CONCUSSION AS A RISK FACTOR FOR LOWER EXTREMITY MUSCULOSKELETAL INJURY IN COLLEGIATE ATHLETES

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Determining when it is safe for an athlete to return-to-play (RTP) after sustaining a concussion is a primary concern for healthcare professionals. The purpose of this study was to investigate the relationship between sport-related concussion and subsequent occurrence of lower extremity musculoskeletal injury in collegiate athletes. This study also aimed to establish if a relationship exists between the length of recovery-time needed by an athlete prior to returning to play after a concussion and risk of lower extremity musculoskeletal injury. We also examined the contribution that sex may have on recovery time and lower extremity musculoskeletal risk after a concussion. A retrospective, matched-cohort study design utilizing a review of medical records of collegiate athletes from the past ten years was conducted.

A total of 164, athletes across 10 different sports were included in this study. Eighty-two concussed athletes (58 male, 24 female) were each randomly matched with one non-concussed athlete by sex, sport, position, calendar year, and body mass index (BMI). Data pertaining to any lower extremity musculoskeletal injury that had occurred, in the 90-day period prior to the concussed subjects' concussion and in the subsequent 180-day period after the concussed athlete RTP, was collected and analyzed for each concussed athlete and their matched control.

The results of this study revealed that concussed athletes were at increased risk of future lower extremity musculoskeletal injury after RTP following a concussion. Sixty-two percent of concussed athletes selected for this study sustained a lower extremity musculoskeletal injury

within 180 days after RTP following their concussion as compared to 26% of matched control athletes. These results indicate that the odds for an athlete with history of concussion, sustaining a lowering extremity musculoskeletal injury after RTP following a concussion is 7.37 greater than an athlete with no history of concussion. The number of days it took for athletes to RTP after a concussion was not statistically different in athletes who sustained a subsequent lower extremity musculoskeletal injury and those who did not. Although not statistically significant, female athletes demonstrated longer concussion recovery times and a greater incidence of lower extremity musculoskeletal injury following a concussion.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

Sport-related concussions are a rapidly increasing phenomenon.[1-4] Over the last 10 years, an upsurge in reported sport-related concussions has been seen across professional, collegiate and high school athletic participants.[1-4] It can be hypothesized that an overall greater awareness of the consequences of concussion, the adoption of mandatory concussion policies within many sport organizations, the development of more objective and sensitive diagnostic tools and an increase in overall sports participation could all be contributing factors to this phenomenon.[1,2,4] In the United States alone, it is estimated that 1.6 - 3.8 million sport-related concussions occur annually.[5] Generally speaking, concussion is a head injury that is defined as a "complex pathophysiological process affecting the brain, induced by biomechanical forces."[6] Sport-related concussions typically result from a direct or indirect blow to the head that causes a rapid-onset, transitory impairment in neurological function.

Determining when it is safe for an athlete to return-to-play (RTP) after an injury is a primary concern for healthcare professionals. To date there is no standard or universally accepted, RTP criteria for concussion; however current emphasis is placed on return-to-baseline neuropsychological (NP) testing, clinical balance testing, and symptom-free activity following graduated exertion.[6,7] Increasing availability of computer-based NP testing and the development of inexpensive balance testing has provided medical professionals with a more consistent and objective way to assess some of the clinical signs of concussion.[8-11]

Research on the consequences of sport-related concussions is constantly evolving. The acute consequences of a sport-related concussion encompass an array of areas including, presence of; clinical symptoms (somatic, cognitive and emotional), physical signs, behavioral changes, cognitive impairments, and sleep disturbances.[6] The chronic or long-term consequences of concussion appear to be more difficult to ascertain. Cumulative impact forces to the brain, as seen in sports like boxing, American football and soccer, have been linked to chronic traumatic encephalopathy (CTE), and are believed to be risk factors in the development and progression of anxiety disorders, depression, Alzheimer's disease, Parkinson's disease and amyotrophic lateral sclerosis (ALS).[12-15]

Another consequence of sport-related concussion that is currently being postulated in research is the increased risk of musculoskeletal injury following a concussion. In the last two years, preliminary research in this area has reported that previously concussed athletes had anywhere from a 1.5 to 4 times increased risk of a subsequent musculoskeletal injury when compared with athletes who had not sustained a concussion.[16-20]

If a relationship exists between concussion and lower extremity musculoskeletal injury, further studies should be conducted to determine the underlying reasons behind this relationship. With that in mind, an emphasis on a concussion-rehabilitation program could be developed and implemented prior to returning the athlete to play to address deficits that may remain following a sports-related concussion.

1.1 BACKGROUND: SPORT-RELATED CONCUSSION

1.1.1 Defining Sport-Related Concussion

A concussion is a subset of a broader category of head injuries termed traumatic brain injury (TBI).[6] In the 2010 position statement produced by The Demographics and Clinical Assessment Working Group of the International and Interagency Initiative toward Common Data Elements for Research on Traumatic Brain Injury and Psychological Health, TBI is defined as, "an alteration in brain function, or other evidence of brain pathology, caused by an external force."[21] While all concussions are considered TBIs, not all TBIs are concussions. The causative mechanism for a TBI can include, but is not limited to: 1) an object striking the head, 2) the head striking an object, 3) the brain accelerating or decelerating within the skull without external trauma on the skull itself, 4) the brain tissue being penetrated by a foreign body or 5) a force that results from a blast or explosion.[21] Mechanisms 1 through 3 are typical underlying causes of a sport-related concussion, while mechanisms 4 and 5 are more typical of motor vehicle accidents, occupational injuries, or combat derived etiologies. Although most would recognize a direct blow to the head as a mechanism of injury for a sport-related concussion, it is imperative to realize that indirect forces to other parts of the body may be transmitted to the head and result in a concussion.[6] The biomechanical mechanism of injury for a concussion can be described as a result of either linear or rotational forces transmitted to the brain.[22,23] These two types of forces can result from a physical insult to the head or torso that causes a person's body and/or head to rapidly decelerate while the brain continues to move within the confines of the skull. This movement of the brain inside the skull occurs because the brain is suspended inside the cranium in cerebral spinal fluid and is loosely anchored to the skull by its surrounding dura mater and accompanying connective tissues. Abrupt and sudden forces applied to the head and/or torso can cause a rapid deceleration of the skull with a subsequent continual movement of brain until it reaches an unyielding contact point within the protective boundaries of the skull.

A variety of definitions exist for sport-related concussion in literature. In the 2012 Zurich Consensus Statement on Concussion in Sport, concussion is defined as "a complex pathophysiological process affecting the brain, induced by biomechanical forces."[6] The 2013 American Medical Society for Sports Medicine position statement for concussion in sport defines concussion as "a traumatically induced transient disturbance of brain function and involves a complex pathophysiological process."[7] In 2014, the National Athletic Trainers' Association published a position statement on the Management of Sport Concussion. To form this position statement, Broglio and colleagues[24] utilized the research that employed the definition of concussion that was cited by the American Academy of Neurology in 1997. This 1997 article defined concussion as "Trauma-induced alteration in mental status that may or may not involve loss of consciousness."[25] Although a variety of definitions currently exist for sport-related concussion, increased investigation in this area has researchers, educators and scientists adopting and creating more universally common descriptions and classifications. Sport-related concussions can be serious and have long lasting effects; however because they typically are not life threatening, sport-related concussions are often referred to in literature as mild traumatic brain injuries (mTBI).[7]

1.1.2 Epidemiology and Risk Factors for Sport-Related Concussion

Sport-related concussions are a world-wide public health concern.[26] This concern stems from the increasing number of individuals at all levels sustaining sport-related concussions, the rising healthcare costs incurred for the treatment of concussions and the potential short and long-term consequences of concussions. Although it is estimated that up to 3.8 million sport-related concussions occur annually in the United States in both recreational and organized sport, it has also been theorized that as many as 50% of concussions may go unreported. [7,27-29] In 2013, Meehan and colleagues[30] reported that 148 adolescent athletes, out of 486 being treated for a current sport-related concussion, recounted a previous unreported insult to the head that caused at least one of the signs and symptoms listed on the Post-Concussion Symptom Scale (Figure 1). These statistics translate into approximately one-third of the athletes in their study reporting a previously undiagnosed concussion.

In 2008, there were an estimated 44 million youth athletes, 400 thousand collegiate athletes and 16 thousand professional athletes in the United States.[31-33] While these numbers are already large, athlete participation is continually on the rise. The number of male athletes participating at the collegiate level has grown steadily over the last three decades.[32] During that same time period, due in large part to Title IX, participation levels in collegiate women's sports have increased even more dramatically. In the 1981-1982 athletic seasons, the NCAA reported 244,039 total athletes (169,800 male and 74,239 female athletes). By the 2011-2012 athletic season, the number nearly doubled to 459, 253 total athletes (261,150 male and 198,103 female athletes).[32] Those numbers translate into an 88% increase in overall athletic participation with a sex-specific increase of 54% in male participation and an astounding 167% increase in female participation. In 2002, Hootman and colleagues[34] published a manuscript that outlined the epidemiology of collegiate sport-related injuries from 1988 to 2004. During that time, both anterior cruciate ligament (ACL) and concussion injuries revealed significant increases.[34] It was theorized by the authors that the increase in reported sport-related concussions were reflective of improved concussion recognition tools and possibly an actual increase in concussion rates during that time period.[34]

Concussions can occur at any level of participation and in almost every sport. In the United States, sports with the highest prevalence of concussion include football, ice hockey, soccer, lacrosse, wrestling and basketball.[1,7,34] In regards to NCAA sports, football has consistently had the most participants and the most reported concussions.[32,34] A 16 year aggregate of data analyzed from the NCAA Injury Surveillance System (ISS) provided an estimate of 3,753 concussions occurring throughout 15 NCAA sports each year, with over half of the concussions occurring in football.[34] Data collected from the NCAA's ISS also indicates the three most common injuries during games in NCAA football from 1988 through 2004 were injuries to the knee (17.8%), ankle (15.6%) and concussions (6.8%).[35]

Common risk factors for sport-related concussion include: previous history of concussion, sex, and sport type.[7] Previous history of a concussion increases an athlete's risk of a subsequent concussion by two to three times in both high school and collegiate athletes. [7,36,37] In 2003 Guskiewicz and colleagues[37] reported that football players with a self-reported history of 3 or more concussions were at 3 time's greater risk of sustaining a subsequent concussion as compared with football players with no concussion history. Guskiewicz's study also reported a dose-response relationship, as they also observed a 2.5 times elevated risk of subsequent concussion in athletes with 2 previous concussions and a 1.4 times elevated risk of subsequent concussion in athletes with 1 previous concussion when compared with football players with no concussion history.[37] These statistics, combined with the results of studies that have identified the deleterious cumulative effects of multiple concussions, highlight the need to adequately educate athletes on concussion signs and symptoms, management and RTP criteria.

1.1.3 Sex Considerations for Sport-Related Concussion

It has been recognized, in both high school and collegiate settings, that the sport with the most documented concussions is football.[1,34] However, when considering athlete exposures (AE), the NCAA ISS data for collegiate athletes reveals that football has a concussion rate of 0.37 per 1000 AE, while women's ice hockey has a concussion rate at 0.91 per 1000 AE.[34] Furthermore, when comparing athletes who participate in similar sports, females were shown to have higher concussion rates than males at both the high school and collegiate levels.[1,34,38,39] In a prospective, 11 year study conducted from 1997 – 2008 in high school athletes, Lincoln and colleagues[1] found that females had an almost 2 times greater risk of concussion than males who participated in similar sports. Specifically, the study reported the risk ratios of 1.7:1 (basketball), 2.1:1 (soccer) and 1.9:1 (softball/baseball) for females when compared with males.[1] Lacrosse was the only sport in that study that had higher concussion rates for males than females with a risk ratio of 0.66:1 (female to male ratio).

Evidence of sex as a risk factor for concussion has been explored to some extent in previous literature. Many potential theories have surfaced regarding the role that sex plays in concussion including sociological factors, biomechanical issues, healthcare provider attitude in diagnosis, and differences in style of play and variation in rules governing the game. [1,34,38,40-42]

1.1.4 Consequences Following Sport-Related Concussion

The presence of post-concussive symptoms, physical signs, behavioral changes, cognitive impairments and/or sleep disturbances are some of the most common immediate consequences of a sports-related concussion.[6] The most frequently reported symptom of a concussion in both high school and college-aged athletes is headache, followed by dizziness.[7,37-39,43] Current evidence indicates that many of the signs and symptoms association with sport-related concussions are transitory and that eighty to ninety percent are reported to resolve within 7 - 10 days; with most athletes typically returning-to-play within that same time period.[6,44,45]

Although concussive symptoms are usually short-lived, approximately 10-15% of all individuals who are diagnosed with a concussion report symptoms that persist longer than 10 days.[6] It is imperative that all signs and symptoms are resolved prior to returning an athlete to participation and it is recommended that any athlete who experiences signs and/or symptoms that last longer than 10 days be treated via a multidisciplinary approach with a team of health-care providers specifically trained in the management of sports-related concussion. [6] Premature RTP after a sports-related concussion can result in the athlete prolonging their current recovery time or incurring a subsequent injury that can have catastrophic or long-term effects.[46,47]

Second Impact Syndrome (SIS) has been described in the literature as an acute consequence of an athlete returning to sport prior to full recovery from a previous concussion.[47] In SIS, a previously concussed athlete receives a subsequent concussive episode that can result in permanent neurological dysfunction or even death.[46] The presence and mechanisms of SIS remains controversial amongst researchers; however because numerous cases exist the theorized condition of SIS remains a concern among healthcare professionals.[12,46,48-50]

Recently there have been several studies published that implicate concussion as a possible risk factor for subsequent injury.[16-18] In 2014 Nordstrom and colleagues[18] looked at injuries following a concussion in European Football and reported a 2.2 times greater risk in overall injury to those footballers who sustained a concussion. Although this study looked at overall injury rates, which included upper and lower extremity musculoskeletal injuries as well as subsequent concussions, 67% of the reported injuries were musculoskeletal injuries to the lower extremity.[18] In 2015, Pietrosimone and colleagues[16] were able to link concussion frequency, via data collected by The Health Survey of Retired National Football League (NFL) Players, to an increase in musculoskeletal injuries during their careers as football players. In 2015, Lynall and colleagues[17] examined lower extremity musculoskeletal injury rates in collegiate athletes pre- and post-concussion during time increments that spanned up to 365 days. Data collected in this study indicated that within the first year post-concussion, musculoskeletal injury rates nearly doubled in concussed college-aged athletes when compared to matched controls.[17]

For many years, it was thought that the signs and symptoms associated with a concussion were largely due to a functional disturbance and not a true structural injury.[6] However, researchers have begun to study the physiological effects of concussion on the brain utilizing neuroimaging techniques like Functional Magnetic Resonance Imaging (fMRI) and Magnetic Resonance Spectroscopy (MRS).[51-55] An fMRI study published by Dettwiler and colleagues[51] in 2014 revealed persistent brain hyper activation, two months post sport-related concussion, even though NP testing in those athletes had returned to normal ranges. Other research has indicated that changes in postural control were detected in athletes who sustained a concussion, even in the presence of effective postural stability.[56] In the last 10 years, researchers have begun to examine the time-dependent dynamics of postural control after a concussion, specifically looking for corrective or repetitive patterns in postural sway.[56-58] Traditionally, studies examine the amplitude in center of pressure (COP) measurements in an effort to quantify postural stability. However, researchers like Sosnoff and Cavanaugh utilized approximate entropy (ApEn), a non-linear dynamical measure that identifies the likelihood of patterns existing in a specific time series, to characterize the dynamics of postural control. Cavanaugh and colleagues[58] found that concussed subjects had no changes in postural stability following a concussion (as measured by COP displacement amplitude), yet displayed changes in oscillation patterns as measured by ApEn. Results of these investigations raise additional concerns about currently practiced RTP criteria for athletes who have sustained a sport-related concussion.

Recovery time for a sport-related concussion differs for each athlete and therefore a comprehensive approach to care following a sport-related concussion is critical in successfully returning an athlete to play.[59] An understanding of factors that can prolong an athlete's recovery can be a useful resource when considering an athlete's plan of care. Predictors for post-concussion outcomes include previous history and number of concussions, presence of post-traumatic migraines (PTM), severity and duration of symptoms, sex, and age.[6,37,60-64] Specific post-concussive symptoms that have been linked to longer recovery time and therefore prolonged RTP include symptom severity, duration and number as well early headache, feeling of fatigue or fogginess, early amnesia and or disorientation.[7,65,66]

When to return an athlete to play after receiving a sport-related concussion is an important topic in concussion research. Much of the research conducted concerning RTP decisions after a sport-related concussion is focused on management guidelines, the cumulative effects of multiple concussive episodes, overall prognoses, and the increased risk and consequences of the athlete incurring a subsequent concussion if returned to sport too soon.[12-18]

1.2 LOWER EXTREMITY MUSCULOSKELETAL INJURY

1.2.1 Epidemiology and Risk Factors for Lower Extremity Musculoskeletal Injury

Lower extremity musculoskeletal injuries are a frequent occurrence in sport. Across 15 NCAA sports, more than half of all injuries reported in games and practices were to the lower extremity.[34] Specifically, injuries to the knee and ankle are the most common injuries reported in athletics at both the high school and collegiate level. [34,67]

With a multitude of articular surfaces and surrounding structures in the lower extremity, many intrinsic risk factors have been linked to lower extremity musculoskeletal injury. Studies aimed at identifying risk factors for knee and ankle injuries have looked at a plethora of intrinsic sources including, but not limited to: neuromuscular control, bony anatomy, kinematics, neurocognitive function, and overall sex differences.[68-74] Playing surface, weather conditions, shoe quality/construction, and direct contact with an opponent are a portion of the extrinsic factors reported in the literature.[72,75,76] Specifically, direct contact with an opponent during landing and contact with the playing surface itself during landing have been shown to be the top two mechanisms of ankle injury during basketball. [77]

Landing kinematics and technique has also been linked to knee ligament injuries. Studies indicate that the presence of neuromuscular control differences in males and females during landing may be a possible contributing factor, explaining the sex differences seen with ACL injuries.[71,78-81] Specifically, increased knee flexion moment and increased valgus motion and moment at the knee during landing have been shown to be key predictors for female athletes at increased risk for ACL injury. [71,78] Other risk factors that have been associated with lower extremity musculoskeletal injury in both sexes have included; previous injury, time spent in warm-up, age of athlete, anatomical anomalies, range of motion, functional strength asymmetries, increased BMI, increased body weight, proprioception deficits and alterations in postural sway. [68,72,74,77,82-84]

Results from a 2007 study by Swanik and colleagues[70] revealed statistically significant differences in pre-injury measures of cognitive functioning in athletes who sustained noncontact ACL injuries and those of matched controls. The results of Swanik's study indicated a relationship between decreased neurocognitive performance and subsequent noncontact ACL injuries.[70] Although not a study on concussions, the results of Swanik's research further implicates the importance of investigating the influence of a sports-related concussion's role in lower extremity musculoskeletal injury due to alterations in brain activity.

1.2.2 Sex Considerations for Lower Extremity Musculoskeletal Injury

It has been postulated that many of the previously mentioned intrinsic risk factors for knee injury are related to differences in sex.[72,85] Sex variations in anatomy, ligamentous laxity, BMI, neuromuscular control, and sex hormones have all been studied in an attempt to understand the link between sex and injury risk.[71-73,82]

It has been widely reported that female athletes are at greater risk for ACL injury than males.[72,82,86,87] Some of the most significant findings in this area involve injury risk differences in basketball and soccer. Female soccer players and basketball players have an overall 3 times greater risk of developing an ACL injury than do their male counterparts.[82] A study conducted utilizing NCAA ISS data, revealed the rate of ACL injury differed significantly between sexes. During a 5 year period (1989-1993) women's soccer players' ACL injury rate averaged 2.4 times that of the their male counterparts, while women's basketball players' ACL injury rate averaged 4.1 times that of their male counterparts.[87]

In 2016, Kucera and colleagues[88] reported an overall increased incidence of lower extremity musculoskeletal injuries in female versus male cadets. Specifically, Kucera described an increased incidence of hip, knee, lower leg and ankle injuries in female cadets as compared with their male counterparts.[88] To date, a connection between ankle injury and sex has not been clearly defined in sport. Several studies reported sex differences in ankle injury rates in sport; however, these rates differed per sport type and age.[89,90]

1.2.3 Consequences of Lower Extremity Musculoskeletal Injury

Besides multiple days lost to injury, many lower extremity musculoskeletal injuries can carry a huge financial and psychological burden.[91] Injuries to the knee, specifically the anterior cruciate ligament (ACL), frequently necessitate surgical intervention and subsequent extensive rehabilitation. In a study that analyzed injury patterns in high school sports, Powell and colleagues[67] reported that injuries to the knee accounted for nearly 60% of sports-related surgeries.[86] With nearly 130,000 ACL reconstructions completed each year in the United States, the financial burden for the surgical intervention and post-operative care are reported to approach $1 billion dollars annually.[92,93] Regardless if surgical reconstruction is completed, injuries to the ACL can place the athlete at greater risk for developing chronic pain and early onset osteoarthritis.[93-96]

1.3 ASSOCIATION BETWEEN CONCUSSION AND LOWER EXTREMITY MUSCULOSKELETAL INJURY

To date, much research in sports medicine has been aimed at identifying modifiable risk factors for lower extremity musculoskeletal injury. Neuromuscular retraining intervention programs designed to increase strength, flexibility, agility, balance, and landing kinematics have been implemented with varying success.[97-105] In spite of research and increased efforts to instill prevention programs, lower extremity musculoskeletal injuries persist as a significant and common injury in sports.[106]

Current research indicates that sports-related concussions can cause deficits in central nervous system functioning that can linger long after the athletes have returned to play. [57,58] These deficits have been reported in patients whose concussive symptoms have resolved and whose NP and balance testing have seemingly returned to a pre-concussion baseline. Deficits have also been reported in gait, both acute and chronic, following a concussion.[107,108] Catena et al.[107] reported that concussed, college-aged subjects used a slower, more conservative gait strategy and increased medial/lateral motion when challenged with a dual-task scenario; while Howell et al.[109] reported a regression in balance during gait in concussed adolescent athletes over a two-week period of time after returning to activity following a concussion. Since deficits in motor and postural control have been identified as risk factors for lower extremity musculoskeletal injury, athletes who return to play following a concussion may be at increased risk of injury.[58,110,111]

Researchers have begun to investigate links between neurocognitive functioning and lower extremity injury; however, examining if a relationship exists between concussion and subsequent lower musculoskeletal injury risk is just beginning to be explored. [16-20,70,112]

1.4 DEFINING THE PROBLEM

Lower extremity musculoskeletal injuries make up over 50% of all reported injuries that occur in NCAA sports.[34] Time lost to these injuries can be substantial and may result in a need for surgical intervention. In NCAA football, 27% of lower extremity injuries in fall games, 25% of lower extremity injuries in fall practices and 34% of lower extremity injuries in spring practices resulted in a loss of sport participation for 10+ days. [35] With an estimated $1 billion dollars in healthcare costs annually for treatment of ACL injuries alone, identifying risk factors for lower extremity musculoskeletal injuries is an important focal point in research.

With the growth in awareness of concussion, the numbers of diagnosed and reported sport-related concussions have continued to increase. Return to play criteria following a concussion typically includes protocols that may not be sensitive enough to detect lingering changes in brain activity or deficiencies in postural sway in the athlete. Clearing an athlete for full participation prior to addressing these issues may put the athlete at increased risk of lower extremity musculoskeletal injury.

1.5 PURPOSE OF THIS STUDY

The purpose of this dissertation is to establish if a relationship exists between sport-related concussion and subsequent occurrence of lower extremity musculoskeletal injury in college-aged athletes. This study will also investigate if there is a relationship between the length of recovery-time needed by an athlete prior to returning to play after a sport-related concussion and risk of lower extremity musculoskeletal injury. We will also examine the contribution that sex may have on recovery time and lower extremity musculoskeletal risk after a sport-related concussion. A medical records review will examine concussed athletes' injury history for 180 days post-concussion, once he/she has been discharged from care and has returned to play. Subsequent injury and time to injury will be recorded for any lower extremity musculoskeletal injury that occurs during that 180-day time period.

1.6 SPECIFIC AIMS AND HYPOTHESES

Specific Aim 1: To establish if a relationship exists between sport-related concussion and subsequent lower extremity musculoskeletal injury in Division 1, collegiate athletes.

Hypothesis 1: Concussed athletes, who return to play after being cleared by a health care provider, will have a greater risk of incurring a subsequent lower extremity musculoskeletal injury as compared to non-concussed athletes, matched on sex, sport, position, calendar year, and BMI.

Specific Aim 2: To establish if a relationship exists between length of recovery time needed before an athlete returns to play following a concussion and subsequent lower extremity musculoskeletal injury in Division 1, collegiate athletes.

Hypothesis 2: Athletes who require a greater amount of recovery time prior to returning to play will have a greater risk of incurring a lower extremity musculoskeletal injury than those athletes with a shorter recovery time.

Specific Aim 3: To establish if a relationship exists between concussed athletes of a specific sex and incidence of lower extremity musculoskeletal injury in Division 1, collegiate athletes.

Hypothesis 3: Female concussed athletes will have a higher incidence of subsequent lower extremity musculoskeletal injury than male concussed athletes.

Specific Aim 4: To establish if a relationship exists between sex and recovery time after a sport-related concussion in Division 1, collegiate athletes.

Hypothesis 4: Female concussed athletes will require a greater amount of recovery time prior to returning to play than male concussed athletes.

1.7 STUDY SIGNIFICANCE

The outcomes of this study may help determine whether a relationship exists between sport-related concussion and increased risk of subsequent lower extremity musculoskeletal injury. If a relationship does exist, further research will need to be conducted to 1) determine the underlying factors behind this relationship and 2) determine if these factors are modifiable. Ultimately, this study may serve to spearhead improvements to the post-concussion, return-to-play guidelines currently in existence and as a result, decrease incidence of lower extremity musculoskeletal injury.

2.0 REVIEW OF LITERATURE

The following review of literature aims to highlight concussion epidemiology, risk factors, signs and symptoms, and currently accepted return to play criteria for an athlete after a sport-related concussion. This review will also cover descriptive epidemiology of lower extremity musculoskeletal injury as well as currently identified risk factors for lower extremity musculoskeletal injury and a general review of knee and ankle anatomical considerations as they relate to injury. It is the author's intent that this review lay the foundation to establish a possible link between the presence of sports-related concussion and increased risk of musculoskeletal injury to the lower extremity.

2.1 DEFINITION OF CONCUSSION

There are multitudes of definitions that exist for concussion; however, authors appear to agree that sport-related concussions are typically categorized as a subset of a Traumatic Brain Injury (TBI) termed mild traumatic brain injury (mTBI). A TBI can be defined as "an alteration in brain function, or other evidence of brain pathology, caused by an external force." [21] The phrase *alteration in brain function* is further defined as meeting one of the following clinical signs:

- any loss of consciousness or decreased level of consciousness

- any loss of memory (anterograde or retrograde)
- any neurological deficits
- any change in mental state that occurs directly following the injury

The phrase *external force* is further defined as one of the following mechanisms:[21]

- an object striking the head
- the head striking an object
- the brain accelerating or decelerating within the skull without external trauma on the skull itself
- the brain tissue being penetrated by a foreign body
- a force that results from a blast or explosion.

Although sport-related concussions can be serious and have long-lasting effects, they are typically non-life-threatening. Due to this fact, sport-related concussions and mTBI are often used synonymously in sports medicine research and publications.[7]

In a 2015 epidemiological update on concussion, Voss and colleagues[113] defined mTBI or concussion as a “mild, non-penetrating, traumatic injury associated with a brief alteration in brain function.” Although controversy continues concerning the exact diagnostic criteria between an mTBI and TBI, experts appear to be in agreement that a TBI is characterized by a change in brain function, whereas an mTBI is characterized by a *brief* change in brain function.[21,113] While the 2015 epidemiological update was an overview in terms of the general population, Voss and colleagues[113] further identified and focused their discussion on the two high-risk populations for mTBIs: athletes and members of the military.

Due in large part to the complexity and varying nature of concussions, to date, there is no single, agreed upon definition of concussion recognized by all organizations and health care providers. In terms of research devoted to sport-related concussions, definitions employed by authors in the last 5 years are becoming more similar but still remain slightly varied. Definitions currently recognized in position/consensus statements include:

- "trauma-induced alteration in mental status that may or may not involve loss of consciousness." (National Athletic Trainers Association, 2014) [24]
- "a traumatically induced transient disturbance of brain function and involves a complex physiological process." (American Medical Society for Sports Medicine, 2013) [7]
- "a complex pathophysiological process affecting the brain, induced by biomechanical forces." (4th International Conference on Concussion in Zurich, 2012) [6]
- "a pathophysiological process affecting the brain induced by biomechanical forces." (American College of Sports Medicine, 2011) [114]

Specific recommendations and protocol for diagnosing a concussion may vary from organization to organization. In 2014, in a position statement dedicated to the management of sport concussion, the National Athletic Trainers' Association recommended that when a sport-related concussion is suspected, the athlete should be removed from participation immediately and examined by a physician or designate (e.g. athletic trainer).[24] Furthermore, a concussion diagnosis should be accomplished via a systematic clinical evaluation by a physician or designate and the diagnosis should be supported by a battery of assessment tools, which include testing of: neurocognitive function, postural control, and self-reported symptoms.[24,115] When used as a diagnosis for sport-related concussion, tests of neurocognitive function should be interpreted by an appropriately trained neuropsychologist.[24,116]

2.2 EPIDEMIOLOGY OF SPORTS-RELATED CONCUSSION

It is estimated, in the United States alone, that somewhere between 1.6 - 3.8 million sport-related concussions occur annually in both recreational and organized sport activity.[5] With an estimated 50% of all concussions going unreported each year, it is important for clinicians and the public to understand the signs and symptoms of concussions and the possible catastrophic events that could occur if the athlete is returned to sport too soon. [27,28] In 2013, Meehan and colleagues[30] published research that revealed almost one-third of athletes, who were seen across two sports-concussion clinics, sustained a previously undiagnosed concussion. The study further reported that the athletes with a previously undiagnosed concussion were shown to exhibit higher Post Concussion Symptom Scale (PCSS) scores as well as an increased prevalence in loss of consciousness with their current concussion than the concussed athletes without a previous undiagnosed or unreported concussion.[30] The results of this study further emphasize the importance of recognition, reporting and appropriate treatment of sport-related concussions in an attempt to avoid further and possibly more serious injury.

The overall frequency of sport-related concussions is often expressed in literature as an injury rate per 1000 athlete exposures (AE). A single AE can be defined as the combined athlete's participation in a single game or practice. From data collected during the years 1988 to 2002, Hootman and colleagues[34] found a steady increase in reported sport-related concussions in NCAA sports. Specifically, during that time period the reported frequency of sport-related concussion in the NCAA rose from 0.17 per 1000 AE to 0.34 per 1000 AE. [34] According to data collected by the High School Reporting Information Online (HS RIO), high school athletes experienced a similar increase in reported sport-related concussions. During the years 2005-

2012, the frequency of reported concussions in high school athletes rose from 0.23 per 1000 AE to 0.51 per 1000 AE. [4]

2.2.1 Risk Factors of Sports-Related Concussion

Participation in sports is a risk factor for concussions; however, participating in sports that are considered collision or contact sports report the highest incidence of concussion. [4,7,24] Although it has been recognized, in both high school and collegiate settings, that the sport with the most documented concussions is football, when reporting the rates in terms of AE, NCAA ISS data shows football with a concussion rate of 0.37 per 1000 AE and women's ice hockey with 0.91 per 1000 AE.[4,34] Also, when comparing sports where there is a male and female equivalent (sex-comparable sports), female sports reported higher injury rates in both the NCAA (Table 1) and high school settings (Table 2). The only exception to this was found with NCAA men's and women's lacrosse.

Sex as a risk factor for sport-related concussion has been discussed previously in the literature. [1,4,7,36,38,113,114,117-119] To date, most research has focused on if there is a link between sex and concussion and not the causative reasoning behind the link. However, theories surrounding differences in hormones, neck strength, head-neck segment mass and girth as well as differences in self-reporting behaviors between sexes have emerged as possible attributable reasons.

Table 1. Concussion frequency in NCAA sex-comparable sports from 1998-2004 [34]

NCAA Sport	Concussion Frequency AE per 1000
Baseball	0.07
Softball	0.14
Men's Basketball	0.16
Women's Basketball	0.22
Men's Soccer	0.28
Women's Soccer	0.41
Men's Ice Hockey	0.41
Women's Ice Hockey	0.91*
Men's Lacrosse	0.26
Women's Lacrosse	0.25

**data collected from 2001 – 2004 only*

Table 2. Concussion frequency in high school, sex-comparable sports from 2011-2012 [4]

HS Sport	Concussion Frequency AE per 1000
Baseball	0.14
Softball	0.30
Boys' Basketball	0.24
Girls' Basketball	0.37
Boys' Soccer	0.41
Girls' Soccer	0.73

A review of concussion literature reveals that one of the most commonly reported risk factors for sport-related concussion is previous history of a concussive episode.[7,24,36,120] Schulz and colleagues[36] followed high school athletes in North Carolina for three years and found that previous history of a concussion increased an athletes' risk by greater than 2 times that of athletes with no previous concussion history. A study by Guskiewicz and colleagues[37] in 2003 observed a similar increase in the likelihood of a concussion with each succeeding concussion. Specifically, Guskiewicz reported a three times greater risk of concussion in NCAA football players who had reported 3 previous concussions when compared to NCAA football players with no reported previous concussions. [37] It has also been reported that rates of concussion increase during game-day competition in comparison with practice. [35,114,118,119,121] In an epidemiological study published in 2007, Dick and colleagues[35] reported a 10 times greater risk of an NCAA football player incurring a concussion during regular season game play than in regular season practice. More recently, in a study published in 2015, Dompier and colleagues[121] looked at youth, high school and collegiate football players and reported a significant increase in concussions during games as compared to practices across all levels of play. Specifically, Dompier reported game injury rates versus practice injury rates of 3.74:0.53 per 1000 AE in collegiate football, 2.01:0.66 per 1000 AE in high school football, and 2.38:0.59 per 1000 AE in youth football.[121] Increased intensity level, speed, number of player-to-player contacts and magnitude of collisions during game play are hypothesized reasons behind the increased concussion rates seen in game play versus practice.[35,121]

2.2.2 Consequences of Sports-Related Concussion

The overall increase in public exposure of sport-related concussion has also brought a rise in awareness of the consequences associated with this condition. Signs and symptoms are acute consequences of sport-related concussion that are of particular interest in the early recognition and diagnosis of the condition. In years past, terminology like “ding,” “getting your bell-rung”, or even “punch-drunk” were frequently associated with athletes who sustained an insult to the head or body that caused a concussion. Terms, like the ones aforementioned, are currently discouraged as they minimize the consequences and possible severity of sport-related concussions.[24] It has been reported in the literature that sport-related concussions frequently result in a multitude of signs and symptoms, which can be categorized as physical, cognitive, emotional and sleep-related in nature.[43,114,122-124]

Both signs and symptoms are important in the assessment of a concussion; however, there are substantial limitations when assessing the presence of post-concussion symptoms. Since symptoms are subjective, clinicians rely heavily on the candor and honesty of the athlete. Especially in the absence of clinical signs, it is imperative that the athlete be forthright when conveying the presence or absence of post-concussive symptoms. In a 2013 study that included both male and female athletes across six different high school sports, Register-Mihalik and colleagues[125] observed an under-reporting concussion symptom rate of 40%. The most common reasons behind the under-reporting as seen by Register-Mihalik were the athletes not believing that the injury was severe enough to report and not wanting to be removed from play.[125] Similar under-reporting symptom rates and reasons for under-reporting of symptoms have been noted in previous literature.[27,28,30]

Post-concussive signs and symptoms can vary per individual and may surface and change during any part of the athlete's recovery from their concussive episode.[126] The most commonly reported symptom of a sport-related concussion in both high school and college-aged athletes is headache.[7,37-39,43] Other common signs and symptoms include, but are not limited to: dizziness, tinnitus, blurred vision, anxiety, amnesia, attention deficits, loss of balance, poor coordination, slowed reaction times, confusion, alterations in consciousness, photophobia, sensitivity to sound, and disrupted sleep patterns.[38,114,122-124,127] In an attempt to make the assessment of concussion signs and symptoms more objective, common scales and symptom checklists have been made available. The Post-Concussion Symptom Scale, the Graded Symptom Scale Checklist, the Post-Concussion Symptom Checklist, and the Concussion Signs and Symptoms Checklist are available online, free of charge to the public.[128] Clinicians are encouraged to use symptom scales, like the PCSS (Figure 1) when documenting and tracking the presence, progression and resolution of post-concussive symptoms.

Historically, loss of consciousness (LOC) was often regarded as a hallmark sign of a serious concussion; lending its presence or absence as the basis to create concussion grading criteria.[25,129,130] Concussion grading scales like the Colorado Medical Society Guidelines, the American Academy of Neurology Concussion Grading Scale, and the Cantu Evidence Based Grading System for Concussion were based in part on the athlete's level of consciousness, with loss of consciousness (LOC) in all three scales the main criteria for the most severe grading.[25,129,130] Research, however, has shown that LOC occurs in less than 10% of all sport-related concussions and the presence of LOC alone is not indicative of concussion severity.[7,24,38,43,131] Recommendations now exist that discourage the use of grading-scales to manage a concussion and instead encourage clinicians to evaluate and treat patients on an individual basis.[6,24]

Name: ____________________ Age/DOB: _____________ Date of Injury:___________

Post Concussion Symptom Scale

No symptoms"0"-------Moderate "3"---------Severe"6"

Time after Concussion

SYMPTOMS	Days/Hrs ________	Days/Hrs ________	Days/Hrs ________
Headache	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Nausea	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Vomiting	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Balance problems	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Dizziness	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Fatigue	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Trouble falling to sleep	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Excessive sleep	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Loss of sleep	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Drowsiness	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Light sensitivity	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Noise sensitivity	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Irritability	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Sadness	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Nervousness	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
More emotional	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Numbness	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Feeling "slow"	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Feeling "foggy"	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Difficulty concentrating	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Difficulty remembering	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
Visual problems	0 1 2 3 4 5 6	0 1 2 3 4 5 6	0 1 2 3 4 5 6
TOTAL SCORE	_____	_____	_____

Use of the Post-Concussion Symptom Scale: The athlete should fill out the form, on his or her own, in order to give a subjective value for each symptom. This form can be used with each encounter to track the athlete's progress towards the resolution of symptoms. Many athletes may have some of these reported symptoms at a baseline, such as concentration difficulties in the patient with attention-deficit disorder or sadness in an athlete with underlying depression, and must be taken into consideration when interpreting the score. Athletes do not have to be at a total score of zero to return to play if they already have had some symptoms prior to their concussion.

Figure 1. Post-Concussion Symptom Scale (PCSS)

Identifying reliable and valid tools to objectively test the presence and duration of a concussion is of primary concern to researchers and healthcare professionals alike. It has been postulated that although most clinical signs and symptoms of a concussion appear to resolve within a 7 -10 day time period, evidence suggests that the currently utilized NP and balance testing may not be sensitive enough to detect subtle physiological changes associated with sport-related concussions.[57,132] Balance deficits following a concussion have been studied for many years. Balance can be defined as the body's ability to maintain its center of mass (COM) over its base of support. Balance is achieved and maintained by a body's ability to receive sensory information from its peripheral muscles and joints, eyes, and vestibular organs. The information received from these areas is then centrally processed by the brain. Concussive forces to the body that are transmitted to the brain can directly impact the sensorimotor system's ability to process incoming information and therefore can result in balance deficits.

A body's ability to resist forces while simultaneously maintaining its center of mass within the boundaries of its base of support is frequently termed postural stability. The quantification of sway that is observed when a person is attempting to maintain postural stability can be defined as postural control.[58] An increase in the amount of sway corresponds with a decrease in postural control. Alterations in postural control following a concussion can be transient, but have also been shown to be long-term.[58,111]

In 2005, Cavanaugh and colleagues[56] retrospectively analyzed pre and post-concussion Sensory Organization Test (SOT) data in a group of Division I athletes. During the SOT, subjects stand on a dual force plate that is contained within a three-sided surround. The SOT protocol includes eighteen, 20 second trials during which the subject is asked to stand as still as possible. Anterior and posterior sway is recorded during each trial. The trials are conducted in three groups of six. Each testing group includes one trial from each of the following sensory conditions (Figure 2):

1. Eyes open, fixed platform surface and background
2. Eyes closed, fixed platform surface and background
3. Eyes open, fixed platform surface and sway-referenced (moving) background
4. Eyes open and sway-referenced surface (moving platform), fixed background
5. Eyes closed and sway-referenced surface (moving platform), fixed background
6. Eyes open, sway-referenced surface (moving platform) and visual background (moving background)

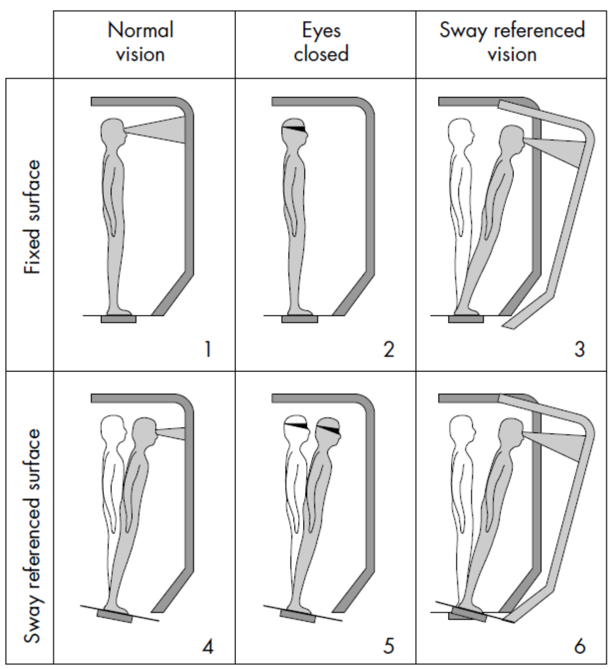

Figure 2. Sensory Organization Test

Cavanaugh's study specifically examined COP measurements recorded during the SOT to calculate composite equilibrium scores (ES) and approximate entropy (ApEn). The equilibrium score, a common clinical measure of postural stability, is based on an algorithm that uses COP measurements to estimate postural sway; a higher ES indicates greater postural stability. Approximate entropy is an algorithm that characterizes the dynamics of postural control by quantifying irregularity and the probability of patterns existing in a specific time series.[58,133] Approximate entropy is a non-linear dynamic statistic that provides an estimate of postural sway predictability. Values calculated for ApEn range from 0-2. A person swaying in a very predictable manner will have a low ApEn value. It was reported by Cavanaugh that an increase in sway predictability pattern after injury, as measured by ApEn, would indicate that the postural control system has become more constrained. It is theorized that this condition would render the postural control system less able to formulate appropriate responses necessary during the maintenance of postural control.[56,58] In his 2005 study, Cavanaugh reported a clinically normal composite ES 48 hours post-concussion in his sample of athletes, indicating an absence of postural instability. A clinically normal ES is defined as a score no more than 5% below the athlete's preseason composite ES value. Nevertheless, those same athletes (with clinically normal ES) displayed significant changes in ApEn values 48 hours after concussion when compared with their preseason values.[58] These findings indicate that the current use of ES to determine postural stability post-concussion may not be sensitive enough to detect changes or deficits in postural control.

Within the last two years, researchers have begun to study the potential link between concussion and lower extremity musculoskeletal injury. [16-18,20] Most recently, in 2016, Brooks and colleagues[20] completed a retrospective analysis of NCAA, Division I football, soccer, hockey, basketball, wrestling, volleyball, and softball athletes during the 2011-2014 athletic seasons. This study retrospectively followed 87 concussed players for 90 days after their return-to-play date and for one year prior to their recorded concussion. Concussed players were matched with up to 3 controls each based on sports team, sex and games/matches played during the 90-day observation window. Brooks reported, that in their sample, the odds of sustaining an acute, non-contact, lower-extremity musculoskeletal injury was 2.48 times greater in concussed versus non-concussed athletes.[20] In 2015, Lynall and colleagues[17] completed a similar retrospective analysis of NCAA, Division I athletes from 13 different sports (men's cross country, field hockey, football, men's lacrosse, men's and women's soccer, men's and women's swimming, rowing, softball, wrestling, women's basketball, and women's tennis) from 2010 – 2013. Forty-four concussed athletes were identified and matched with 58 controls based on sex, sport, competition playing time, age, height and weight. Lynall's study followed concussed athletes and their matched controls for 365 days pre-concussion and 365 days post return-to-play. The results of this study reported significant increases in injury risk in concussed athletes at 180 days post-concussion and 365 days post-concussion, but not 90 days post-concussion.[17] In 2015, Pietrosimone and colleagues[16] examined data from a health history survey completed by 2,429 retired NFL football players. Pietrosimone's study was based on subject recall information on "general medical history, joint injury history and overall health status." Although the study's design was not able to indicate if concussion resulted in increased risk of musculoskeletal injury, the results did suggest that the retired NFL players with a greater number of concussions also had increased odds of reporting a musculoskeletal injury.[16] These studies begin to ascertain the possibility that consequences of sport-related concussion may remain even after the apparent clinical resolution of the condition.

Prior to recent international exposure, research, subsequent rule changes and position statements outlining recommendation for sport-related concussion treatment, athletes would frequently return to participation immediately following a concussive episode. Within the last 15 years' researchers, clinicians and organizations have made strides towards implementing protocol that serve to standardize their RTP decisions. If evidence would confirm that concussion is a risk factor for lower extremity musculoskeletal injury, current return-to-play criteria for sports-related concussion would once again need to be evaluated.

2.2.3 Return-to-Play Guidelines for Sports-Related Concussion

Prior to returning-to-play after a sport-related concussion, the athlete should be cleared by a health care provider that has been trained in the recognition and treatment of concussions. Common recommendations for return-to-play after suffering a sport-related concussion include the athlete to returning-to-baseline in NP and balance testing, and undergoing a graduated physical progression that involves sport-specific activities and risk for contact. Athletes must remain symptom-free at rest, as well as throughout and after activity in order to be deemed discharged from care.[6,7,134] The 4th International Conference on Concussion in Sport held in Zurich in November of 2012 unanimously decided that no athlete should return-to-play on the same day as the concussive episode.[6] This recommendation was centered around evidence that NP deficits and symptoms following a sport-related concussion may be delayed and therefore not measureable initially via sideline tests.[6,37,135,136] Currently, national organizations like the NATA, NCAA, National Football League (NFL), and the National Hockey League (NHL) have adopted return-to-play guidelines which stipulate that an athlete should not return to play on the same day as a concussive episode and subsequently should return to baseline on pre-concussion testing prior to returning to participation.[24,137-140] Although guidelines like these are becoming more commonplace in organizations, the management of sport-related concussion continues to be scrutinized in youth, collegiate and professional sports.

As a direct result of the 5th International Conference on Concussion in Sport held in Berlin in October 2016, specific recommendations for RTP following a sport related concussion were developed. These recommendations include an initial rest period of 24-48 hours followed by a graduated return to sport that involves a progressive stepwise rehabilitation strategy.[141] Recommendations include a minimum of 24 hours for each step in the RTP progression.[141] Specific guidelines for graduated return to sport strategy from the 2017 Consensus Statement on Concussion in Sport are outlined in Table 3.

Table 3. Graduated return-to-sport (RTS) Strategy (McCrory, et al.)[141]

Stage	Aim	Activity	Goal of each step
1	Symptom-limited activity	Daily activities that do not provoke symptoms	Gradual reintroduction of work/school activities
2	Light aerobic exercise	Walking or stationary cycling at slow to medium pace. No resistance training	Increase heart rate
3	Sport-specific exercise	Running or skating drills. No head impact activities	Add movement
4	Non-contact training drills	Harder training drills, eg, passing drills. May start progressive resistance training	Exercise, coordination and increased thinking
5	Full contact practice	Following medical clearance, participate in normal training activities	Restore confidence and assess functional skills by coaching staff
6	Return to sport	Normal game play	

NOTE: An initial period of 24–48 hours of both relative physical rest and cognitive rest is recommended before beginning the RTS progression.
There should be at least 24 hours (or longer) for each step of the progression. If any symptoms worsen during exercise, the athlete should go back to the previous step.
Resistance training should be added only in the later stages (stage 3 or 4 at the earliest). If symptoms are persistent (eg, more than 10–14 days in adults or more than 1 month in children), the athlete should be referred to a healthcare professional who is an expert in the management of concussion.

2.3 LOWER EXTREMITY MUSCULOSKELETAL INJURY EPIDEMIOLOGY

Musculoskeletal injuries to the lower extremity comprise over half of the reported injuries sustained by athletes. Regardless the level of competition, injuries to the ankle and knee persist as the two most commonly injured body parts during sports participation. [34,67,142] In a collaboratively published analysis of injury data gathered via the NCAA ISS from the years 1988 through 2003, Hootman and colleagues[34] reported that greater than 50% of all injuries in NCAA sports occur to the lower extremity with the majority of those occurring to the knee and ankle. Across all NCAA sports, women's soccer recorded the highest incidence of injury to the lower extremity, with nearly 70% of all reported injuries classified in this category.[34,143] In terms of professional sports, Lawrence and colleagues[144] reviewed injury reports from NFL games played during the 2012-13 & 2013-14 regular season and found that 61.9% of injuries during those seasons were to the lower extremity. Specifically, this study revealed that injuries to the knee (17.8%), the ankle (12.4%), and the hamstring (8.7%) were found to be the three most common injuries suffered during NFL games.[144] In 2010, Drakos and colleagues[145] analyzed injury data compiled by the National Basketball Athletic Trainers Association from the 1988-89 to 2004-05 basketball seasons. Drakos reported that during that 17 year time-period, lower extremity musculoskeletal injuries comprised 62.4% of all injuries in the National Basketball Association (NBA), with the ankle being the most frequently injured body part (14.7%).[145] Similar results have been reported when analyzing athletic injuries in secondary school levels as well. [67,142,146] In a three year study that analyzed records of over 75,000 player seasons (1 player on 1 team in 1 season), Powell and colleagues[67] reported that lower extremity injuries comprised nearly 60% of all injuries that occurred at the high school level. In a 20 year descriptive study, Beachy and colleagues[142] reported similar tendencies towards lower extremity injuries in middle school athletes. Specifically, Beachy reported that 70% of all injuries recorded by the schools' athletic trainers were to the lower extremity with the ankle and the knee the two most likely body parts to be injured by both males and females.[142]

Even in upper extremity dominant sports like volleyball, softball and baseball, injuries to the lower extremity appear to occur more frequently than injuries to the upper extremity. According to data collected between 1988 and 2004, Agel and colleagues[147] reported greater than 55% of all injuries reported in NCAA women's volleyball were to the lower extremity with only 20% of all injuries occurring to the upper extremity. In that same time period, Marshall and colleagues[148] reported that injuries to the lower extremity comprised approximately 42% of all injuries in NCAA softball while upper extremity injuries comprised 33% of the total injury volume. Overall injury data for NCAA baseball revealed slightly different tendencies. Although Dick and colleagues[149] reported that upper extremity injuries comprised the majority of all reported injuries in NCAA baseball (45%) and that lower extremity injuries made up slightly more than 33%, they also found that in games, the most frequently injured body part was the upper leg (11%) and then the ankle (7.4%) followed by the shoulder (6.5%). Similar overall results were reported in Major League Baseball (MLB). Utilizing MLB disabled list data from 2002 – 2008, Posner and colleagues[150] reported that 51.4% of all injuries were to the upper extremity and 30.6% to the lower extremity. Like the NCAA study, the MLB study took all players into consideration, irrespective of position. However, Posner's study also analyzed data to field players only (eliminating pitchers from the analysis) and found that when excluding pitchers from the analysis, the majority of injuries were to the lower extremity (47.5%) while injuries to the upper extremity comprised 32.1% of the total injury pool.[150]

Regardless of sport, ankle ligament injuries were the most common injury described in research within collegiate, high school and middle school sports.[34,67,142] Hootman's research found that 14.8% of all injuries reported in NCAA sports from the years 1988 to 2004 were to the ankle, with one out of every five ankle injuries resulting in 10+ days of time loss.[34] Both Powell and Beachy found similar results in their studies, reporting percentages for ankle injuries approaching 26% of the overall injuries reported in high school sports and slightly greater than 19% in middle school sports.[67,142] The NCAA sport with the most reported ankle injuries was men's basketball, where over one-fourth (26.2%) of the injuries reported fell in this category.[34,151] Although NCAA women's volleyball did not report the same volume of ankle injuries as men's basketball, ankle injuries in women's volleyball made up 44.1% of the overall injuries reported in matches; making ankle injuries in volleyball the most frequent type of injury seen across all NCAA sports during games.[147]

In literature and research, various definitions of injury severity exist; however, injury severity in sport is frequently measured and defined according to the number of days an athlete would be absent from sports participation due to injury.[152,153] Identifying and addressing injuries that necessitate longer return-to-sport time frames is of importance to clinicians and healthcare providers. Understanding and anticipating appropriate time-frames can aid in the development of suitable return-to-play criteria and rehabilitation programs, while stressing the importance of implementing injury prevention strategies.[153] Throughout 15 collaborative epidemiological studies that reviewed injury data in 15 NCAA sports over a 16 year time-span, severity of injury was defined as an injury that resulted in a minimum of 10 consecutive days of limited or total loss of participation in sports.[34] Sports in these aforementioned studies included: men's basketball, women's basketball, baseball, softball, women's field hockey, football, gymnastics, men's ice hockey, women's ice hockey, men's lacrosse, women's lacrosse, men's soccer, women's soccer, and volleyball. It was reported that in each of those 15 sports, the lower extremity accounted for the highest percentage of severe injuries in games, and all but baseball reported the lower extremity injuries accounted for the highest percentage of severe injuries in practices.[35,143,147-149,151,154-162] In 2009, Darrow and colleagues[146] looked at the severity of injuries in high school athletics. Darrow defined a severe injury as any injury that caused the athlete to miss > 21 days of sport participation. Darrow reported that the two most common severely injured body parts in high school athletes were the knee (29%) and ankle (12.3%). [146] Although Darrow's research concluded that in his sample, high school football had the highest rate of severe injuries, it was also found that when analyzing sex comparable sports (i.e., soccer, basketball, baseball/softball) severe injury rates were higher amongst female athletes.[146] Darrow's research also concluded that female comparable sports reported higher numbers of severe knee injuries and a higher number of overall severe ligamentous injuries when compared with male sports. [146] In regards to all sports analyzed, the percentage of severe injuries to the knee and ankle in females (knee, 43.8%; ankle, 19.1%) were higher than that of males (knee, 22.2%; ankle, 9.2%).[146]

Common mechanisms of lower extremity musculoskeletal injuries differ depending on sport and competition level. In 2013, Swenson and colleagues[163] analyzed ankle and knee injury data from a random sample of 100 high school athletic programs from across the United States. To be included in the study, athletic programs needed to contain the following sports: football, boys' and girls' soccer, girls' volleyball, boys' and girls' basketball, wrestling, baseball and softball. Swenson reported from the years 2005 – 2011, the primary mechanism of injury for acute ankle sprains in both sexes were contact with another player (42.4%), contact with the playing surface (26.7%) and noncontact (25.5%).[163] In terms of knee injuries, Swenson reported that the overall analysis of all sports combined indicated that the primary mechanism involved contact with another person (50.3%); however, noncontact mechanisms were more common in girls' volleyball (42.9%), boys' basketball (35.3%) girls' basketball (35.7%), girls' gymnastics (57.7%), and girls' lacrosse (51.9%).[164] In comparison with the high school sports that reported "contact with another player" as the primary mechanism of knee injury (football, boys' soccer, girls' soccer, wrestling and ice hockey) the majority of the sports with a "noncontact" primary mechanism are known to involve large amounts of jumping, which indicate that landing technique during sports participation may be a contributing factor to these results.

In the NCAA, it has been reported that practice and game injury rates differ by division and season.[34] Across all divisions, preseason games accounted for the lowest injury rates, reporting six injuries per 1000 AE; whereas in season games accounted for the highest injury rates, 14.5 per 1000 AE. [34] Across all divisions, injury rates for practice were highest in preseason (6.63 per 1000 AE) and lowest in the post season (1.35 per 1000 AE). However, when looking at injury rates between divisions, Division I athletes had higher practice and game injury rates when compared with Division II and Division III athletes. [34] Justification for these differences include the variability in the intensity between practice and game situations, the length and load of preseason practices in comparison to in season and post season practices, combined with the overall initial level of conditioning that athletes may exhibit at the beginning of preseason activity.[34]

Preventing lower extremity musculoskeletal injuries has been the focus of considerable sports medicine research. Clinicians and researchers strive to identify modifiable risk factors that predispose athletes to injury in an effort to create, implement, and alter current training programs and activity in an attempt to decrease injury rates.

2.3.1 Lower Extremity Musculoskeletal Injury Risk Factors

The lower extremity functions to support the weight of the upper body, assist with the maintenance of balance, and provide locomotion. The lower extremity is comprised of 62 bones that are joined together to form a multitude of articulations. Each articulation or series of articulations has a purpose that lends itself to the efficiency and accuracy at which the lower extremity is able to successfully perform its functions. Joint congruency, muscle strength, articular cartilage, frictional forces, and the integrity of ligamentous and capsular constraints mechanically assist each articulation in obtaining the mechanical joint stability needed for lower extremity functionality. The other component necessary for effective and efficient functionality of the lower extremity is mediated via the sensorimotor system. The sensorimotor system, a subcomponent of the motor control system, relies on feedback from the peripheral mechanoreceptors in order to obtain functional joint stability.[165] Mechanoreceptors are sensory organs that send neural signals from their peripheral location to the central nervous system in response to mechanical deformation.[166] Mechanoreceptors are found within the articular surfaces, muscles, tendons, ligaments and skin. Information obtained from the mechanoreceptors can influence and effect functional joint stability and postural control.[165] Functional joint stability requires the effective and constant processing of afferent information (feedback control) and the anticipatory actions (feedforward control) to the muscles that serve to move and stabilize the joints that they cross. [165]

With so many articulations and surrounding soft tissue in the lower extremity, many intrinsic risk factors have been identified for the lower extremity musculoskeletal injury. Intrinsic risk factors that have been linked to lower extremity musculoskeletal injury include neuromuscular coordination asymmetries, strength asymmetries, sex, familial predisposition, cognitive function, previous history of injury, anatomical variations, surgical history, and body mass index. [70,72,74,167-171]

In a prospective study observing 10,393 basketball players (3421 males, 6972 females), McKay and colleagues[77] reported previous history of ankle injury as the strongest predictor for the occurrence of ankle sprains. In this study 73% of players who sustained and ankle injury reported a previous history of ankle injury.[77] In terms of the knee, identifying risk factors for injuries to the anterior cruciate ligament (ACL) is possibly the most studied. Unlike the ankle, risk factors for knee injury, particularly the ACL, are much more difficult to isolate. Research indicates that it may be multiple risk factors, working in combination, that affect the risk of ACL injury. [72,73,167]

Previous musculoskeletal injury to the lower extremity can affect the dynamic components necessary for joint stability. These dynamic components (feedback and feedforward neuromuscular control) provide the input necessary for functional stability. Previous injury to the lower extremity can also result in a mechanical instability of the affected joint. Mechanical instability results from a loss of the integrity of the static and/or dynamic structures surrounding and within the affected joint. In 1996, Lephart and Henry[172] introduced the Functional Stability

Paradigm. This paradigm visually illustrates the interrelationship between mechanical and functional instability after injury and their influence on re-injury. (Figure 3)

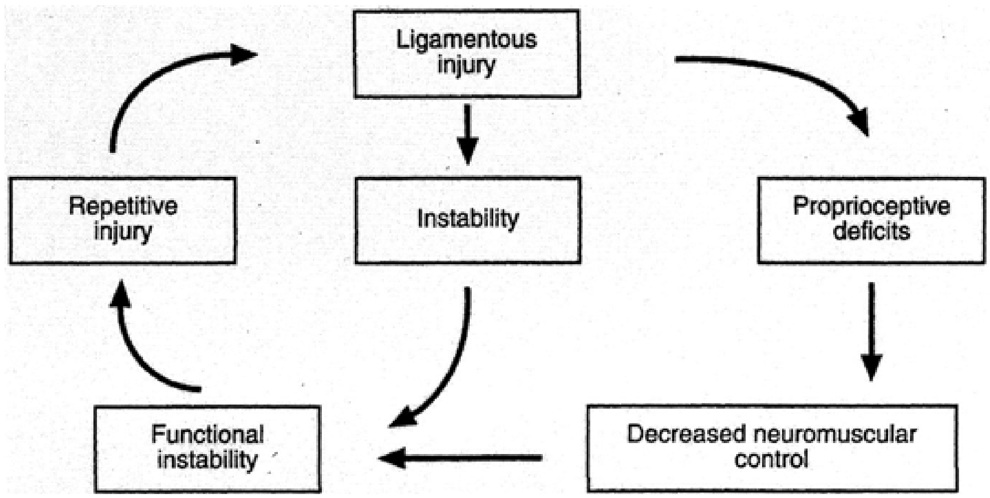

Figure 3. Functional Stability Paradigm [172]

Deficiencies in balance have been linked to increased injury risk in a variety of athletic populations.[173] Balance deficits leading to increased injury risk have been associated with newly incurred injuries as well as previous injury to the lower extremity.[174-176] A person's ability to maintain balance requires the body to accurately assess and process continuous feedback from the somatosensory, vestibular and visual systems while simultaneously providing appropriate neuromuscular responses.

In 2007, Swanik and colleagues[70] investigated a possible link between cognitive functioning and ACL injury risk by comparing preseason baseline NP scores of subjects who sustained a subsequent non-contact ACL (NCACL) injury with that of matched controls. The instrumentation used in this study was ImPACT ® version 2.0, a computer-delivered assessment tool that is commonly used to evaluate levels of neurocognitive functioning in concussed athletes. Swanik reported statistically significant differences between the NCACL group and matched controls in reaction time (P = .002), processing speeds (P = .001), visual memory (P = .000) and verbal memory (P = .045). [70] Specifically, athletes who would go onto sustain a NCACL injury had slower reaction times and processing speeds, and performed significantly worse on tests of visual memory and verbal memory than their matched controls. The results of Swanik's study indicated a relationship between decreased neurocognitive performance and subsequent noncontact ACL injuries.[70] Although differences in NP scores were statistically significant between groups, it is notable that the noncontact ACL group's NP scores fell in categories that were considered low average to average, and did not reach the level of neurocognitively "impaired" as defined by testing standards.[70,177] This fact may be of clinical significance when utilizing NP scores to determine return-to-play eligibility or when identifying individuals that may be at greater risk for an NCACL injury during the preseason screening process.

Playing surface, weather conditions, shoe quality/construction, and direct contact with an opponent are a portion of the extrinsic factors for lower extremity musculoskeletal injury reported in the literature.[72,75,76] Although many studies have been published in this area, overall results on identifying significant extrinsic risk factors for lower extremity musculoskeletal injury have been mixed. It has been theorized that both reduction and increase in frictional forces between the shoe and playing surface can increase an athlete's risk of injury. A reduction in frictional forces is theorized to be seen during inclement weather, whereas an increase in frictional forces could be attributed to the type of shoe worn or the playing surface itself.[178]

Research in the area of the shoe construction and increased risk for ACL injury has shown varied results. [178-180] The type of playing surface in isolation also has mixed support. In a 2015 study on female youth soccer players, O'Kane and colleagues[181] reported a 2.8 times greater risk of sustaining a lower extremity injury when athletes played on natural grass fields as compared to artificial turf. In contrast, a 2010 study by Bjorneboe and colleagues[182] reported no difference in injury risk when comparing artificial turf and natural grass. With varying competition levels, sports, ages and sexes represented in research, conflicting results in the literature may lead clinicians to believe that a combination of risk factors may contribute to injury.

In recent years, increasing evidence exists that musculoskeletal injury risk can be multifactorial and many times, sex specific.[73,84,85,183] In a 2014 study, Beynnon and colleagues[85] examined ACL injuries in high school and collegiate athletes, and concluded that sex, sport type and level of competition were independently associated with first-time, non-contact ACL injuries. In terms of sex, Beynnon reported a 2.10 times greater risk of non-contact ACL injury in females as compared to males. In terms of level of competition, Beynnon reported a greater risk of non-contact ACL injury in collegiate athletes as compared to high school athletes (RR = 2.38). And in terms of sport type, soccer (RR = 1.77) and rugby (RR = 2.23) have the greatest risk of suffering a non-contact ACL injury as compared with basketball, lacrosse, football, field hockey and volleyball.[85] In 2003, Uhorchak and colleagues[84] completed a 4 year, prospective study with a class of 859 (739 men and 177 women) United States Military Cadets aimed at identifying risk factors for noncontact ACL injuries. Results indicate a sex difference in risk factors; observing a disproportionate number of risk factors in female as compared with male cadets.[84] In female cadets, numerous significant risk factors were identified for non-contact ACL injury, with the risk exponentially increasing when multiple risk factors were seen in combination: greater than normal ACL laxity, narrow femoral notch width, higher than average BMI ($R^2 = 0.625$).[84] This model correctly predicted 75% of NCACL injuries. Significant risk factors for male cadets included anatomical characteristics, such as: femoral notch width and joint laxity.[84] Unlike the female cadets, the risk factors identified for male cadets successfully predicted those cadets who did not suffer a NCACL injury, but failed to predict any cadets who did suffer a NCACL injury.

In 2005, Beynnon[183] studied the effects that sex, sport type and level of competition would have on first-time ankle sprains. In terms of sex, Beynnon reported an association between first-time ankle sprains for female athletes and the type of sport; however, did not report such an association with males. Unlike Beynnon's 2014 non-contact ACL study, the 2005 first time non-contact ankle sprain study did not demonstrate that level of competition influenced injury risk in their study sample.[183]

These aforementioned studies contribute the body of research that currently exist that identifies sex differences in injury and further emphasize the complexity of identifying risk factors for lower extremity musculoskeletal injury.

2.3.2 Lower Extremity Anatomical Considerations

2.3.2.1 The Ankle

The ankle is a complex grouping of articulations that work together to obtain proper movement and function during ambulation and balance. The articulation between the distal tibia, distal fibula and talus form the talocrural joint. A thin joint capsule surrounds this joint while it is externally reinforced by a series of medial and lateral ligaments. Both the medial and lateral ligaments have a role in providing static stability to the talocrural joint. The most common mechanism of injury for the talocrural joint is inversion and plantarflexion. During this mechanism the lateral three ligaments are stressed, with the anterior talofibular ligament (ATF) being the most commonly injured of the three.

The subtalar joint is a set of articulations produced by the posterior, middle and anterior facets of the calcaneus as it articulates with the inferior portion of the talus. Within the subtalar joint a separate joint capsule internally encloses the posterior and anterior-middle articulations. The posterior capsule is reinforced by the medial, posterior and lateral talocalcaneal ligaments. Other ligaments that provide static stabilization to the joint are the calcaneofibular ligament and the tibiocalcaneal fibers of the deltoid ligament. The majority of the static stability of the subtalar joint comes from the interosseous (talocalcaneal) and cervical ligament that serve to bind the calcaneus and talus together.

The musculature that surrounds the ankle and foot control movement, impart thrust, offer shock absorption and provide dynamic joint stability. Groups of muscles, tendons, nerves and blood vessels of the lower leg are contained by a fascial lining that serves to distinctly separate each group into four compartments: the anterior, lateral, superficial posterior and deep posterior. Muscles that cross the ankle and insert on the foot have a major role in the dynamic function of the foot and ankle.

2.3.2.2 The Knee

The three main articulations at the knee include tibiofemoral joint, patellofemoral joint and proximal tibiofibular joint. The stability of the knee relies primarily on the dynamic and static restraints and not its bony configuration.

The tibiofemoral joint is comprised of the round condyles of the distal femur articulating with the flat plateaus of the tibia. A medial and lateral meniscus sit atop the tibial plateaus and serve to transform their flat surfaces into shallow seats that receive the femoral condyles and ultimately add static stability to the joint. A fibrous capsule encloses the medial and lateral portions of the tibiofemoral joint. Although the capsule itself provides static stability to the knee, the capsule also receives reinforcement and support from surrounding muscles and ligaments. The lateral joint capsule of the knee is reinforced by the iliotibial (IT) band, the lateral collateral ligament (LCL), and the anterolateral ligament (ALL). The medial joint capsule is reinforced statically by the medial collateral ligament, posterior oblique ligament, medial patellar retinacular fibers and dynamically by the tendons of the Sartorius, Gracilis and the Semitendonosus. Two intracapsular ligaments, the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL), cross within the articular capsule providing the knee with additionally stability as they limit anterior and posterior translation of the tibia on a fixed femur.

2.4 SUMMARY

When an athlete suffers a concussion, they are sustaining an injury to the brain. Although most frequently categorized as transient, this brain injury can cause long-lasting changes to postural control, cerebral functioning, and gait.[57,132] Since the results of a sport-related concussion can produce alterations in postural sway and deficiencies in postural control, and these types of deficiencies have been linked to lower extremity musculoskeletal injury, then it is plausible to consider that a relationship could exist between the two. In addition, if traditional methods of post-concussion balance assessment are not sensitive enough to detect subtle deficiencies in postural control, a question emerges concerning an athletes' risk for sustaining a subsequent musculoskeletal injury once they return-to-play following a sport-related concussion. If a relationship exists between concussion and lower extremity musculoskeletal injury, an increased emphasis on a concussion-rehabilitation program that would address the aforementioned deficits could be implemented prior to returning the athlete to play.

2.5 METHODOLOGICAL CONSIDERATIONS

This study plans to examine the causal relationship between the presence of concussion and the occurrence of subsequent musculoskeletal injury in collegiate athletes. In order for this study to determine a causal relationship, three criteria must be simultaneously met. The first criterion is that the temporal sequence of events must be ascertained. Specific to this study, this means that exposure (concussion) must precede the outcome (lower extremity musculoskeletal injury).[184] The second criterion requires that a statistical association be found between concussion and subsequent lower extremity musculoskeletal injury. And the third criterion is that the statistical relationship must be valid and not resulting from any error, confounding, or bias.[184] This section will cover the justification behind the methodologies selected for this study.

2.5.1 Medical Chart Review

A medical charts review is a widely accepted method of obtaining data for research studies that uses prerecorded, patient-centered data as the principal means to answer a research question.[185,186] The medical charts being reviewed for this proposed study are from a local, Division 1, NCAA Institution.

A medical chart review was chosen rather than a prospective, longitudinal study due to the time constraints of the researcher. An argument was also made against using an injury self-report survey to obtain data about the history of a sports-related concussion and subsequent injuries throughout their participation in collegiate athletics. A study by Pietrosimone and colleagues[16] published in 2015 used a self-report, health history survey to look at the association between concussion history and musculoskeletal injury in retired NFL players. Participants that completed the health history survey were asked to recall the frequency of musculoskeletal injury and the number of concussions that they recalled having during their time in the NFL. The survey instrument did not require the participants to report when the musculoskeletal injuries or concussions occurred. The results of their study did reveal an association between the history of concussions and a history of musculoskeletal injuries in retired NFL players; however, Pietrosimone acknowledged limitations in discerning causality in this association due to the inability to determine temporal sequencing of the self-reported concussion(s) and lower extremity musculoskeletal injuries.[16] Although self-reported clinical history in patients has been shown to yield reliable results, the data collection windows in the methodology for the currently proposed study require precise diagnostic, return-to-play, and time-sensitive data in order to address the author's proposed aims.[187] Furthermore, concerns arise when assessing the validity of self-reported data in a subject pool that may have neurocognitive impairments, as seen in individuals who have suffered a concussion.

For the above stated reasons, medical charts review was chosen as the data collection method for this proposed study.

2.5.2 Selection of Concussed Athletes

Concussed athletes were selected by querying the ImPACT® electronic records database and identifying the University of Pittsburgh athletes with the most recently diagnosed concussions, working back in time until 82 concussed athletes who fit the inclusion criteria were selected. There are currently 10 years of medical records for athletes that participated at the University of Pittsburgh; however, diagnostic testing, treatment options and return-to-play criteria for athletes who have sustained a sports-related concussion have progressively changed during that time. By selecting the most recently concussed athletes, this study was sampling from a pool of the most up-to-date and standardized medical records in terms of concussion protocol.

If the review of medical records reveals that an athlete had more than one documented concussion, only the data surrounding the first concussion was used in this study.

2.5.3 Sport Selection

The athletes eligible for inclusion in this study were current or past members of the football, men's basketball, women's basketball, men's soccer, women's soccer, baseball, softball, women's volleyball, women's gymnastics and wrestling teams at the University of Pittsburgh. These sports were selected because they represent the sports at the University of Pittsburgh with the greatest risk of sports-related concussion and risk of lower extremity musculoskeletal injury. Due to the increased risk of concussion, all of the sports used in this study, with the exception of volleyball, had undergone preseason baseline neurocognitive testing for the past 10 years. Volleyball began baseline neurocognitive testing 5 years ago.

It was also important to include sex comparable sports (men's basketball/women's basketball, men's soccer/women's soccer, baseball/softball) in order to address Specific Aims 3 and 4 that address the influence that sex may have on lower extremity musculoskeletal injury and recovery time after a sports-related concussion.

2.5.4 Matching of subjects

Sex, sport-type, player-position, BMI, the number of athlete exposures, and types of athlete exposures both (practice vs games), have all been identified as factors that can influence the risk of lower extremity musculoskeletal injury.[34,72,74,76,84,144] Matching subjects by sex, sport, position, calendar year, and BMI will aid in controlling covariates and ultimately contribute to this study's internal validity and efficiency.[188] Previous research in this area has used similar matching criteria.[17,20]

A 1:1 match was chosen for this study due to the limitations and difficulty noted in previous research when attempting to complete 1:2 and 1:3 subject matching. [17,20]

2.5.4.1 Creation of Sport and Position Matching Groups

Matching groups were created based on sport and position to aid in identifying appropriate matches for the concussed athletes. Matching groups were developed in an attempt to account for the unique demands and injury risk incurred by each athlete position within its respective sport. A 2016 study that aimed to examine influence of concussion on musculoskeletal injury, created matching groups according to sport and position (Table 4).[20] Due to the results of sport-specific epidemiological studies and content expertise of the author, alterations to the matching groups used by Brooks' were developed for this proposed study (Table 5).[144,150] Specifically, two additional position groups were established for football. Tight ends, wide receivers, and defensive backs were put in a separate group, while a quarterbacks group was added. Quarterbacks appear to have been excluded entirely in Brooks' study. Due to the types of injuries seen in baseball and softball pitchers and the restriction of their play in both practice and games, a separate category was developed in those sports.

Table 4. Sport and Position Matching Groups (Brooks' et al.) [20]

Sport	Group A	Group B	Group C
Football	running backs, fullbacks, tight ends, wide receivers, defensive backs, linebackers	offensive lineman, defensive lineman	NA
Basketball	forwards, guards	centers	NA
Soccer	forwards, midfielders	defenders	goalkeepers
Softball/Baseball	infielders	outfielders	utility players
Volleyball	hitters, setters	defensive specialists	NA
Wrestling	matched within 3 weight classes above or below competition weight	NA	NA

Table 5. Sport and Position Matching Groups (current study)

Sport	Group A	Group B	Group C	Group D
Football	running backs, fullbacks, linebackers	tight ends, wide receivers, defensive backs	offensive lineman, defensive lineman	quarterbacks
Basketball	forwards, guards	centers	NA	NA
Soccer	forwards, midfielders	defenders	goalkeepers	NA
Softball/Baseball	infielders	outfielders	utility players	pitchers
Volleyball	hitters, setters	defensive specialists	NA	NA
Wrestling	matched by weight class	NA	NA	NA
Gymnastics	matched by event(s)	all around	NA	NA

2.5.4.2 Calendar Year Matching

The number of athlete exposures (both in practice and games) were not recorded for the University of Pittsburgh athletes in our subject pool; therefore, in an attempt to control for athlete exposures, concussed subjects will also be matched with non-concussed subjects by the calendar year/season in which the concussion occurred. By doing this, the 90-day observation period prior to the concussion and the 180-day observation period after the concussed athlete returns to play (for both the concussed athlete and the matched non-concussed athlete), will yield identical practice and game athlete exposures.

Consideration was given to matching by academic year in school (freshman, sophomore, junior, senior); however, matching by academic year in addition to calendar year will be too restrictive and may eliminate all matching possibilities for some subjects.

2.5.4.3 Body Mass Index Matching

Body Mass Index (BMI) was calculated for each athlete based on the height and weight reported on the preparticipation exam from the season in which the athlete sustained their concussion. Each athletes' BMI was categorized into one of the following matching groups: Underweight (<18.5), Normal Weight (18.5 – 24.9), Overweight (25-29.9), Obese (>29.9). Each concussed athlete was matched with a non-concussed athlete in the same BMI group.

2.5.5 Lower Extremity Musculoskeletal Injury History Measurement

Data pertaining to any documented lower extremity musculoskeletal injury that had occurred, in the 90-day period prior to the concussed subjects' sports-related concussion and in the subsequent 180-day period after the concussed athlete returns-to-play, was collected and analyzed. The same time periods will be collected and analyzed for the concussed athlete's matched control. Following the concussed athlete and their matched control prior to the documented concussion, was designed to account for previous injury history.

Longer pre-concussive data collection windows and post return-to-play data collections windows have been used in other studies.[17,20] However, when considering the subject pool for the currently proposed study, the use of data collection windows that exceed the 90 day and 180 day respective thresholds will eliminate a large pool of athletes as eligible subjects. Freshman athletes who sustain a concussion within their first three months of participation and senior athletes whose return to play falls within 180 days of graduation will be automatically be eliminated from the study.

3.0 METHODOLOGY

3.1 EXPERIMENTAL DESIGN

A retrospective matched-cohort study design utilizing a review of medical records of University of Pittsburgh athletes from the past ten years was conducted. Medical records allowed for identification of concussion history and subsequent musculoskeletal injuries in the study group. This study aimed at providing evidence that a relationship exists between concussion and subsequent lower extremity musculoskeletal injury.

3.2 SUBJECTS

This study was approved by the Institutional Review Board (IRB) at the University of Pittsburgh prior to medical records review and collection of data.

The subject pool was drawn from both male and female NCAA, Division 1 athletes who participated for the University of Pittsburgh during the years 2007-2016. Data collection began by identifying 82 of the most recent concussed University of Pittsburgh athletes. A roster of eligible matched controls was developed and confirmed via medical records review. Each concussed subject was randomly matched with one non-concussed subject by sex, sport, position, calendar year, and BMI. Matching subjects by sex, sport, position, calendar year, and BMI aided in controlling covariates and ultimately contributed to this study's internal validity.

3.2.1 Inclusion Criteria

Subjects were included in this study if they participated in University of Pittsburgh athletics from the years 2007 - 2016 as a member on one of the following university-recognized teams: football, men's basketball, women's basketball, men's soccer, women's soccer, baseball, softball, women's volleyball, women's gymnastics and wrestling.

Identification of concussed athletes was accomplished through an electronic database search that contains neuropsychological (NP) testing scores for all university athletes. The electronic database permits the user to filter by "Test Type". The database stores information on pre-participation baseline NP testing as well as testing administered after concussive episodes. The NP database will allow the researcher to filter and identify only those subjects with a Test Type category of "Post-Injury 1". The "Post-Injury 1" category type is used for athletes who have undergone NP testing after a suspected concussive episode. Once concussed athletes were identified, concussion diagnosis was confirmed via medical records review. Subject securement began with the most recently diagnosed concussions and went back in calendar time until 82 eligible subjects were identified. In order for the athlete to be placed on the concussed subject roster, each athlete's medical records must of included: 1) concussion diagnosis from a healthcare provider (athletic trainer, team physician, or neuropsychologist), 2) return-to-play documentation, 3) a minimum of 180 days of post-return-to-play records, and 4) a minimum documentation of 90 days pre-concussion.

Diagnosis of concussion was based on a record of the athlete receiving an insult to the head or body during athletic participation that was followed by documented symptoms and/or signs of concussion, including the results of NP testing. Recovery from concussion and subsequent return-to-play decisions will be defined in the medical records as the athlete 1) being symptom-free at rest and exertion, 2) returning to baseline or acceptable range NP testing (as indicated by neuropsychologist or clearing physician), and 3) written verification from health care provider that athlete is cleared to return to full participation.

Athletes with no previous history of concussion while at the University of Pittsburgh were potential subjects for the non-concussed group. Non-concussed athletes were further classified into groups by sex, sport, position, calendar years participating, and BMI. These sex/sport/position/BMI/calendar years - specific rosters permitted random selection for the 1:1 matching of subjects.

If a concussed subject had multiple concussions while at the University of Pittsburgh, only the data corresponding to the first concussive episode was eligible for this study.

3.2.2 Exclusion Criteria

Subjects were excluded from the study if their medical records reveal:

- athlete had a self-reported previous concussion prior to participating in athletics at the University of Pittsburgh
- the diagnosed concussion was a result of a non-sports-related activity
- the concussed athlete was not able to fully participate in sport for a minimum of 180 days before incurring a subsequent concussion

- the concussed athlete did not return to sport for a minimum of 180 days prior to the completion of their athletic eligibility and subsequent closing of their medical record
- the athletes sustained musculoskeletal injury (during the 180 day observations window) that resulted from a motor vehicle accident (MVA) or an event outside of normal every day activities
- the athlete had any pre-existing, diagnosed condition or disease documented in their medical records that may interfere with central processing. Conditions that would warrant exclusion include, but are not limited to alcoholism, psychological disorders and vertigo.[189]
- any athlete with record of penetrating wounds to head resulting in a TBI
- any athlete with positive imaging results that would indicate structural damage to the brain

3.3 POWER ANALYSIS AND SAMPLE SIZE

To date, few previous studies have examined the relationship between concussion and subsequent lower extremity musculoskeletal injuries. Assuming the probability of musculoskeletal injury in the non-concussed control subjects is 0.15 and the odds ratio (OR) for injury in the concussed subjects is 2.5; a total sample size of 164 subjects was needed. With a 1:1 matched study design of one athlete with history of concussion matched with one athlete with no history of concussion, this sample size included 82 concussed subjects and 82 non-concussed subjects. This sample size, calculated utilizing PS – Power and Sample Size Calculations, Version 3.1.2, permitted the researcher to reject the null hypothesis of an odds ratio equal to 1 with power of 0.80 and a two-sided alpha=0.05.

3.3.1 Medical Record Review

This research involved a review of medical records and therefore was compliant with Health Insurance Portability and Accountability Act (HIPAA) Privacy Rule (46 CFR Part 160; Part 164 (subparts a, e)). As per the University of Pittsburgh Institutional Review Board's (IRB) requirements, a Medical Record Review by Investigator with Patient Care Responsibilities form was completed. Approval of this form allowed the author to review medical records under the supervision of a University of Pittsburgh team physician, an appropriately credentialed UPMC professional. As a recognized team physician at the University of Pittsburgh, the team physician had normal access to athlete medical records, as they were related to his patient care responsibilities. As per requirements, this physician was listed as the Primary Investigator (PI) on the IRB for this study. As part of the IRB approval process, an expedited application with a request for a waiver of consent and a waiver of HIPAA Authorization was completed and approved.

3.4 VARIABLES COLLECTED

A standardized form was developed and was used during medical records review and data collection (Appendix A). Variables collected included: sex, sport, position, calendar years participating, height, weight, presence/absence of concussion, related diagnostic criteria for concussion, date of concussion, date of return-to-play after concussion, validation of return-to-play criteria, musculoskeletal injury presence, date, type, and mechanism of injury (during both 90-day pre-concussion and 180-day return to play, post-concussion windows).

3.4.1 Sex

Subject sex was collected and used in matching 82 non-concussed athletes to each of the 82 concussed athletes. Collecting sex addressed the increased risk of injury that has been associated with female versus male athletes.

3.4.2 Sport and Position

Each concussed athlete's sport and position was collected and used in matching 82 non-concussed athletes to each of the 82 concussed athletes. Collecting sport and position addressed the increased risk of injury associated with certain sports and player positions within that sport (Table 4).

3.4.3 Calendar year

The calendar year in which the concussed athlete was injured was collected and used in matching 82 non-concussed athletes to each of the 82 concussed athletes identified in the experimental group. Collecting calendar year permitted the researcher to match the controls by calendar year. This matching helped control for number of athlete exposures as the concussed and non-concussed matched control had data collection windows at the same time of year.

3.4.4 Height and Weight

Height and weight of the concussed athlete as noted in their preparticipation exam (PPE), for the sports season in which the athlete's concussion was obtained and used to calculate the athlete's BMI. Height and weight of the non-concussed matched control was also recorded during the same time period, and was used to calculate each athlete's BMI. Collecting BMI helped the researcher address the increased risk of injury associated with BMI.

Collecting sex, sport, position, calendar year, height and weight, allowed us to control for the influence that those variables had on our outcome variable (lower extremity musculoskeletal injury).

3.4.5 Dates of Concussion and Return-to-Play (Concussed Group Only)

The dates of the concussive episode and subsequent return-to-play were collected for all concussed subjects. These dates were used when calculating the total time before return-to-play following a concussion, the 90-day pre-concussion observation window, and were used in calculating the 180-day observation window for the concussed subject and their matched controls.

3.4.6 Neuropsychological Testing Scores (Concussed Group Only)

Each University of Pittsburgh athlete completes computerized NP testing during their initial Pre-Participation Exam (PPE). Results of these baseline tests were saved into an electronic database of NP scores and a hard copy of each athlete's individual scores were placed into their medical record. All athletes who sustain a concussive episode while participating in university athletics undergo subsequent computerized NP testing. The results of each athlete's post-concussive NP testing were saved into the electronic database and a hard copy placed into their medical record. The NP testing instrument utilized by the sports medicine team at the University of Pittsburgh is Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT®), Version 2.0.

ImPACT® is a computer-driven NP test battery that takes approximately 25 minutes to administer. All ImPACT® testing was completed as a standard component of each athlete's PPE in order to provide a baseline measurement in the event that the athlete was exposed to a concussive episode during athletic participation. All ImPACT® tests were administered by the athletic trainers employed by the University of Pittsburgh's Department of Athletics. ImPACT® provided the electronic database that houses NP testing records.

ImPACT® attempts to quantify cognitive functioning by utilizing a series of tests that measure: attention span, working memory, response variability, non-verbal problem solving, and reaction time. ImPACT® is composed of six modules. The results of these six modules yield five composite ImPACT® test scores.

For the purpose of this study, the ImPACT® electronic database served as a tool to identify subjects for the concussed group. Baseline and post-concussive ImPACT® scores for each subject was also collected as it is one variable utilized in the return-to-play criteria.

3.4.7 Return-to-Play Criteria (Concussed Group Only)

All criteria used in determining that the athlete could return-to-play was collected. Return-to-play criteria included acknowledgement of all the following: 1) the athlete being symptom-free at rest and exertion, 2) return to baseline or acceptable range in NP testing (and all corresponding scores), and 3) written verification from a health care provider that the athlete is cleared to return to full participation (discharge from care).

3.4.8 Musculoskeletal Injury (Concussed and Non-Concussed Groups)

For the purpose of this research, lower extremity musculoskeletal injury was defined as a newly incurred musculoskeletal injury (traumatic or overuse) to any of the anatomical structures distal to and including the hip joint. Musculoskeletal anatomical structures comprise both soft and hard tissues including: epithelial tissues, connective tissues (tendons, ligaments, cartilage, fat, blood vessels, fascia), muscle, nerves and bone.[190] Furthermore, injury was defined as any event that necessitated medical attention by an athletic trainer and/or physician.[191] Athletes who had sustained a previous musculoskeletal injury (“re-injuries”) were included if the athlete had returned to full participation at the time of the re-injury.[192]

Acquisition of all musculoskeletal injuries were collected, but only those injuries classified as the following were analyzed: ligament sprains/ruptures/tears, muscle strains/tears, as well as noncontact fractures, stress reactions, subluxations and dislocations.

Concussed athletes were followed in their medical records for 90 days before their concussion date and 180 days after their return-to-play date. If a musculoskeletal injury occurred during the 90-day time period prior to the athletes’ diagnosed concussion or during the first 180 days after their return-to-play following the concussion, the presence, type, and date of that musculoskeletal injury was documented. Time-to-event (TTE) was calculated for each subject that sustained a lower extremity musculoskeletal injury during that time period.

Non-concussed athletes were be followed for the identical 90 and 180-day time periods as their matched concussed athlete. If a musculoskeletal injury occurred during either of the 90-day pre-concussion or the 180-day post-concussion periods for the non-concussed group, the presence, type, and date of that musculoskeletal injury was documented. Information pertaining to any documented musculoskeletal injury, in either the concussed or non-concussed athletes, during the testing windows, was collected.

3.4.9 History of Lower Extremity Injury (Concussed and Non-Concussed Groups)

History of lower extremity musculoskeletal injury for 90 days pre-concussion and 180 days following return-to-play after a sustaining a concussion was collected for all concussed athletes and their matched and non-concussed athletes. This data allowed us determine history of lower extremity musculoskeletal in the subject pool, prior to and following a sports-related concussion.

3.5 DATA REDUCTION

The length of time that was needed post-concussion to meet the return-to-play criteria and ultimately return to full participation was calculated by analyzing the concussion injury date and return-to-play dates in each of the concussed subjects. BMI was calculated by using the height and weight of each concussed athlete (and their matched non-concussed athlete) as recorded in their PPE during the season in which their concussion has taken place.

3.6 DATA ANALYSIS

Statistical analyses were run using STATA, 13 (StataCorp LP, College Station, TX) and SPSS – Statistics, 23 (IBM Corporation, Armonk, NY). Descriptive statistics (mean, standard deviation, median, interquartile range for continuous variables, proportion for categorical variables) was calculated and reported for all variables. Data was assessed for normality. Conditional logistic regression was conducted for Aim 1 to investigate the association between the history of concussion and the risk of sustaining a lower extremity musculoskeletal injury, after adjusting for sex, sport, position, BMI, and calendar year in which the concussion occurred. Mann Whitney U tests were conducted for Aims 2 and 4 to investigate the association between the time it takes to recover from a concussion and future lower extremity musculoskeletal injury as well as the role that may sex have on concussion recovery time. A Fisher's Exact test was conducted for Aim 3 to assess the association between concussed athletes of a specific sex and incidence of lower extremity musculoskeletal injury. Statistical significance levels of 0.05 (two-sided), were established *a prioi.*

4.0 RESULTS

The purpose of this study was to establish if a relationship exists between sport-related concussion and subsequent occurrence of lower extremity musculoskeletal injury in Division 1, collegiate athletes. Data used in this study were compiled via medical chart review of athletes from the University of Pittsburgh who participated during the 2007/2008 to 2016/2017 athletic seasons.

4.1 SUBJECTS

A total of 574 potential concussed athletes were screened for inclusion in this study. Eighty-two of the most recently concussed athletes, from the years 2007 – 2016, who met the inclusion criteria, were selected (58 males, 24 females). Concussed athletes were excluded from the study if: the subject sustained a second concussion within the 180 days after returning to play, RTP documentation following the concussion was absent from the subject's medical file, the concussion mechanism was not related to sport participation, the athlete's medical records did not extend 90 days pre-concussion or 180 days after RTP post-concussion, or the medical record revealed documentation of a pre-existing medical condition that may interfere with central processing.

A roster of potential control athletes without any recorded history of concussion were selected for each concussed subject, matched on sex, sport, primary position, calendar year participating and Body Mass Index (BMI). One matched control athlete was randomly selected for each concussed athlete. A flowchart outlining athlete selection is presented in Figure 4.

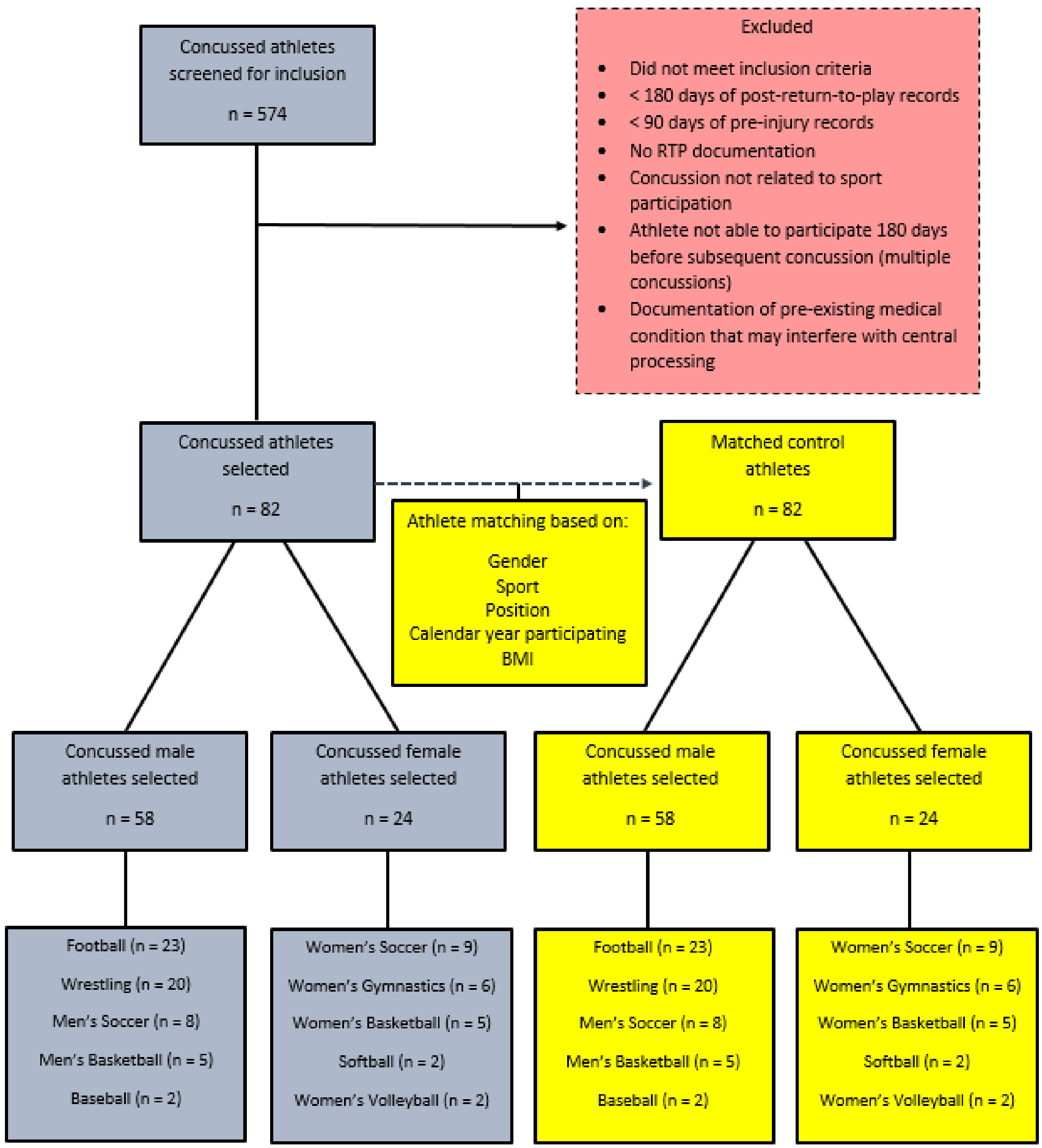

Figure 4. Athlete Selection Flowchart

All subjects were selected from the cohort of athletes who participated as a member of one of the following NCAA, Division 1 - recognized teams: football, men's basketball, women's basketball, men's soccer, women's soccer, baseball, softball, women's volleyball, women's gymnastics and wrestling. Athlete characteristics are displayed in Table 6.

Table 6. Athlete Characteristics

		Concussed Athletes					Non-Concussed Athletes				
		N	**Mean**	**SD**	**Median**	**IQR**	**N**	**Mean**	**SD**	**Median**	**IQR**
Age (years)	**All**	82	19.4	1.2	19.0	18.0 - 20.0	82	19.7	1.3	19.5	19.0 - 21.0
	Male	58	19.6	1.2	19.0	19.0 - 20.3	58	19.8	1.3	20.0	19.0 - 21.0
	Female	24	19.1	1.1	19.0	18.0 - 20.0	24	19.5	1.1	19.0	19.0 - 20.8
Height (cm)	**All**	82	177.4	10.9	177.8	169.4 - 185.4	82	178.5	10.2	177.8	172.7 - 188.0
	Male	58	181.9	9.0	182.9	174.6 - 188.0	58	182.2	9.3	182.9	175.3 - 188.0
	Female	24	166.4	6.4	166.4	161.6 - 170.2	24	169.6	5.7	170.8	165.7 - 172.7
Weight (kg)	**All**	82	82.8	21.0	79.4	66.8 - 95.3	82	84.4	20.5	79.4	67.6 - 96.8
	Male	58	91.0	19.3	88.5	77.3 - 101.4	58	92.1	19.4	89.8	77.1 - 101.0
	Female	24	62.9	7.1	61.9	56.9 - 66.7	24	65.8	5.7	64.9	61.8 - 68.2
BMI	**All**	82	26.0	4.6	24.8	23.1 - 27.4	82	26.2	4.5	25.0	23.5 - 28.3
	Male	58	27.4	4.7	26.3	24.4 - 29.4	58	27.6	4.6	26.2	24.7 - 29.7
	Female	24	22.7	1.8	22.6	21.01 - 24.3	24	22.9	1.6	22.9	21.8 - 24.2

N = number of subjects, SD = standard deviation, IQR = interquartile range, cm = centimeters, kg = kilograms

Distribution of males and females throughout the sample was 71% and 29% respectively. Although not a planned outcome, the distribution of males and females in this study's sample directly correlated with the average distribution of males and females from the University of Pittsburgh that were rostered during the 2007/2008 – 2016/2017 athletic seasons (69% and 31% respectively). Football athletes contributed the largest portion of athletes to this study (n = 46, 28%) followed by wrestling (n = 20, 24%). Relative frequency of athlete selection by sport is illustrated in Figure 5. Distribution of athletes across sport and position are described in Table 7.

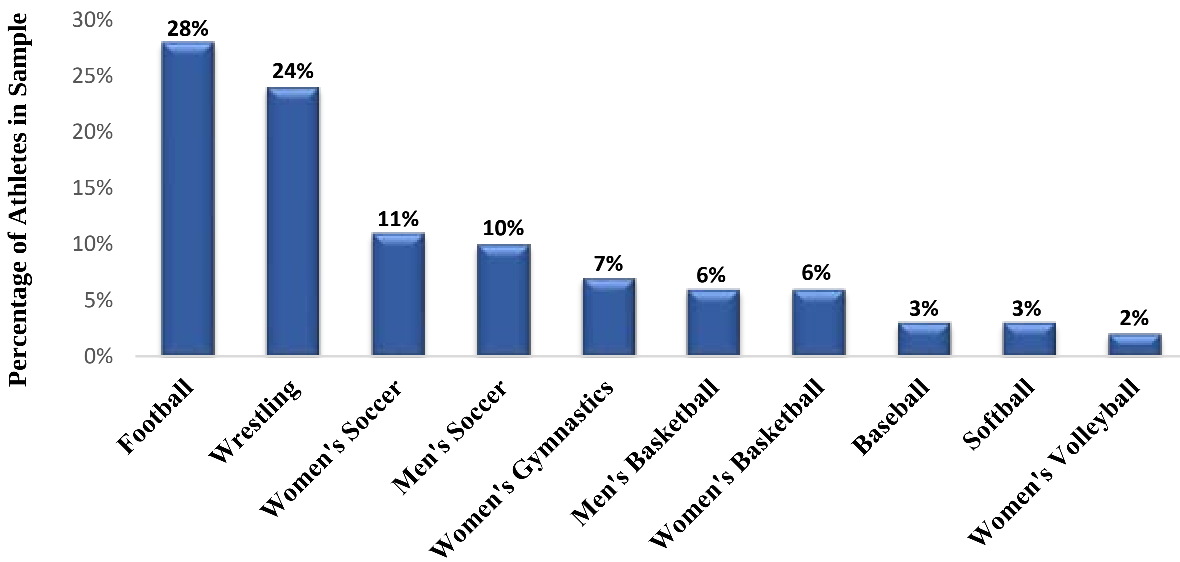

Figure 5. Relative Frequency Distribution of Athletes by Sport

Table 7. Concussed Athletes by Sport and Position

Sport	Position	Exposed (Concussed) Cases Men (N = 58)	Women (N = 24)
Football	Quarterbacks	2	
	Running Back, Full Back, Line Backer	9	
	Tight End, Wide Receivers, Defensive Backs	8	
	Offensive Lineman, Defensive Lineman	4	
Wrestling †	133 - 157 lbs	8	
	165 - 197 lbs	9	
	Heavyweight	3	
Baseball	Infielders	1	
	Outfielders	-	
	Pitchers	1	
Softball	Infielders		1
	Outfielders		1
	Pitchers		-
Soccer	Forwards, Midfielders	5	2
	Defenders	1	5
	Goalkeepers	2	2
Basketball	Forwards, Guards	5	5
Volleyball	Hitters		1
	Defensive Specialists		1
Gymnastics	All Around		2
	Vault, Floor, Balance Beam		4

† *cases were matched with individual weight class*

4.2 LOWER EXTREMITY MUSCULOSKELETAL INJURY

History of lower extremity musculoskeletal injury for 90 days pre-concussion and 180 days following return-to-play (RTP) after a sustaining a concussion were collected for all concussed athletes and their matched controls. Any injury to the lower extremity during the 90-day pre-concussion period was calculated as the athlete having a history of lower extremity musculoskeletal injury. Only the first lower extremity musculoskeletal injury in the 180-day post-RTP window was included when analyzing for the outcome. Lower extremity musculoskeletal injury was defined as a newly incurred musculoskeletal injury (traumatic or overuse) to any of the anatomical structures distal to and including the hip joint, that required medical attention and resulted in restriction or limitation in athletic participation. During the 180-day, post-RTP window, the knee and ankle were the two most commonly injured body parts across both the concussed and non-concussed athletes. Specifically, injuries to the knee comprised 35.3% of all lower extremity injuries in the concussed group and 33.3% of all lower extremity injuries in the non-concussed group; while injuries to the ankle comprised 31.4% of all lower extremity injuries in the concussed group and 33.3% of all lower extremity injuries in the non-concussed group. Lateral ankle sprains were the most common specific injury across both the concussed and non-concussed groups, comprising 25.5% and 33.3% of all lower extremity injuries respectively. A description of lower extremity musculoskeletal injuries by anatomical region and type for both the concussed and non-concussed athletes are listed in Table 8. Distribution of lower extremity musculoskeletal injuries by anatomical region and group during the 180-day post-RTP window are illustrated in Figure 6.

Table 8. Number of Athletes Who Sustained a Lower Extremity Musculoskeletal Injury and Type of Injury by Anatomical Region, during the 180-Day Period after RTP

Anatomical Region	Type	Concussed (N = 51)	Non-Concussed (N = 21)
Foot	midfoot sprain	2 (3.9%)	1 (4.8%)
	stress reaction	4 (7.8%)	0
Ankle	lateral sprain	13 (25.5%)	7 (33.2%)
	medial sprain	2 (3.9%)	0
	high sprain	1 (2.0%)	0
Shin/Calf	calf strain	1 (2.0%)	0
	tibial stress reaction	1 (2.0%)	0
	peroneal strain	0	1 (4.8%)
Knee	ACL sprain	5 (9.8%)	0
	PCL sprain	1 (2.0%)	0
	MCL sprain	5 (9.8%)	2 (9.5%)
	LCL sprain	3 (5.8%)	1 (4.8%)
	meniscal tear	1 (2.0%)	1 (4.8%)
	popliteus strain	1 (2.0%)	0
	patellar subluxation/dislocation	2 (3.9%)	1 (4.8%)
	hyperextension	0	2 (9.5%)
Thigh	quadriceps strain	1 (2.0%)	1 (4.8%)
	hamstrings strain	5 (9.8%)	2 (9.5%)
Hip	adductor strain	3 (5.8%)	2 (9.5%)
	Total:	100%	100%

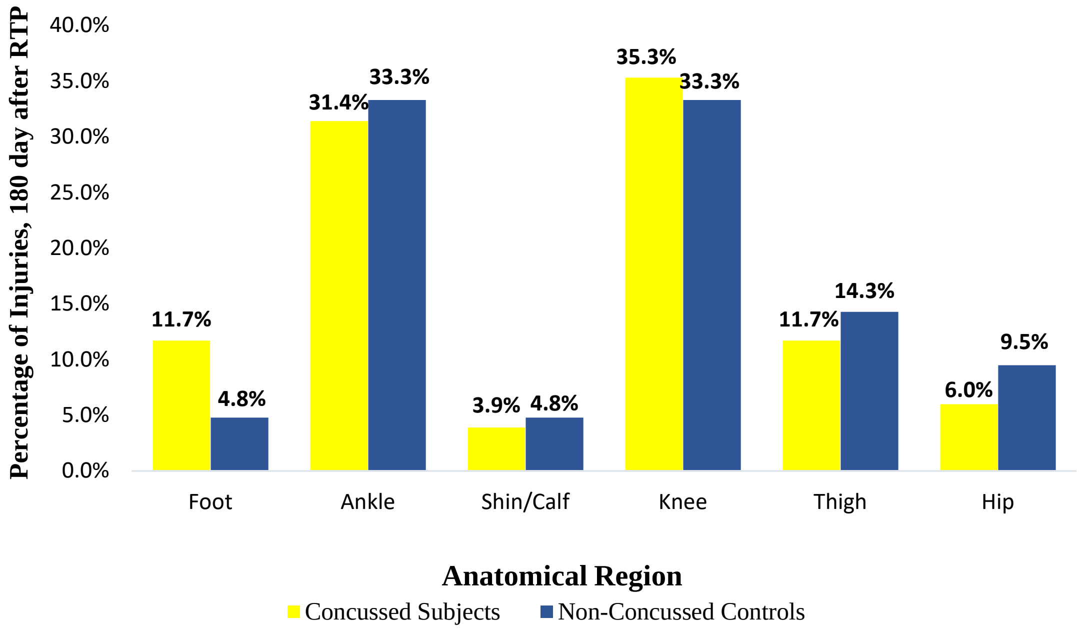

Figure 6. Distribution of Lower Extremity Musculoskeletal Injuries by Anatomical Region and Athlete Group, During the 180-Day Period after RTP

Fifty-one out of eighty-two (62%) concussed athletes in our study sustained a lower extremity musculoskeletal injury during the 180-day period after RTP. The average time it took a concussed athlete to sustain a lower extremity musculoskeletal injury was 74 days (Median = 67) and ranged from 2 – 180 days. The majority of the concussed athletes (61%) sustained their lower extremity musculoskeletal injury within the first 12 weeks of the 180-day period after RTP. The frequency and time it took a concussed athlete to sustain a lower extremity musculoskeletal injury after the athlete returned to play following a concussion across all sports is displayed in Figure 7.

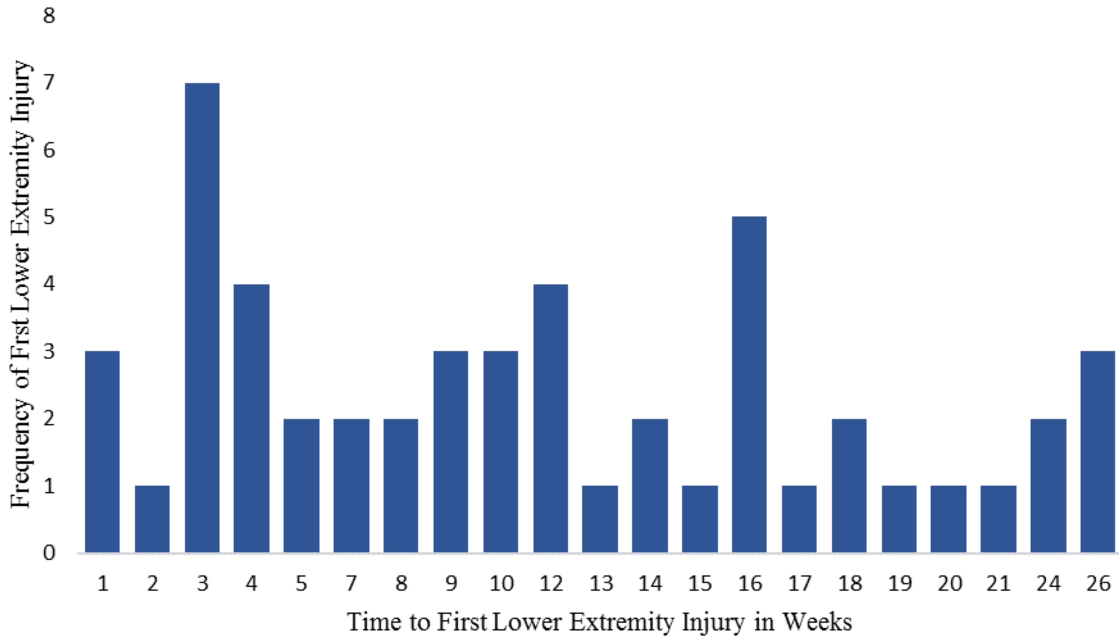

Figure 7. Frequency and Time to Lower Extremity Musculoskeletal Injury after Concussion in Concussed Athletes, During the 180-Day Period After RTP

4.2.1 Association between Concussion and Lower Extremity Musculoskeletal Injury

The first specific aim of this study was to investigate the relationship between sport-related concussion and subsequent lower extremity musculoskeletal injury in college-aged athletes. Conditional logistic regression was used to investigate this relationship while accounting for history of lower extremity injury.

The frequency of lower extremity musculoskeletal injury during the 180-day observation window following RTP was greater in concussed athletes (62.2%) when compared with matched controls (25.6%), (Table 9).

Table 9. Incidence of Injury in Concussed and Non-Concussed Athletes, during the 180-Day Period after RTP

	Lower Extremity Musculoskeletal Injury		
Concussion	Yes	No	Total
Yes	51 (62.2%)	31 (37.8%)	82
No	21 (25.6%)	61 (74.4%)	82
Total	72	92	164

Conditional logistic regression was used to investigate the association between history of concussion and the risk of sustaining a lower extremity musculoskeletal injury, during the 180-day period after RTP, accounting for history of lower extremity injury. The conditional logistic regression model included history of concussion and history of lower extremity musculoskeletal injury as predictors (Table 10). There was a significant prediction of future lower extremity musculoskeletal injury by history of concussion and history of lower extremity musculoskeletal injury, $\chi 2$ (2, N = 80) = 26.96, $p < 0.001$. The likelihood of future injury increased by 637% for concussed athletes as compared to non-concussed athletes, $\beta = 2.00$, $p < 0.001$. There was no effect of history of lower extremity musculoskeletal injury on future lower extremity musculoskeletal injury. The odds for an athlete with a history of concussion, sustaining a lower extremity musculoskeletal injury after returning to play following a concussion, is 7.37 times greater in that same time period, as compared to an athlete with no history of concussion after adjusting for history of lower extremity musculoskeletal injury.

Table 10. Conditional Logistic Regression, Including History of Concussion and History of Lower Extremity Musculoskeletal Injury as Predictors of the Risk of Lower Extremity Musculoskeletal Injury, During the 180-Day Period after RTP

	Coef.	SE	z	P>z	[95% CI]
History of Concussion	2.00	0.51	3.92	0.000	1.00 - 3.00
History of LE Injury	1.23	0.98	1.25	0.211	0.70 - 3.16

Coef. = Beta coefficient, SE = standard error, z=z statistic, CI = confidence interval

	OR	SE	z	P>z	[95% CI]
History of Concussion	7.37	3.76	3.92	0.000	2.71 - 20.02
History of LE Injury	3.42	3.36	1.25	0.211	0.50 - 23.48

OR = odds ratio, SE = standard error, z = z statistic, CI = confidence interval

The second conditional logistic regression model included only history of concussion as the predictor (Table 11). There was a significant prediction of future lower extremity musculoskeletal injury by history of concussion, $\chi 2$ (1, N = 80) = 25.31, $p < 0.001$. The likelihood of future injury increased by 600% for athletes with history of concussion as compared to athletes with no history of concussion, $\beta = 1.95$, $p < 0.001$. The odds for an athlete with history of concussion sustaining a lower extremity musculoskeletal injury after returning to play following a concussion is 7 times greater, in that same time period, than an athlete with no history of concussion.

Table 11. Conditional Logistic Regression, Including History of Concussion as a Predictor of the Risk of Lower Extremity Musculoskeletal Injury, During the 180-Day Period after RTP

	Coef.	SE	z	P>z	[95% CI]
History of Concussion	1.95	0.48	4.07	0.000	1.00 - 2.88

Coef. = Beta coefficient, SE = standard error, z=z statistic, CI = confidence interval

	OR	SE	z	P>z	[95% CI]
History of Concussion	7.00	3.35	4.07	0.000	2.74 – 17.87

OR = odds ratio, SE = standard error, z = z statistic, CI = confidence interval

4.2.2 Recovery Time from a Concussion and Lower Extremity Musculoskeletal Injury

The second specific aim of this study was to establish if a relationship existed between length of recovery time needed before RTP following a concussion and subsequent lower extremity musculoskeletal injury in college-aged athletes. Descriptive statistics for number of days recorded between concussion and RTP by outcome, sex and sport are displayed in Table 12.

Table 12. Number of Days between Concussion and RTP by Outcome, Sex and Sport

	N	Mean	SD	Median	Range	IQR
All concussed athletes	82	18	27.9	10	1 - 166	7 - 17
Concussed athletes with No LE Injury	31	19	25	11	1 - 127	7 - 18
Concussed athletes with LE Injury	51	18	29.7	9	3 - 166	6 - 17
Male	58	18	32	9	2 - 166	6 - 15
Female	24	17	16	15	1 - 76	7 - 20
Football	23	11	8.4	8	3 - 34	5 - 13
Wrestling	20	23	39.4	10	2 - 147	6 - 18
Men's Soccer	8	34	54.5	11	9 - 166	9 - 34
Women's Soccer	9	23	22.8	17	6 - 76	9 - 32
Gymnastics	6	14	7.5	15	1 - 22	9 - 21
Women's Basketball	5	14	13.1	7	4 - 36	6 - 27
Men's Basketball	5	7	1.3	7	5 - 8	6 - 8
Baseball	2	24	25.5	24	6 - 42	6
Softball	2	18	0.7	18	17 - 18	17
Volleyball	2	6	3.5	6	3 - 8	3

N = number of subjects, SD = standard deviation, IQR = interquartile range

The average time it took an athlete to return to play following a concussion across all groups was 18 days (Median: 10 days; IQR: [7 – 17 days]). The sport with the longest RTP time following a concussion was Men's Soccer (Mean, 34 days; Median, 11 days; IQR, [9 – 34 days]) while the sport with the shortest RTP following a concussion was Women's Volleyball (Mean, 6 days; Median 6 days).

A Mann-Whitney U test was conducted, following testing for normality, to compare the number of days it took an athlete to recover from a sports-related concussion and return to sport, between concussed athletes who sustained a subsequent lower extremity musculoskeletal injury and those concussed athletes who did not sustain a subsequent lower extremity musculoskeletal injury. Results of the Mann-Whitney U test indicated that the number of days it took for athletes to return to sport after a sport-related concussion was not statistically different in concussed athletes who sustained a subsequent lower extremity musculoskeletal injury (Median = 9) and those concussed athletes who did not sustain a subsequent lower extremity musculoskeletal injury (Median = 11), U = 718.0, p = .491.

Current evidence indicates that many of the signs and symptoms associated with sport-related concussions are transitory and that eighty to ninety percent are reported to resolve within 7 - 10 days; with most athletes typically returning-to-play within that same time period.[6,44,45] Using the data from our study, a Fisher's Exact test was used to investigate the influence that the typical 7-10 day RTP time periods may have on incidence of lower extremity musculoskeletal injury. Occurrence of lower extremity musculoskeletal injury in both RTP comparison timeframes are listed in Tables 13 and 14.

Table 13. Occurrence of Lower Extremity Musculoskeletal Injury in Concussed Athletes with RTP ≤ 7 Days vs those that Took Longer to RTP

	Lower Extremity Musculoskeletal Injury		
RTP time	Yes	No	Total
≤ 7 days	18 (69%)	8 (31%)	26
≥ 8 days	33 (59%)	23 (41%)	56
Total	31	51	82

The frequency of lower extremity musculoskeletal injury in concussed athletes who took 7 or less days to RTP following their concussion was greater (69%) when compared with concussed athletes who took 8 or more days to RTP (59%).

Table 14. Occurrence of Lower Extremity Musculoskeletal Injury in Concussed Athletes with RTP ≤ 10 Days vs those that Took Longer to RTP

	Lower Extremity Musculoskeletal Injury		
RTP time	Yes	No	Total
≤ 10 days	31 (67%)	15 (33%)	46
≥ 11 days	20 (56%)	16 (44%)	36
Total	31	51	

The frequency of lower extremity musculoskeletal injury in concussed athletes who took 10 or less days to RTP following their concussion was greater (67%) when compared with concussed athletes who took 8 or more days to RTP (56%).

The tests revealed no statistical difference between athletes and their incidence of LE musculoskeletal injury after they RTP following a concussion when comparing RTP timeframes of: ≤ 7 days and > 7 days, $p = .359$ and ≤ 10 days and > 10 days, $p = .466$.

4.2.3 Effect of Sex on Lower Extremity Musculoskeletal Injury after a Concussion

The third specific aim of this study was to establish if a relationship existed between concussed athletes of a specific sex and the incidence of subsequent lower extremity musculoskeletal injury. Among concussed athletes, a greater percentage of females sustained a lower extremity musculoskeletal injury as compared to males during the 180-day observation window following RTP.

A Fisher's Exact test was used to investigate the association between sex and incidence of lower extremity musculoskeletal injury. Occurrence of lower extremity musculoskeletal injury by sex are found in Table 15 and displayed graphically in Figure 8.

Table 15. Occurrence of Lower Extremity Musculoskeletal Injury in Concussed Athletes by Sex

	Lower Extremity Musculoskeletal Injury		
Sex	Yes	No	Total
Male	33 (57%)	25 (43%)	58
Female	18 (75%)	6 (25%)	24
Total	31	51	82

The frequency of lower extremity musculoskeletal injury in female concussed athletes was greater (75%) when compared with male concussed athletes in the 180-day period after RTP following a concussion (57%).

The test revealed no statistical difference between male and female athletes and their incidence of LE musculoskeletal injury after they RTP following a concussion, $p = .142$.

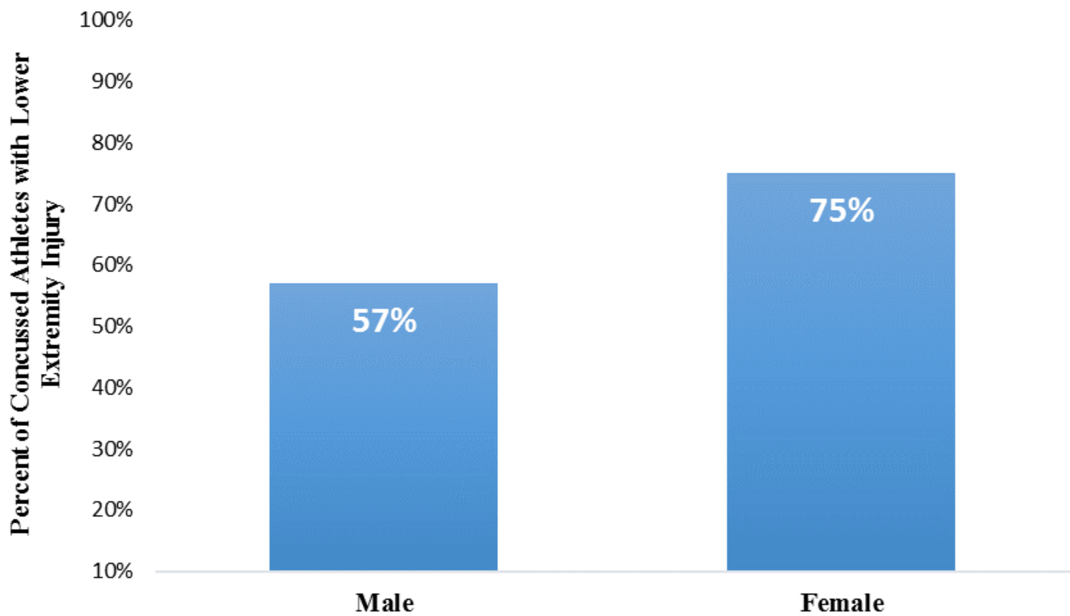

Figure 8. Incidence of Lower Extremity Musculoskeletal Injury in Concussed Athletes by Sex, During the 180-Day Period after RTP

4.2.4 Influence of Sex on Recovery Time after Concussion

The fourth specific aim of this study was to establish if a relationship existed between sex and recovery time after a sport-related concussion in college-aged athletes. Descriptive statistics for number of days recorded between concussion and RTP by sex are displayed in Table 12. The recovery time needed (weeks) from concussion to RTP between males and females is shown in Figure 9.

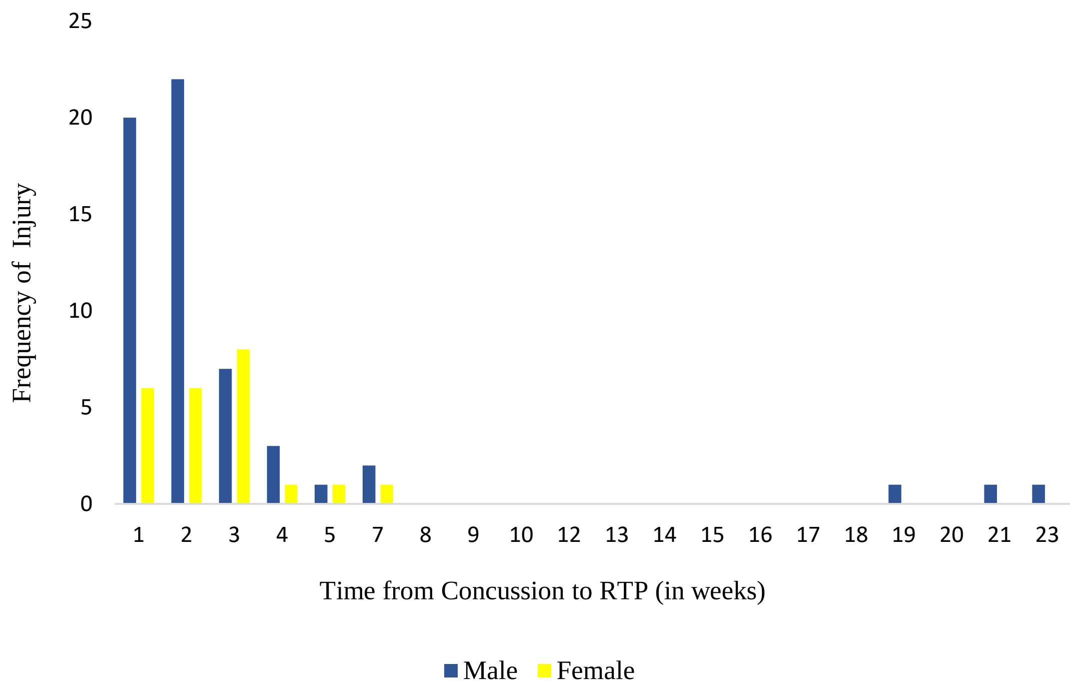

Figure 9. Number of Weeks between Concussion and RTP for Concussed Athletes by Sex

The average time it took a female athlete to return to play following a concussion was slightly less, 17 days (Median: 15 days; IQR: [7 – 20 days]), as compared with male athletes, 18 days (Median: 9 days; IQR: [6 -15 days]). There were multiple outliers in the data that contributed the skewness of the distribution. Specifically, there were three male athletes that took substantially longer to RTP following their concussion than the rest of the athletes (127 days, 147 days, 166 days). In comparison, the longest period prior to RTP following a concussion for the female group was 76 days.

A Mann-Whitney U test indicated that the number of days it took an athlete to recover from a sports-related concussion and return to sport was not statistically different in female collegiate athletes (Median = 14.5) than male collegiate athletes (Median = 9.0), U = 559.0, p = .164.

5.0 DISCUSSION

The main purpose of this research was to establish if a relationship existed between sport-related concussion and subsequent lower extremity musculoskeletal injury in collegiate athletes. This research also aimed to investigate if there was a relationship between the length of recovery time needed by an athlete following a sport-related concussion and subsequent risk of lower extremity musculoskeletal injury as well as the contribution that sex may have on injury risk and recovery time following a sport-related concussion. In order to investigate these aims, a retrospective matched-cohort study design utilizing a review of medical records was conducted. The results of this study revealed that concussed athletes were at increased risk of future lower extremity musculoskeletal injury after RTP following a concussion. The odds for an athlete with history of concussion, sustaining a lowering extremity musculoskeletal injury after RTP following a concussion is 7.37 greater than an athlete with no history of concussion, in that same time period, after adjusting for history of lower extremity musculoskeletal injury. The number of days it took for athletes to RTP after a sport-related concussion was not statistically different in athletes who sustained a subsequent lower extremity musculoskeletal injury and those who did not. The role that sex may have on RTP time following a concussion and risk of lower extremity musculoskeletal injury was not clearly defined by this study. Although not statistically significant, female athletes did demonstrate longer concussion recovery times and a greater incidence of lower extremity musculoskeletal injury following a concussion.

Regardless of age, sporting activity, or competition level, injuries to the lower extremity occur frequently when participating in sports.[34] In an attempt to decrease injury rates, sports medicine researchers have aimed to identify risk factors for lower extremity musculoskeletal injury. In spite of research and efforts to implement injury prevention programs, lower extremity musculoskeletal injuries persist as a significant and common injury in sports.[106]

Over the last 10 years, an upsurge in reported sport-related concussions have been seen across all levels of athletic participation.[1-4] Recently, researchers have begun to investigate the possible influence that concussion may have on the incidence of lower extremity musculoskeletal injury.[17-20,193]

5.1 SUBJECT SELECTION AND MATCHING

A 1:1 matched study design was completed for this study. Matching one athlete with a history of concussion with one athlete with no history of concussion based on sex, sport, position, calendar year, and BMI all aided in controlling covariates and ultimately contributed to the internal validity and efficiency of this study.[188,194] Tightly matching on these variables, which have been identified as risk factors for lower extremity injury, allowed us to assume comparability in our matched pairs so that concussion as a risk factor for subsequent injury could be studied while controlling for the influence of sex, sport, position, exposure, and BMI may have on lower extremity injury.[194]

A 1:1 match was completed for this study due to limitations seen in previous research that attempted to use 1:2 and 1:3 subject matching.[17,20] It is acknowledged that a higher matching scheme (i.e., 1:2 or 1:3) may have increased the power of the study; however, this study's subject pool would not have supported a subject matching protocol of this magnitude.[194,195] Six out of the ten sports included in our study rostered 25 athletes or less per year. A smaller number of rostered players available for subject selection, coupled with the number of variables used in our matching protocol, limited potential matches; therefore demonstrating the practical problem seen with matching on multiple variables.[194] Previous research that studied the relationship between concussion and lower extremity injury in collegiate athletes have attempted 1:2 and 1:3 subject matching with varying success.[17,19,20] In 2015, Lynall et al.[17] attempted a 1:2 subject match, using data collected over a three year period of time from a cohort of NCAA, Division 1 athletes. Lynall's study attempted to match each athlete with a history of concussion with two athletes with no history of concussion, based on sex, sport, competition playing time, age, height and weight. Lynall's study noted the difficulty presented in matching with multiple variables and reported identifying 58 control subjects for the 44 concussed subjects, therefore resulting in mixed 1:1 – 1:2 matching range for the study.[17] In 2016, using a similar cohort of Division 1 athletes, Brooks et al.[20] attempted to match one athlete with history of concussion with up to three athletes with no history of concussion based on sex, sport, game exposure and position. Brooks was able to complete 1:3 matching on 35% of the concussed athletes, while the remaining concussed athletes were matched with non-concussed athletes at 1:2 (40%) and 1:1 (25%) ratios.[20] Similarly in 2016, Herman et al.[19] attempted a 1:2 subject match, using data collected over a seven year period of time from a cohort of NCAA, Division 1 athletes. Herman's study, which matched subjects based on sport, starting status, and main position played, resulted in 64% of concussed subjects being matched with two non-concussed athletes and the remaining 36% of concussed subjects matched at a 1:1 ratio.[19] Each study's ability to successfully match subjects with more than one control could be attributed to the number of variables used in the subject matching protocol and the number of available non-concussed subjects who fit the inclusion criteria for each study.

The distribution of males and females in this study's sample (71% and 29% respectively) directly correlated with the average distribution of males and females from the athletes rostered at the University of Pittsburgh during the 2007/2008 – 2016/2017 athletic seasons (69% and 31% respectively). The contributions of athletes with history of concussion to the sample are a product of both the number of rostered athletes as well as inherent risk of concussion within the sport. Football and wrestling contributed the highest percentage of athletes with history of concussion (28% and 24% respectively). As illustrated by Figure 5., although there are some disparities between number of rostered athletes and number of subjects in this study, baseball rostered 11% of all athletes during the 2007/2008 – 2016/2017 athletic seasons while contributing only 2% of all subjects to our study and wrestling rostered 10% of all athletes during the 2007/2008 – 2016/2017 athletic seasons and contributed 24% of the subjects to our study, this phenomenon may be explained by the inherent risk of concussion in those sports.

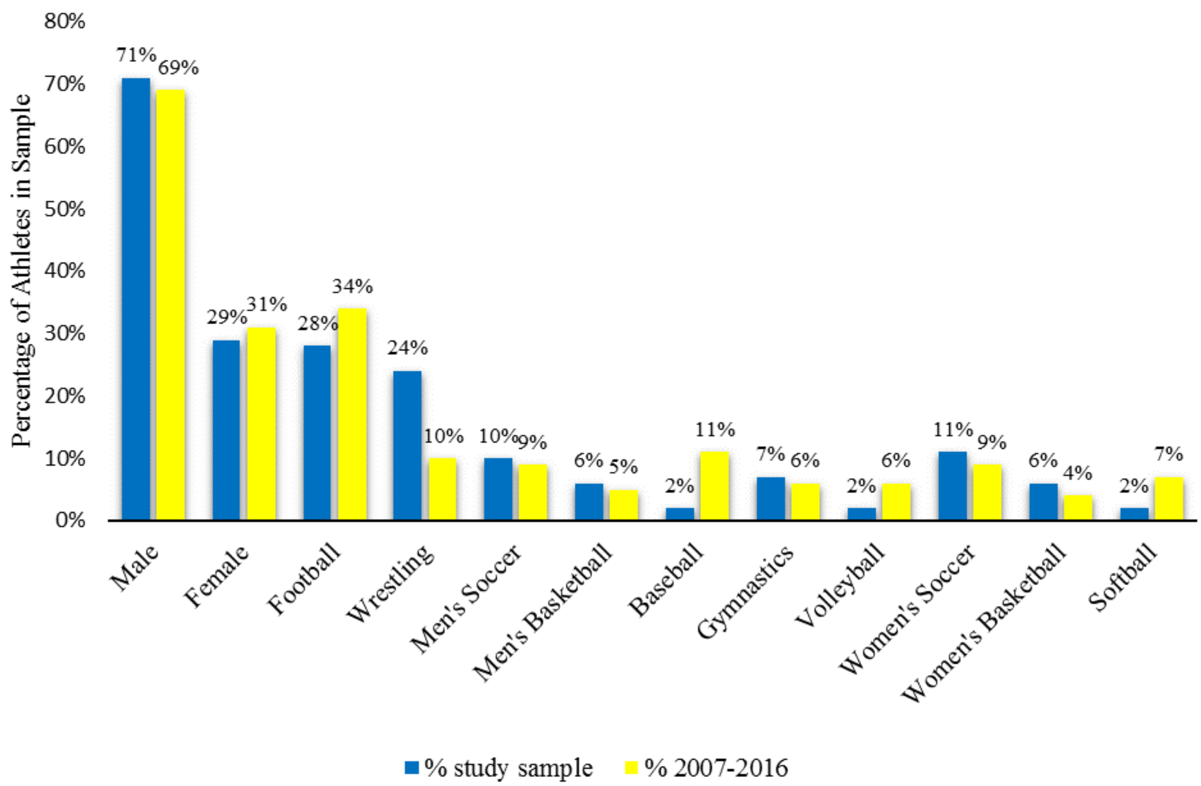

Figure 10. Relative Frequency Distribution of Sex and Sport in Current Study Compared with Roster Athletes at the University of Pittsburgh from 2007 - 2016

5.2 LOWER EXTREMITY MUSCULOSKELETAL INJURY

History, type and anatomical location of all lower extremity musculoskeletal injuries were collected for concussed athletes and their matched control athletes. History of lower extremity musculoskeletal injury was accomplished by recording any lower extremity musculoskeletal injury that occurred during the 90 days preceding the concussion. Previous studies investigating the relationship between concussion and subsequent lower extremity injury in collegiate and professional athletes incorporated pre and post-concussion data collection windows of up to one year[17,18] while others included shorter 90 day post-concussion data collection windows and collected no pre-concussion injury data.[19,20] The data collection windows for this study were chosen after reviewing the recommendations of previous research and considering the subject pools available for this study. In 2015, Lynall and colleagues[17] collected injury data in collegiate athletes for 365 days post-RTP after a concussion and analyzed this data at three different time intervals: 90 days, 180 days and 365 days. Lynall reported a significant difference in lower extremity injury when comparing concussed and non-concussed athletes in the 180-day and 365-day window post-concussion, but not in 90-day window.[17] The results of Lynall's study made a strong argument for 180-day data collection window; however, a data collection window in excess of 180 days would have resulted in extreme subject attrition in our current subject pool. For this present study, selecting a pre-concussion window of longer than 90 days would eliminate many of the freshman athletes from subject rosters and selecting a post-concussion window of greater than 180 days would eliminate the senior athletes. Given the limited number of athletes with a concussion in our subject pool after satisfying the inclusion and exclusion criteria, the elimination of freshman and senior athletes would have rendered the sample size too small to sufficiently power our study.

In this current study, data on all lower extremity musculoskeletal injuries were collected; however, only injuries that were classified as ligament sprains/strains/ruptures/tears, muscle strains/tears, non-contact fractures/subluxations/dislocations were analyzed. Injuries classified as contusions, lacerations, abrasions, or infections, injuries which could not reasonably be correlated with the exposure, were not analyzed. Medical records used for this study did not consistently contain information concerning mechanism of injury and therefore categorizing injuries as traumatic or overuse was not always possible. Preceding studies that aimed to investigate concussion's role in lower extremity musculoskeletal injuries differed slightly on the type of injuries included in the data analysis. Some studies excluded fractures,[19,20] while others contained all acute injuries to the lower extremity, including contusions, in their analyses.[17,18] Determination of types of injuries included in this study were based on the researcher's clinical expertise and identified limitations in previous research.

Injuries to the knee and ankle made up the majority of lower extremity musculoskeletal injuries in both the concussed athletes and non-concussed athletes in our study (66.7% and 66.6% respectively).[34,196] In addition, lateral ankle sprains were the most common specific lower extremity musculoskeletal injury reported in this study, with 25.5% of all lower extremity injuries in the concussed athletes and 33.3% of all lower extremity injuries in the matched control athletes falling into this category. These results were consistent with previously published research in this area. In Hootman's 2007 epidemiological review of 15 collegiate NCAA sports, it was reported that over 50% of all injuries were to the lower extremity with knee and ankle accounting for the largest percentage of injuries in this group.[34] In 2007, Fong et al.[196] reviewed 227 epidemiological studies on injury patterns, from 38 different countries, across 70 sports, at varying levels of competition, age ranges, and abilities. Fong reported that 64% of all sports analyzed throughout these studies listed injury to the lower extremity as the most commonly injured body region while with the most commonly injured body part across all sports was the ankle (34%) followed by the knee (20%). [196]

5.2.1 Association between concussion and lower extremity musculoskeletal injury

The first aim of this study was to determine if a relationship existed between sport-related concussion and lower extremity musculoskeletal injury. It was hypothesized that athletes, who returned to play after being cleared by a health care provider, would have a greater risk of incurring a subsequent lower extremity musculoskeletal injury as compared to non-concussed athletes, matched on sex, sport, position, calendar year, and BMI.

Results of this investigation found a significant relationship between sport-related concussion and subsequent risk of lower extremity musculoskeletal injury in University of Pittsburgh, Division I athletes during the 2007/2008 – 2016/2017 athletic seasons. Sixty-two percent of concussed athletes selected for this study sustained a lower extremity musculoskeletal injury within 180 days after RTP following their concussion as compared to 26% of matched control athletes during that same time period. These results indicate a 637% increase in future lower extremity injury for concussed athletes as compared to non-concussed athletes, after adjusting for previous history of lower extremity injury giving a concussed athlete and a 600% increase when not adjusting for previous lower extremity musculoskeletal injury. History of lower extremity injury has been extensively studied as risk factor for future lower extremity injury.[72,74,167,169] In spite of research, the role that previous history of lower extremity injury plays on future injury remains controversial. The slight decrease in risk (from 637% to 600%) when not adjusting for previous history of lower extremity injury increases the ambiguity on whether previous history of lower extremity injury in itself is a risk factor for lower extremity injury. In these two models, the odds of lower extremity musculoskeletal injury for a concussed athlete was 7.37 and 7.0 times greater than an athlete with no previously diagnosed concussion respectively.

Previous research has reported odds of concussed athletes sustaining a lower extremity musculoskeletal injury following a concussion ranging from 1.97 – 3.39 times greater than that of non-concussed athletes.[17,19,20] There are currently three published studies that aimed to investigate the relationship of concussion on future lower extremity musculoskeletal injuries in collegiate athletes.[17,19,20] Although all three studies have reported an increased risk of concussed athletes sustaining a lower extremity injury when compared to non-concussed athletes, the subject matching ratios, definition of lower extremity musculoskeletal injury and data collection time frames varied across all three. In 2015, Lynall et al.[17] studied the risk of lower extremity injury following a concussion in collegiate athletes, across 13 different NCAA sports over 3 periods of time: 90-days post RTP, 180-days post RTP, 365-days post RTP. History of lower extremity musculoskeletal injury was also collected for 365 day prior to concussion for each subject. A total of 44 athletes with a history of concussion were matched with up to 2 athletes (N=58) with no history of concussion by sex, sport, competition playing time, age, height and weight. Lynall and colleagues[17] defined musculoskeletal injury as any injury recorded by the certified athletic trainer or physician in the athlete's medical record; however, included only acute, sport-related lower extremity musculoskeletal injuries in their analysis. Musculoskeletal injuries did not have to result in a loss of time to begin included their analysis. The result of their study reported an increased risk of lower extremity injury up to 365 days after RTP post-concussion in concussed subjects when compared with matched non-concussed controls, noting significantly higher rates of lower extremity injury up to 180-day post RTP and 365-day post RTP (2.02 and 1.97 times increased risk respectively). No increased risk of lower extremity injury was noted in the up to 90-day post RTP comparison.[17]

In 2015, Brooks et al.[20] studied the risk of lower extremity injury following a concussion in collegiate athletes, across 10 different NCAA sports. A total of 87 athletes with history of concussion were matched with up to 3 athletes (N=182) with no history of concussion based on sex, sport, game exposure and position. Information on lower extremity musculoskeletal injuries that occurred 90-days post RTP was collected for each concussed athlete and their matched control(s). History of lower extremity musculoskeletal injuries was also collected for 365 days prior to concussion for each subject. Similar to our study, Brooks and colleagues[20] defined lower extremity injury as an injury to the hip, groin, thigh, knee shin ankle or foot that could be classified as either noncontact; acute fractures, muscle strains/tears, or ligament sprains/ruptures and used similar position groups during subject matching (Table 4 and 5). Brooks reported the odds of sustaining lower extremity injury in athletes with history of concussion 2.48 times higher 90-days post RTP when compared with matched non-concussed controls during that same time period.[20]

Herman et al.[19] published the most recent study investigating the relationship between concussion and subsequent lower extremity injury. A total of 90 concussed athletes across 4 NCAA, Division 1 sports were matched with up to 2 athletes (N=148) based on sport, starting status and main position played. Unlike the previous studies, the only male sport that Herman included was football. The other sports included women's lacrosse, soccer and basketball. Herman also permitted athletes with multiple concussions in his study; allowing athletes with a previous history of concussion in both the concussed and non-concussed group as long as the concussion occurred more than 6 months prior. Herman and colleagues[19] defined musculoskeletal injury as a strain, sprain, dislocation or rupture. Information on lower extremity musculoskeletal injuries that occurred 90-days post RTP was collected for each concussed athlete and their matched control(s). History of lower extremity musculoskeletal injuries prior to concussion was not collected. Herman reported the odds of sustaining a lower extremity musculoskeletal injury were 3.39 times greater in athletes with a history of concussion than that of their matched controls.[19]

The results of our study support previous findings of previous research that history of concussion increases the risk of lower extremity musculoskeletal in college-aged athletes. Fluctuations that exist in the degree of increased risk between studies could be attributed to the variations seen when defining; lower extremity musculoskeletal injury, inclusion/exclusion criteria for subjects, data collection windows, game/practice exposures, and the current study's strict adherence to matching all subjects on stated variables. All of the subjects in this current study were strictly matched on sex, sport, position, BMI, and calendar year. If a concussed athlete could not be matched with a non-concussed athlete on all of the matching variables, the subject was excluded from our study.

Previous studies that investigated the influence of concussion on subsequent lower extremity injury in collegiate athletes used electronic medical records for data collection.[17,19,20] Our study required the review of hard, medical record files for data collection with no standardized record keeping between clinicians or prompts for specific injury information. Information concerning mechanism of musculoskeletal injury, severity, time lost to injury, and exposures were inconsistently reported. Initial study design defined lower extremity musculoskeletal injury as any event that necessitated medical attention by an athletic trainer and/or physician AND 2) resulted in restriction or limitation of the athlete's participation for one or more days past the day of injury. Although all of the injuries recorded in this study met the first criteria stipulated by the definition, most of the medical records did not include time lost to injury data for musculoskeletal injuries. In order to secure records for 82 concussed and 82 non-concussed matched controls, all injuries that were reported in the athletes' medical record that satisfied the inclusion criteria were included in the analysis. The current study also collected all injuries (both acute and chronic) that could reasonably be attributed to our predictor variable, concussion. It is conceivable that alterations seen after a concussion in gait, reaction time, postural stability and balance could contribute to both acute and chronic lower extremity musculoskeletal injuries. Brooks, Lynall and Herman excluded all overuse injuries in their analyses.[17,19,20] Since data collection periods varied from 90 days after RTP following a concussion to 365 after RTP following a concussion, excluding all overuse injuries from analyses may have minimized the role that altered gait patterns following a concussion have on subsequent injury.

5.2.2 Association between concussion recovery time and lower extremity musculoskeletal injury

The second aim of this study was to determine if a relationship existed between length of recovery time needed after a sport-related concussion and subsequent lower extremity musculoskeletal injury. It was hypothesized that athletes who required a greater amount of recovery time prior to returning to play would have a greater risk of incurring a lower extremity musculoskeletal injury than those athletes with a shorter recovery time.

The results of our study did not support this hypothesis. The average recovery time following a concussion across those concussed athletes who sustained a lower extremity musculoskeletal injury (Mean, 18 days; Median, 9 days; IQR [6-17 days]) and those concussed athletes who did not sustain a lower extremity musculoskeletal injury (Mean, 19 days; Median, 11 days; IQR [7-18 days]) was not significantly different. Across all sports, men's soccer averaged the longest return to play times (Mean, 34 days; Median, 11days; IQR, [9-34 days]) and the single longest individual RTP time after a concussion (166 days) while volleyball recorded the shortest average (Mean, 6 days; Median, 6 days). The differences between the inherent risk of concussion in soccer and volleyball could explain these results. In the 2007 epidemiological study of collegiate injuries across 15 NCAA sports, Hootman et al.[34] reported overall risk of concussion in men's soccer nearly double the risk seen in volleyball. The data collected in our study revealed that the concussed athletes took anywhere from 1 – 166 days to recover from a concussion and return to sport with an average RTP time of 18 days (Median, 10 days; IQR, [7 - 17 days]) across all athletes. Our overall results on RTP after a concussion were similar to those reported in Brooks' study. Brooks et al.[20] reported that concussed athletes in their study averaged RTP times of 21 days (Median, 9.0; IQR[5 – 15 days]). Previous literature reported that most athletes return to play following a sports-related concussion within 7-10 days.[6,44,45] In 2013, the Consensus Statement on Concussion and Sport reported 80-90% of all sport-related concussions will resolve within 7-10 days, noting that younger athletes may take additional time to return.[6] Consistent with the Consensus statement, in 2013 McKeon et al.[45] investigated trends in RTP in high school athletes and reported that 71.3% of all concussed athletes RTP within 7-9 days, with 88.8% returning by 21 days.

Using this information, separate Fisher Exact tests were conducted to investigate the influence that the currently publicized typical RTP times of 7 days to 10 days have on incidence of lower extremity injury. Regardless of RTP time-frame, the results of our study indicate that the amount recovery time needed prior to RTP following a concussion does not influence the risk of future lower extremity musculoskeletal injury in this cohort of athletes. To our knowledge, no other published study has investigated the relationship between RTP time following a concussion and subsequent risk of lower extremity musculoskeletal injury.

5.2.3 Influence of sex on lower extremity musculoskeletal injury after a concussion

The third aim of this study was to determine if a relationship existed between concussed athletes of a specific sex and the incidence of lower extremity musculoskeletal injury. The role of sex as a predictor for concussion[38,40] and separately as a predictor for lower extremity musculoskeletal injury has been widely studied.[82,85,87,88] Covassin et al.[40] investigated the influence that sex differences have on injuries in collegiate athletes and reported that that female athletes have higher incidences of concussion in game play than do male athletes. Beynnon et al.[85] investigated the influence that sex, sport and level of competition have on acute ACL injury and reported a 2.10 times greater risk of non-contact ACL injury in female collegiate athletes as compared to male collegiate athletes.

It was hypothesized that female concussed athletes would have a higher incidence of subsequent lower extremity musculoskeletal injury than male concussed athletes. The results of this current study did not fully support this hypothesis. In our sample of athletes, 75% of concussed females as compared with 57% of concussed males sustained a lower extremity musculoskeletal injury in the test window following their concussion. The analysis comparing injury incidence in concussed males and females achieved 23.3% power to detect a difference in group proportions of -0.18. The proportion in males was 0.57 and the proportion in females was 0.75. The test statistic used was a two-sided Fisher's Exact Test. The significance level of the test was set at 0.05. This current study was powered for our primary aim (Aim 1); future studies would require more subjects to answer this research question. Although the Fisher Exact testing revealed no statistical significance between male and female athletes and their incidence of LE injury after RTP following a concussion, it is our opinion these results have clinical implications and support the body of evidence that currently exists concerning increased risk of musculoskeletal injuries in the female population.[82,85,87,88]

5.2.4 Influence of sex on recovery time after a concussion

The fourth aim of this study was to determine if a relationship existed between sex and recovery time needed by an athlete after a sport-related concussion. To date research on the influence that sex may have on recovery time following a concussion has been inconclusive.[197-201]

In 2014, Zuckerman et al.[198] studied middle school, high school and college-aged athletes with sport related concussions and reported that females exhibited increased severity, duration and RTP times after their concussion as compared to male athletes. Similarly, in 2013, Covassin et al.[202] compared post concussive testing results in male and female high school and collegiate soccer athletes. Covassin reported that at 8 days post-concussion, female athletes reported a greater number of post-concussion symptoms and scored lower on visual memory tests than did male athletes in their study.[202] Conversely, in 2016, Ono et al.[201] reported identical recovery patterns between sexes after a sport related concussion in youth athletes; however did note increased symptom frequency amongst female athletes as compared with male athletes. Likewise, in 2016, Zuckerman et al.[199] studied the medical records of NCAA, collegiate athletes from 2009 - 2015 and did not find any association between recovery time and sex; however did report an association between recurrent concussion and prolonged recovery times in both male and female athletes.

Our study hypothesized that female concussed athletes will require a greater amount of recovery time prior to returning to play than male concussed athletes. The results of our study did not support this hypothesis. In our study, recovery time from a sports-related concussion ranged from 1 – 166 days in male athletes and 1 – 76 days in female athletes. The median recovery time from a concussion for a male athlete was 9 days as compared with 15 days for a female athlete. Although not statistically significant, a recovery time difference of 6 days between groups is clinically significant when considering the competitive nature and demands of a collegiate athlete both on the field and off. The influence of sex on sport-related concussion outcomes merits further investigation.

5.3 STUDY LIMITATIONS

This current study has some limitations worth noting. One limitation in this study was the variability and quality of medical records. The medical records for athletes at the University of Pittsburgh consist primarily of hard files. The records reviewed in this study were from a time-span of 9 years that included 16 different clinicians. The number of different clinicians responsible for the record keeping and care of the athletes may also be a potential limitation to this study. Although a limitation, quality of medical records and number of different clinicians were consistent across both the concussed and non-concussed athlete groups and therefore would likely affect data for both groups equally. Our data collection was completed retrospectively and therefore relied on the accuracy and the record keeping of each of the reporting clinicians. The organization, style and location of records during that time varied per clinician. The variations seen in record keeping across all clinicians who contributed to the athlete medical records increased the difficulty in obtaining consistent responses to the variables collected. In the last few years, the utilization of electronic medical records have begun to be implemented by the sports medicine team at the University of Pittsburgh. Using electronic medical records may facilitate some standardization and consistency of documentation across multiple clinicians. Another potential limitation was accurate understanding of athlete exposures. Although athlete exposures were accounted for in this study by tightly matching athletes on sex, sport, position and calendar year, having a definitive count for athlete exposures in both games and practices would increase the accuracy of subject matching and ultimately validity of this study. It is widely recognized that incidence of sport-related injury vary depending on, sport, type of participation (practice vs game) and time of season.[34,35,121,143,147-149,151,154,156,161,162] In an epidemiological study across 15 NCAA sports, Hootman et al.[34] reported that collectively across all collegiate sports studied, in-season games accounted for higher injury rates (13.8 injuries per 1000 A-Es) than preseason practice (6.6 injuries per 1000 A-Es), in-season practices (2.3 injuries per 1000 A-Es) and postseason practice (1.4 injuries per 1000 A-Es). It is recommended that future studies in this area account for specific athlete exposures in both practice and games. Another limitation in this research is that the subject sample was from a single university across 10 teams, therefore limiting the generalizability of this study's outcomes to other universities, sports and age-groups.

5.4 CONCLUSION

The purpose of this study was to investigate the influence that sport-related concussion may have on future lower extremity musculoskeletal injury and to examine if there is a connection between recovery time needed before returning to play after a concussion and incidence of lower extremity injury. This study also aimed to investigate the role that sex may have on recovery time from a sports-related concussion and the influence that sex may have on future lower extremity musculoskeletal injury after a concussion.

The results of this study revealed that concussed athletes were at increased risk of future lower extremity musculoskeletal injury after returning to play following a concussion. These findings corroborate a growing body of research on concussion's influence on future injury. The role that sex may have on RTP time following a concussion and risk of lower extremity musculoskeletal injury was not clearly defined by this study. Although not statistically significant, female athletes did demonstrate longer concussion recovery times and a greater incidence of lower extremity musculoskeletal injury following a concussion. These results can carry clinical significance given the demands and competitive nature of collegiate athletics.

5.5 FUTURE RESEARCH

The results of this study and previous research indicate that clinicians and researchers need to begin investigating the causative nature of the associate between concussion and future lower extremity injury so that appropriate interventions can be made prior to returning an athlete to play following a sports-related concussion. Current RTP guidelines following a sports-related concussion include, return to baseline neurocognitive functioning and balance testing, as well as complete resolution of symptoms throughout a graduated physical progression that involves sport-specific activities and risk for contact. Baseline neurocognitive testing has become commonplace for all athletes within collegiate programs. Collecting baseline measurements in physical assessments like postural stability, proprioception, reaction time and physical exertion could perhaps lead to implementing additional objective return to baseline requirements prior to RTP. Future research that would capture data throughout an athletes' entire collegiate career prospectively may give a more accurate and complete picture of the potential influence that concussion may have on injury in this population.

APPENDIX A

MEDICAL RECORDS REVIEW DATA COLLECTION FORM

A.1 MEDICAL RECORDS REVIEW DATA COLLECTION FORM

Data Collection Form ? ×

Subject number:
DOB:
Age:
Sex M=1, F=2:
Sport:
Position:
Ht in inches:
Wt in pounds:
BMI:
BMI category U=1, Norm = 2, Over=3, Obese=4:
Concussed = 1/NonConcussed=2:
Concuss date (xx/xx/xxxx) - Calendar year:
Days lost to concussion:
RTP date (xx/xx/xxxx):
180 RTP Date:
180 day post LE Injury date (xx/xx/xxxx):
Time to injury:
180 day LE MS Injury 1 = NO, 2 = YES:
180 day UE MS Injury 1 = NO, 2 = YES:
180 day Post injury body region 1 = foot, 2 = ankle, 3 = shin/calf, 4 = knee, 5 = quad, 6 = ham, 7 = hip:
90 days preconcussion date:
90 days Pre LE MS Injury 1 = No, 2=Yes:
90 days Pre UE MS Injury 1 = No, 2=Yes:
90 day Pre concussion - MS injury body region:
multiple post LE MS Injuries No=1, yes=2:

New Record
New
Delete
Restore
Find Prev
Find Next
Criteria
Close

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