2 weeks after concussion. The majority of college-aged individuals reach symptom resolution around 2 weeks (Garcia et al., 2018; Wasserman et al., 2016), and thus these post-concussion meta-analysis findings (Scott et al., 2020) and clinical strength measure studies (Reed et al., 2016; Toong et al., 2021) corroborate our present findings, indicating neuromuscular function is likely a negligible consideration once symptoms resolve. It is important to note neuromuscular function was examined in a targeted, isolated condition for the knee extensors with participant’s sole focus being on producing MVIC at a time when symptoms had resolved. It is possible that neuromuscular function is inhibited after concussion, but only when combined with simultaneous cognitive loading such as dual-task gait assessments which have observed movement deficits up to two-months post-concussion (Büttner et al., 2019). Future research should aim to better understand neuromuscular function in both isolated and real-world application after concussion to provide deeper understanding post-concussion consequences.

We observed increased pain perception during the SIB torque electrical stimulation for concussed individuals. Concussed individuals ranked their pain median 1.33 points higher (95% CI 0.01-2.50) on the 0-10 numerical pain scale with a medium effect size ($\rho=0.53$) relative to controls. Pain perception is an afferent, somatosensory neuronal process and follows a different pathway than that of efferent, neuromuscular signaling (Kandel et al., 2013; Riemann & Lephart, 2002). Noxious stimuli specifically transmit neuronal signals from aδ fibers to the spinal cord dorsal root, up the spinothalamic tract, and then integrate into the thalamus (Kandel et al., 2013). It is possible the concussed cohort had altered pain perception as a result of altered neurotransmission and or nociception cortical processing due to concussion inducing dysfunctional neurotransmitter release globally in the brain (Giza & Hovda, 2014). However, pre-injury pain was not examined and greatly limits our understanding of the potential pain differences observed. These clinical implications are also unknown at this time. Additional research is warranted to understand the mechanistic onset for reduced pain perception following concussion and the associated implications.

Though fear of movement was a secondary study outcome, it is a critical psychological consideration when determining when someone is ready to return to physical activity. Previous anterior cruciate ligament research has indicated greater TSK-11 scores are associated with stiffer jump landing biomechanics, potentially increasing injury risk (Trigsted et al., 2018). Research among those recovering from anterior cruciate ligament repair have reported TSK-11 scores of 20 on average when 5-9 months post-surgery (Kuenze et al., 2021; Lisee et al., 2020). Only one study has examined post-concussion fear of movement, which used the 17-item TSK (score range:17-68) among high-school athletes, limiting any comparisons that can be made (Anderson et al., 2019). The authors (Anderson et al., 2019) observed a 30.02±5.20 (44.1% max score) TSK-17 score among concussed individuals at return to play, where as we observed a 14.88±1.96 (33.8% max score) TSK-11 score at asymptomatic. Our findings indicated lower TSK-11 scores among concussed individuals relative to their matched-controls with a large effect size (Table 6.1). These findings likely lack clinical meaningfulness, as the mean difference was 2.50, and the scores were below the TSK-11 high-fear category of ≥24 (Vlaeyen & Linton, 2000). Future research should monitor pre- and post-injury TSK-11 performance throughout concussion recovery and among athletic populations to cumulatively understand the risk and fear of movement after concussion.

Limitations

Our study had several noteworthy limitations. We employed a cross-sectional study design which greatly limits our understanding of pre- to post-concussion neuromuscular changes. It is plausible the lack of neuromuscular group differences could be attributed to the inability to examine individualized change after concussion, and therefore future research should implement a within-subject study design. We also observed a convenience sample of college-aged individuals across the university campus, which may limit the generalizability of our findings to athletic-focused population. Lastly, the supramaximal electrical stimulation parameters were fixed, which has the potential for not invoking true neuromuscular potentiation. However, this is a common issue throughout the majority of clinically applied neuromuscular function assessments reported in the literature (Hart, Pietrosimone, et al., 2010; Norte et al., 2015; Pietrosimone et al., 2011), and was likely counteracted by implementing voltage and amperage values above maximum values required for tetanic knee extension recruitment previously reported (Grindstaff & Threlkeld, 2014).

Conclusion

Concussed individuals did not display altered voluntary or maximum potential knee extension neuromuscular function relative to controls. Concussed individuals displayed greater pain perception during supramaximal knee extension torque, possibly indicating somatosensory concerns require further examination. The heightened musculoskeletal injury risk following concussion might not be attributed to lower extremity neuromuscular function, though future research is warranted before ruling out the neuromuscular system completely.

CHAPTER 7

DISSERTATION FINDINGS SUMMARY

This study is among the first to examine functional movement biomechanics, as well as target specific somatosensory and neuromuscular pathways during the acute and asymptomatic recovery periods after concussion. We observed subtle, but potentially important deficits on single-leg hop, gait, somatosensory, and neuromuscular deficits. The findings presented in this dissertation overall provide a general framework for further research to better implement somatosensory and neuromuscular assessments to ultimately understand the musculoskeletal injury risk following concussion phenomenon.

Specifically, we did not observe any range of motion deficits between groups, regardless of timepoint or single- or dual-task conditions. Plantarflexion moments were significantly greater among concussed individuals during dual-task acutely, while no other joint moments, dynamic postural stability index, normalized peak vertical ground reaction force, or reaction time were statistically significant.

These cumulative findings are similar to previous biomechanical assessments among concussion history cohorts which indicate negligible joint kinematic differences while joint moments demonstrate greater torque loading among concussed (Avedesian et al., 2020; DuBose et al., 2017; Eagle, Kontos, Mi, et al., 2019; Lapointe et al., 2018; Lynall et al., 2018). Numerous biomechanical outcomes are possible and necessary to examine, but very few demonstrated statistical differences. It is important to note this could be caused by true, subtle deficits among concussed individuals and may explain why movement impairments are not observed despite heightened musculoskeletal injury risk years beyond initial injury (Howell, Lynall, et al., 2018; Lynall et al., 2015; Lynall, Mauntel, et al., 2017; McPherson et al., 2018). However, it is also plausible previous findings and our own are simply due to statistical chance and/or type I error. Previous work and our present study have employed relatively small samples that are underpowered and/or prone to familywise errors associated with biomechanical analyses. Future work with larger samples focusing on kinetic outcomes are warranted to truly understand biomechanical movement deficits across concussion recovery.

Gait single-task stride length, gait velocity, and gait RT, and dual-task stride width and gait RT demonstrated shorter and slower walking among concussed individuals acutely, but not once asymptomatic. These findings overall are in line with the well-established post-concussion gait literature indicating single-task gait deficits are often present acutely and normalize by asymptomatic (Büttner et al., 2019; Howell, Buckley, et al., 2018; Howell et al., 2014). Dual-task however adds cognitive interference and tends to negatively impact spatiotemporal parameters, and therefore may be an important consideration for developing more sensitive, standardized concussion assessments.

Plantar touch sensation required significantly greater force among concussed individuals both acutely and once asymptomatic. Plantar pressure-pain thresholds were not statistically different between groups across time, but did demonstrate medium effect sizes for concussed individuals needing more pressure to perceive it as pain. Joint repositioning sense was not statistically different across joint angle trials and displayed small effect sizes and mean differences. The somatosensory outcome findings cumulatively differed in their statistical findings and was an expected outcome due to the various assessment types following unique ascending pathways, and the body locations assessed add additional pathway differences. The various assessments selected and the application body locations were implemented to provide general insights for future research to determine whether somatosensory outcomes were worth future exploration. Touch sensation and pressure-pain sensation may have future merit for post-concussion examination given their valuable utility for sending afferent information to the brain and allowing for rapid processing of information to avoid potentially injurious outcomes (McKeon & Hertel, 2007; Meyer et al., 2004).

No differences in voluntary or maximum potential torque production for knee extensor muscle group were observed during the neuromuscular assessment. These findings indicate if neuromuscular deficits are observed clinically after concussion, it is likely not at the intramuscular level or due to dysfunctional neurotransmission for excitation-contraction coupling. A lack of maximum voluntary isometric contraction torque differences however could be attributed to pre-existing resistance training and motor unit recruitment capabilities prior to injury, and therefore future research should examine the efferent supraspinal and spinal pathway using standardized stimuli methods such as transcranial magnetic stimulation and Hoffmann reflex, respectively.

Importantly, neuromuscular pain was significantly greater among concussed individuals, and is similar, though somewhat contradictory to the somatosensory pressure-pain threshold findings. Pressure-pain thresholds were higher among concussed individuals than controls (i.e. more pressure needed to detect pain), while pain during the neuromuscular assessments superimposed burst was perceived significantly greater. Pressure-pain sensation is considered a tactile sensation due to only just initiating pain, and the ascending pathway is primarily relayed from the dorsal column to the medial lemniscal system, and then to the thalamus (Kandel et al., 2013). The electrical stimulus pain however was a strong, rapid (100ms) noxious stimulus that arrives to the brain from the dorsal horn to the spinothalamic system, and then to the thalamus (Kandel et al., 2013). The differences in afferent transmission and cortical processing may be the underlying reasons for these partially conflicting findings. However, it is also possible that greater noxious stimuli are needed to initiate pain detection, but once it is detected, it is perceived as a more intense stimulus. Future work should aim to examine pre- and post-concussion pain measures in order to better understand the changes occurring after concussion.

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APPENDIX – A

POST-CONCUSSION SYMPTOM SCALE (PCSS) – ORIGINAL

INSTRUCTIONS: Please score yourself on the following symptoms, based on **how you currently feel at this moment in time**.

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

APPENDIX – B

POST-CONCUSSION SYMPTOM SCALE (PCSS) – MODIFIED

INSTRUCTIONS: Please score yourself on the following symptoms, **based on symptoms typically experienced >3 times per week**.

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

APPENDIX – C

TAMPA SCALE OF KINESIOPHOBIA (TSK-11)

INSTRUCTIONS: For each of the statements below, please indicate how much you agree or disagree in regards to your current injury. Please use the following scale:

1	2	3	4
Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree

I'm afraid that I might injure myself if I exercise	1	2	3	4
If I were to overcome it, my pain would increase	1	2	3	4
My body is telling me I have something dangerously wrong	1	2	3	4
People aren't taking my medical condition seriously enough	1	2	3	4
My accident has put my body at risk for the rest of my life	1	2	3	4
Pain always means I have injured my body	1	2	3	4
Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening	1	2	3	4
I wouldn't have this much pain if there wasn't something potentially dangerous going on in my body	1	2	3	4
Pain lets me know when to stop exercising so that I don't injure myself	1	2	3	4
I can't do all the things normal people do because it's too easy for me to get injured	1	2	3	4
No one should have to exercise when he/she is in pain	1	2	3	4

APPENDIX – D

THE TEGNER ACTIVITY SCALE

Please indicate in the spaces below the HIGHEST level of activity that you participated in BEFORE YOUR INJURY and the highest level you are able to participate in CURRENTLY.

BEFORE INJURY: Level__________ CURRENT: Level___________

Level 10	**Competitive sports- soccer, football, rugby (national elite)**
Level 9	**Competitive sports- soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball**
Level 8	**Competitive sports- racquetball or bandy, squash or badminton, track and field athletics (jumping, etc.), down-hill skiing**
Level 7	**Competitive sports- tennis, running, motorcars speedway, handball** **Recreational sports- soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running**
Level 6	**Recreational sports- tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week**
Level 5	**Work- heavy labor (construction, etc.)** **Competitive sports- cycling, cross-country skiing,** **Recreational sports- jogging on uneven ground at least twice weekly**
Level 4	**Work- moderately heavy labor (e.g. truck driving, etc.)**
Level 3	**Work- light labor (nursing, etc.)**
Level 2	**Work- light labor** **Walking on uneven ground possible, but impossible to back pack or hike**
Level 1	**Work- sedentary (secretarial, etc.)**
Level 0	**Sick leave or disability pension**

APPENDIX – E

MUSCULOSKELETAL INJURY HISTORY FORM

Please indicate any injuries you have previously sustained <u>in the past 5 years</u> based on the list below. If "yes" is indicated, please provide the additional information in that row.

	Yes	No	Brief Description	How long ago did this injury occur?	How many times have you had this injury?
Ankle					
Ligament Sprain					
Muscle Strain					
Fracture					
Dislocation					
Surgery					
Knee					
Ligament Sprain					
Muscle Strain					
Fracture					
Dislocation					
Surgery					
Hip					
Ligament Sprain					
Muscle Strain					
Fracture					
Dislocation					
Surgery					
Back/Torso					
Ligament Sprain					
Muscle Strain					
Fracture					
Dislocation					
Surgery					

APPENDIX F

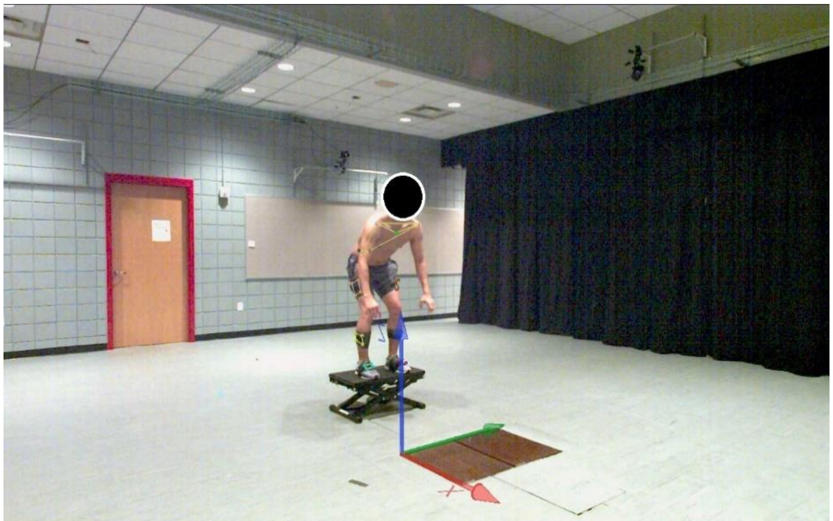
GAIT ASSESSMENT

Appendix F-a: Gait functional movement starting position. Participants stood still at "T" tape line while silent (single-task) or subtracting (dual-task) until the audible beep occurred, signaling to initiate walking as soon as possible after hearing.

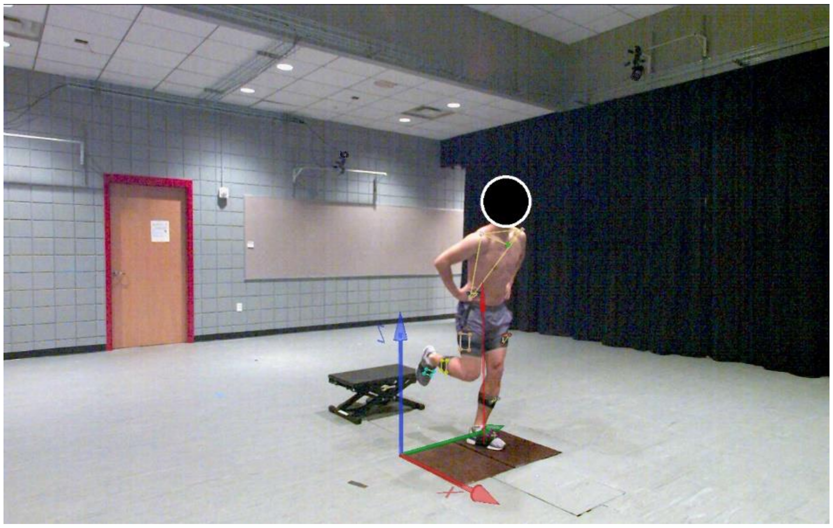
Appendix F-b: Gait functional movement following audible stimulus. Participants were instructed to continue walking at their normal comfortable pace (while under single- or dual-task) until coming completely off the mat.

APPENDIX G

SINGLE-LEG HOP ASSESSMENT



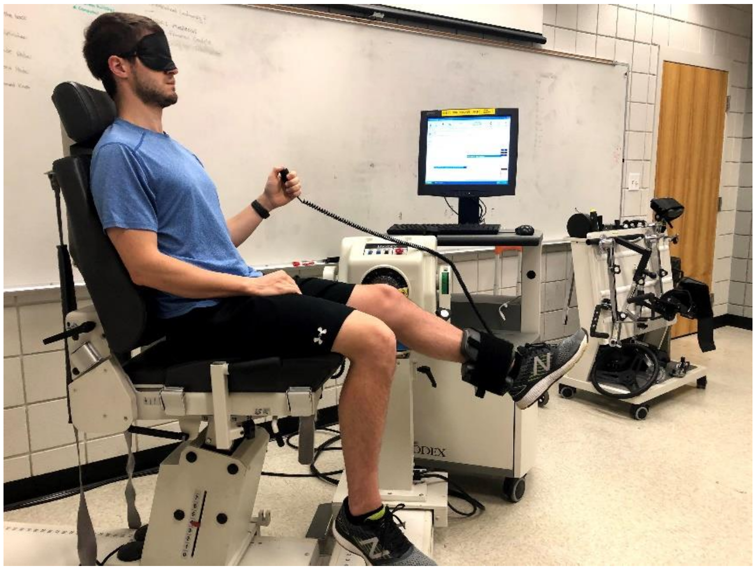
Appendix G-a: Start position for single-leg hop assessment. Participants took an athlete stance while standing stationary while either quiet (single-task) or subtracting (dual-task) until seeing the green light stimulus, signaling to jump from the box to the force plate as quick as possible.



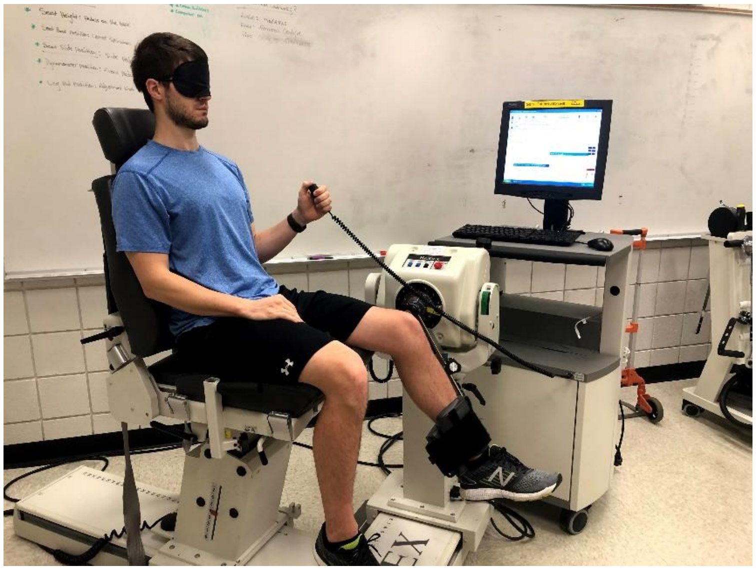
Appendix G-b: Balance position for single-leg hop assessment. After jumping from the box, participants landed on a single-leg with hands on hips and were instructed to stabilize and balance as stable as possible while remaining quiet (single-task or subtracting (dual-task) for 10 seconds.

APPENDIX H

JOINT POSITION SENSE ASSESSMENT



Appendix H-a: Start position for joint position sense for 30- to 60-degree knee flexion trials. Participants were placed in the start position (30-degrees) and told this was the “start position”. After moving to the test position (panel-b), participants returned to this position and were told “test starting now”, where the dynamometer arm moved at 1°/s until they pressed the trigger.

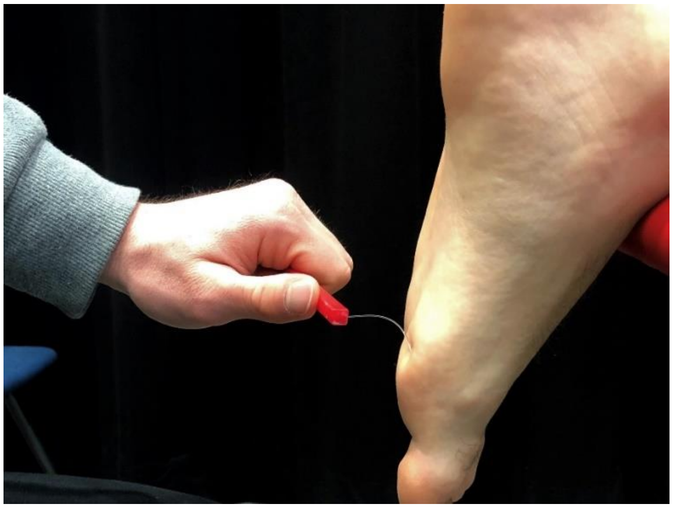


Appendix H-b: Test position for joint position sense for 30- to 60-degree knee flexion trials. Participants were moved from the start position and locked in this position for 10 seconds while told “test position, remember this position”.

APPENDIX I

TOUCH SENSATION ASSESSMENT

Appendix I-a: 20-piece Semmes-Weinstein monofilaments used for the “4-2-1” stepping protocol. For example, the examiner applied a 6.0grm monofilament, and then either a thinner (1.0grm) or thicker (26.0grm) diameter monofilament 4 filaments away based on the participant’s positive (thinner monofilaments applied) or negative (thicker monofilament applied) monofilament detection. Monofilaments were applied in steps of 4 until 3 reversals occurred, indicating a range of sensory detection. The examiner followed the same process outlined above, but continued using “2 steps” until 3 reversals, then again for “1 step”.



Appendix I-b: Example of monofilament application. Monofilaments were applied perpendicular for 1s to the first metatarsal head of the dominant foot surface until a C-shaped bend occurred in the monofilament.

APPENDIX J

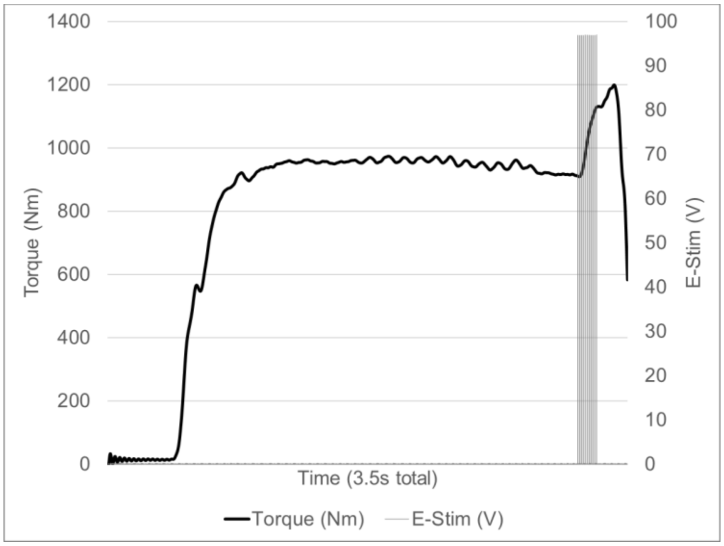
PAIN SENSATION ASSESSMENT

Appendix J: Algometry assessment technique performed. All participants were long-seated supine with their foot held at 90-degrees (neutral) while the algometer pad was applied to the surface where the navicular tuberosity and medial longitudinal arch crossed. The pressure (lbf/cm^2) was applied at 1lbf/s until the participant verbally stated “stop”, indicating the earliest initiation of pain was perceived.

APPENDIX K

NEUROMUSCULAR ASSESSMENT

Appendix K-a: Neuromuscular assessment instrumentation. Participants were secured at the lower leg, waist, and shoulders to the custom-fabricated dynamometer. The dynamometer output (torque) was read by the custom TestPoint software, and the electrical stimulator pictured was computer-operated by the software.



Appendix K-b: Graphical representation of the neuromuscular assessment. The black line indicated a participant’s maximal voluntary isometric contraction (torque) until the electrical stimulation (gray lines) was activated via TestPoint software, resulting supramaximal quadricep activation (i.e., superimposed burst torque).

APPENDIX L

DEMOGRAPHIC SUMMARY TABLE

Table. Demographic Outcomes Between Groups

	Concussed (n=8)		Control (n=8)		
	Mean	(SD)	Mean	(SD)	p-value
Age (yrs)	19.22	(0.97)	19.44	(1.24)	0.678
Height (cm)	179.31	(14.56)	181.53	(9.44)	0.707
Mass (kg)	75.14	(15.26)	77.21	(13.28)	0.763
Concussion history (mean, SD)	0.33	(0.71)	0.11	(0.33)	0.411
Days from injury to acute	3.56	(1.67)	-	-	-
Days from injury to asymptomatic	25.75	(21.30)	-	-	-
Sleep night before at acute (hrs)	4.89	(2.98)	5.78	(2.11)	0.477
Sleep night before at asymptomatic (hrs)	5.75	(2.25)	6.62	(2.83)	0.505
Symptom total at acute	15.50	(5.42)	1.62	(2.83)	<0.001[a]
Symptom total at asymptomatic	2.75	(3.81)	2.62	(5.04)	0.999[a]
Symptom severity at acute	38.38	(19.40)	2.88	(6.22)	<0.001[a]
Symptom severity at asymptomatic	2.88	(4.02)	3.25	(6.43)	0.999[a]
Time from concussion to acute (days)	3.56	(1.67)	-	-	-
Time from concussion to asymptomatic (days)	25.75	(21.30)	-	-	-
Time between testing sessions (days)	22.62	(21.61)	21.5	(21.10)	0.918
	Frequency	(%)	Frequency	(%)	p-value
Sex (male)	5	(0.63)	5	(0.63)	1.000
Concussion history frequency					1.000
0	7	(0.88)	7	(0.88)	
1	1	(0.13)	1	(0.13)	
Musculoskeletal injury history <5 years (yes)[a]	3	(0.38)	1	(0.13)	-
Hand dominance (right)	8	(1.00)	8	(1.00)	1.000
Leg dominance (right)	8	(1.00)	8	(1.00)	1.000

[a] P-values from post-hoc Tukey HSD t-tests from mixed-model ANOVAs.

[b] Outcome not statistically compared between groups due to numerous injury categories and severities.

APPENDIX M

MUSCULOSKELETAL INJURY HISTORY DESCRIPTIONS

Table. Musculoskeletal Injury History in Past 5-years Among Participants (n=4)

Group (participant ID)	Injury History	Injury Location	Injury Type (tissue damaged)	Last Injured	Injury Count
Concussed (3)	Yes	Knee	Sprain (MCL)	4 years	1
Concussed (4)	Yes	Ankle	Sprain (unknown - Lateral)	4 years	1
Concussed (5)	Yes	Ankle	Sprain (unknown - Lateral)	2 years	2
Control (6)	Yes	Ankle	Sprain (unknown - Lateral)	5 years	1

All other participants (n=12) did not have a musculoskeletal injury within the past 5 years. MCL = medial collateral ligament.