

Scoping Review

# Lower Kinetic Chain, Meet the Thinking Brain: A Scoping Review of Cognitive Function and Lower Extremity Injury Risk

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The classic model of non-contact ACL injury includes environmental, anatomical, hormonal and biomechanical risk factors which directly impact either the amount of stress placed on the ligament or the relative capacity of ligament to withstand the forces placed on it. However, cognition also clearly plays a role in successful athletic performance, yet diminished cognitive function is rarely considered a risk factor for injury.

### Objective

To examine the existing literature to determine the extent to which cognitive function (both cognitive ability and task cognitive load) influences non-contact lower extremity injury risk in male and female athletes with a broad variety of athletic expertise.

### Study Design

Scoping Review

### Methods

An electronic search was conducted of CINAHL, SPORTDiscus, Google Scholar, and MEDLINE using the PRISMA method. Search terms included Boolean combinations of “cognition”, “concussion”, “ImPACT”, “cognitive deficit”, “mild traumatic brain injury (mTBI)”, and “neuropsychological function” as cognitive descriptors and the terms “injury risk” and “lower extremity injury” as injury descriptors. Inclusion criteria included papers written in English published between 2000-2021. Exclusion criteria included neurological and cognitively atypical populations, except for concussion (included). Included articles were appraised using the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies.

### Results

Fifty-six studies utilizing across the spectrum of levels of evidence met inclusion criteria. Forty-one articles had good, fourteen had fair, and one had poor methodological quality. Studies examined baseline cognitive function in healthy athletes (n=7); performance during dual-task paradigms (n=13); and the impact of concussion on dual-task performance (n=4), LE injury risk (n=22), or post-concussion testing (n=10). Six articles examining cognitive function and all dual-task studies (including concussion studies)

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found altered biomechanics associated with injury or increased processing demands. Studies related to concussion and injury incidence consistently found an increased risk of LE injury following concussion. Half of the studies that examined concussion and post-concussion cognitive testing demonstrated significant effects.

## Discussion

Consistent across participant demographics, tasks, and dependent measures, fifty-one of fifty-six assessed articles concluded that decreased cognitive ability or increased cognitive load led to risky LE mechanics or a direct increase in non-contact LE injury risk.

## Conclusion

The robustness of results across gender, performance level, sport, cognitive ability, task cognitive load suggest that the inclusion of cognitive training in the design of optimal LE injury prevention programs warrants further study.

Level of Evidence: Ia

## INTRODUCTION

As the saying goes, “an ounce of prevention is worth a pound of cure.” Indeed, it has long been the goal of rehabilitation professionals to develop effective injury prevention programs for athletes due to high injury rates. In the United States, competitive and recreational athletes reported 8.6 million injuries annually with up to 42% of them involving the lower extremity.<sup>1</sup> One common non-contact lower extremity injury, anterior cruciate ligament (ACL) rupture, is often the target of prevention programs. However, these prevention programs have room for further improvement. For example, Noyes & Barber-Westin<sup>2</sup> found that to prevent one non-contact ACL rupture, 70 athletes need to participate in the prevention program. These current programs largely target improving the physical and biomechanical aspects of movement related to injury prevention. One possible missing component is the contribution of cognitive impairment on injury risk.

Participation in sport requires the integration of many different inputs to successfully accomplish a task. Athletes must sort through high amounts of sensory information, while avoiding or challenging an opponent, and attempting to achieve the goal (e.g., score or prevent the score). A possibility of increased injury risk exists where participants respond to unanticipated events or undertake rapid visual-motor decision making - such is the case during athletic participation.<sup>3</sup> Indeed, cognitive integration clearly plays a role in task achievement during sport. The idea that the addition of cognitive load could result in riskier biomechanics during a relatively simple physical task relates to a concept known as the “capacity model of attention”.<sup>4</sup> The cognitive process of attention is considered the bottleneck of information processing, creating a natural limit to an individual’s capacity to perform mental and motor tasks,<sup>5</sup> and different activities impose different demands on this limited capacity.<sup>6</sup> Thus, lower attentional and/or cognitive reserves due to innate natural abilities, previous head injuries, or task load, may leave athletes at a higher risk for non-contact injuries. Widening clinical attention from simply a physical, biomechanical approach to more of a holistic viewpoint could boost the effectiveness of injury prevention programs, at least for some athletes.

To fully understand the effects of cognitive function on lower extremity non-contact injury risk, it is important to define cognition and its relation to kinetics and kinematics. According to Herman and Barth,<sup>7</sup> ‘cognition’ is a process related to the abilities of the cortical and subcortical brain systems to function. It includes some aspects not considered related to non-contact injury risk such as language, intelligence, and social functioning. Other aspects of cognition such as visual attention, self-monitoring, agility, fine motor performance, processing speed and reaction time may hold importance when it comes to injury risk in sports.<sup>7</sup> For the purposes of the present work, the definition of cognition will include processes related to the abilities of the cortical brain systems including visual attention, fine motor performance, processing speed and reaction time. A rich collection of literature exists comparing the above listed domains of cognition and lower extremity injury risk, and these domains are easily measured using standardized approaches, simplifying comparisons across studies.

Cognitive prowess can depend on natural abilities, history of neurologic trauma or the mental load of a task. Researchers, in particular over the last two decades, have investigated the effect of natural cognitive ability on performance of motor tasks<sup>7</sup> or direct injury rates.<sup>8,9</sup> Even more recently, connections between athletes who have suffered a concussion and injury rates have been studied.<sup>10,11</sup> The history of concussion can be considered a modification of cognitive ability and thus that body of literature has been included in the present scoping review. Other researchers have increased the cognitive load of common biomechanical tasks by adding a cognitive component to motor tasks to assess the effects on mechanics in healthy athletes.<sup>4,12</sup>

However, rehabilitation professionals likely lack full comprehension regarding the extent of the connection between cognitive function and non-contact injury risk across this broad literature. Better understanding of the underlying mechanisms responsible for non-contact lower extremity injury can help to determine specific cognitive and neuromuscular activities that facilitate lower extremity injury prevention and/or recovery. The purpose of this scoping review was to examine the existing literature to determine the extent to which cognitive function (both cognitive ability and task cognitive load) influences non-contact lower

extremity injury risk in male and female athletes with a broad variety of athletic expertise.

## METHODS

### LITERATURE SEARCH STRATEGY

Search terms included Boolean combinations of “cognition”, “concussion”, “ImPACT”, “cognitive deficit”, “mild traumatic brain injury (mTBI)” and “neuropsychological function” as cognitive descriptors. The terms “injury risk” and “lower extremity injury” as injury terms (Appendix 1). The following electronic databases were searched: CINAHL, SPORTDiscus, Google Scholar, and MEDLINE with the most recent search conducted in August 2021.

### STUDY SELECTION CRITERIA

Inclusion criteria consisted of English-language studies with a publication range from 2000-2021. Exclusion criteria consisted of neurological and cognitively atypical populations including diagnoses such as Attention Deficit Hyperactivity Disorder (ADHD), traumatic brain injury (TBI), cerebral palsy (CP), multiple sclerosis (MS), amyotrophic lateral sclerosis (ALS) and Autism Spectrum Disorder. One notable exception was the inclusion of concussion as a diagnostic category for this scoping review. Concussion (AKA mild traumatic brain injury or mTBI) is a unique example of potentially impaired cognitive capacity that potentially could increase LE non-contact injury risk. Articles that fell into this category were analyzed separately from all other articles.

Using the article selection strategy suggested by Smith,<sup>13</sup> the initial search yielded 5,335 results (Figure 1). After removing duplicates, 4,824 studies remained. Authors divided the 4,824 articles among themselves and individually assessed whether they met the inclusion criteria or violated the exclusion criteria. Articles that did not clearly meet the inclusion criteria were discussed by the entire group and a determination made by consensus. Studies not meeting the inclusion criteria or violating the exclusion criteria were removed; first by article title (4,688 articles), next by abstract (61 articles) and finally by full text content (19 articles). These articles were removed during full-text screening because they did not satisfy the purpose of this study. Following full-text screening, article references were reviewed for additional content that met the inclusion criteria (nine articles). Finally, 56 articles were included for review (Figure 1).

### DATA SYNTHESIS

Data from each article including experimental design, sample size, participants, task, dependent measures, and results/conclusions were extracted (Appendix 2). Fifty-six articles were classified into five categories based on participant demographics and dependent measures: natural cognitive ability in a healthy population, performance during dual-task paradigms in healthy populations, performance during dual-task paradigms in participants with a

history of concussion, LE injury risk in participants with a history of concussion, and lastly, cognitive testing performance in participants with a history of concussion.

Methodological risk of bias was assessed using the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies from the National Institutes of Health,<sup>14</sup> which includes 14 items. While not all articles fell in the observational and cohort and cross-sectional study categories (see Table 1), the authors chose to use a single quality assessment tool for consistency across all included articles. Each publication was given an overall score of ‘good’, ‘fair’, or ‘poor’ (Table 1) based on this tool. Initial scoring was performed by a single author (MR, MP, TW or DL), then the first four authors (MR, MP, TW and DL) discussed all included papers and reached consensus on scoring.

## RESULTS

### RISK OF BIAS

Discussion and strict adherence to the quality appraisal tool was utilized to come to consensus for all included studies. Forty-one out of the fifty-six articles had strong methodological quality, while fourteen articles had fair methodological quality, and one article had poor quality (Figure 2). Common reasons for articles not having strong methodological quality included: small sample size (based on a lack of a sample size justification, power description, or variance / effect size data), insufficient time between exposure and outcome (determined on a case-by-case basis for each paper), and lack of blinding to participants and researchers.

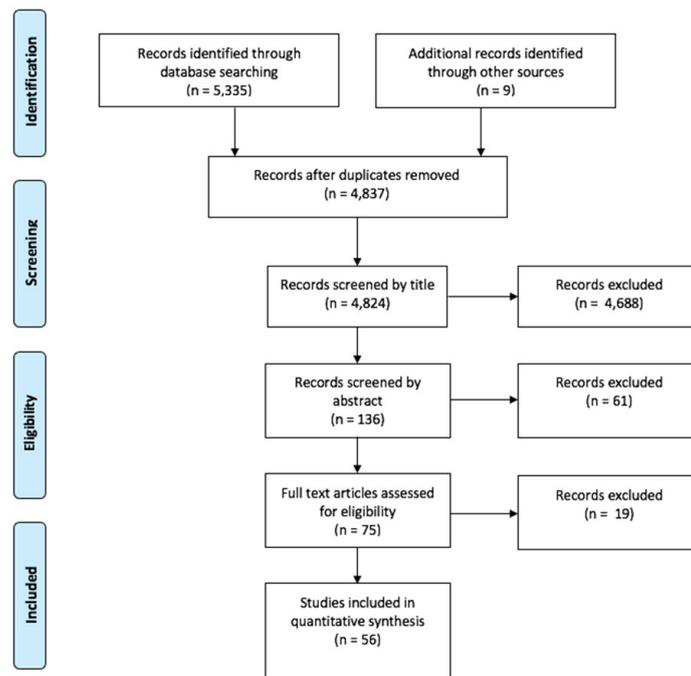
### METHODOLOGICAL DESIGN

Methodological design of the included papers determines the level of evidence for this scoping review. Figure 3 illustrates the number of articles by topical category and experimental approach (Refer to Table 1 for the specific articles that fell into each category). Sixteen studies utilized a prospective cohort design. Twelve studies were retrospective cohort design. Ten studies were prospective quasi-experimental design. Twelve studies used a prospective cross-sectional design. Five studies used retrospective cross-sectional design. One study used a retrospective case control design. The specific demographic data, methods and conclusions for each study are provided in Appendix 2.

### *THE EFFECT OF COGNITIVE ABILITY ON LOWER EXTREMITY MOVEMENT IN HEALTHY ATHLETES*

**Baseline Cognitive ability.** Seven articles examined athletes’ natural cognitive function and its relationship to task performance and injury risk.<sup>7-9,12,15-17</sup> These studies investigated the relationship of a person’s baseline cognition, as defined by each researcher, to injury risk. Six of the seven articles found athletes with lower baseline cognitive function had significantly altered mechanics.<sup>7-9,12,16,17</sup>

Four studies utilized the Immediate Post-concussion Assessment and Cognitive Testing (ImPACT) scores to relate



**Figure 1. PRISMA Flow Diagram.**

cognitive function and injury risk.<sup>8,9,12,15</sup> As the name suggests, the ImpACT is a measurement tool designed to assist with return-to-play decisions post-concussion.<sup>18</sup> Since it gives such a broad cognitive screen, the use of the ImpACT to identify post-concussion cognitive deficits is debated in literature. The test consists of six neuropsychological tests designed to target different aspects of cognitive functioning including attention, memory, processing speed and reaction time. From these six tests, four composite scores are generated including verbal memory, visual memory, visuomotor speed and reaction time. Although this test was designed for concussion management, the domains of the ImpACT may also prove useful as a measurement of baseline cognition. Three studies found a positive relationship between cognitive function and LE injury risk with lower ImpACT score.<sup>8,9,12</sup> These studies varied significantly in participant populations including male football players at one university,<sup>9</sup> recreational female college athletes<sup>12</sup> and male and female athletes at different universities.<sup>8</sup> The study that reported null differences between groups studied 14-17 year old ski and snowboard athletes.<sup>15</sup>

The robustness of findings across participant groups matched the variety of dependent measures included in these studies. Slower reaction times on the ImpACT test correlated with increased vertical ground reaction force with unanticipated jumping conditions<sup>12</sup> and an increased likelihood of lower extremity injury during one football season.<sup>9</sup> Other factors of the ImpACT test including verbal memory, visual memory and processing speed were worse in participants who sustained a non-contact ACL injury.<sup>8</sup> Out of the studies looking at ImpACT scores and baseline cognitive function, one study did not find significant differences on pre-season ImpACT testing for the injured group and non-injured group.<sup>15</sup> This study may have a different

result due to the ages of participants being younger (14-17 v. 18-24 year-olds) or the difference in the environmental demands of downhill skiing (snow conditions may have led to a non-impact ACL injury versus football and unanticipated jumping with relatively stable playing surfaces).

Three studies utilized other methods to define baseline cognitive function. One study utilized the Concussion Resolution Index (CRI) which examines memory, reaction time, speed of decision making, and speed of information processing in a computer test like ImpACT.<sup>7</sup> Herman and Barth found that low performers had increased peak anterior tibial shear force, knee abduction moment, knee abduction angle, and decreased trunk flexion angle on a drop-landing task,<sup>7</sup> often considered mechanics that lead to ACL rupture.

Another tool used to measure cognitive function is the CNS Vital Signs computer-based cognitive tests. A group with chronic ankle instability had significantly lower composite memory, visual memory, and simple attention compared to the control group.<sup>17</sup> Finally, female jumping and cutting athletes with a lower score on the Symbol Digit Modalities Test had significantly increased quadriceps activity before and after ground contact and decreased co-contraction ratio only after ground contact with unanticipated cutting tasks and single leg landing.<sup>16</sup> Together, these results indicate that across sports (note the exception of skiing / snowboarding<sup>15</sup>) measures of cognition and measures of kinetics / kinematics, a negative relationship exists with poorer biomechanical performance and/or increased injury rates in athletes with lower baseline cognitive performance.

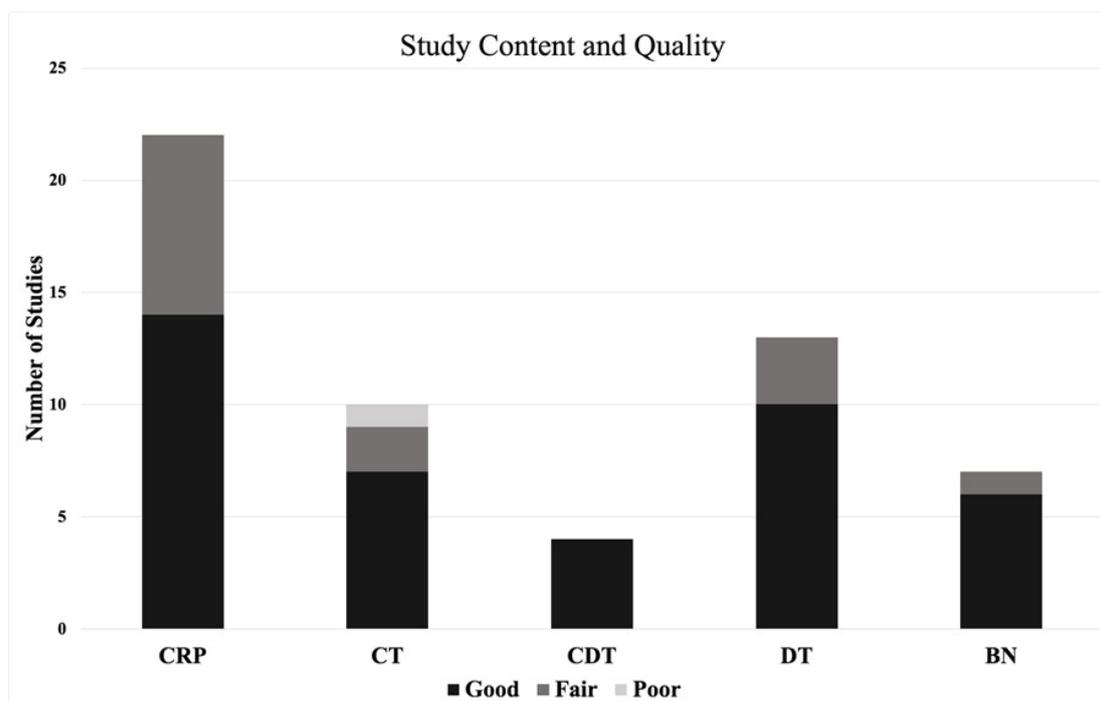
**Table 1. Summary of study topic, methodological design, and appraisal grade.**

No.	Paper	Category	Appraisal	Design
1	Almonroeder (2017). Poorer Performance on a Clinical Test of Reaction Time is Associated With Higher Landing Forces During Lateral Cutting	Baseline Cognition	Good	Prospective Cross-Sectional Study
2	Faltus, et al. (2016). Utilization of Impact Testing to Measure Injury Risk in Alpine Ski and Snowboard Athletes	Baseline Cognition	Fair	Retrospective Cohort Study
3	Herman, et al. (2016). Drop-jump Landing Varies with Baseline Cognition	Baseline Cognition	Good	Prospective Quasi-Experimental Study
4	Rosen, et al. (2020). Males with Chronic Ankle Instability Demonstrate Deficits in Neurocognitive Function Compared to Controls and Copers	Baseline Cognition	Good	Retrospective Cohort Study
5	Shibata, et al. (2018). The Influence of Differences in Neurocognitive Function on Lower Limb Kinematics, Kinetics, and Muscle Activity During an Unanticipated Cutting Motion	Baseline Cognition	Good	Prospective Quasi-Experimental Study
6	Swanik, et al. (2007). The Relationship Between Neurocognitive Function and Noncontact Anterior Cruciate Ligament Injuries	Baseline Cognition	Good	Retrospective Case Control Study
7	Wilkerson, et al. (2012). Neurocognitive Reaction Time Predicts Lower Extremity Sprains and Strains	Baseline Cognition	Good	Prospective Cohort Study
8	Almonroeder, et al. (2017). The Focus of Attention Influences Lower Extremity Mechanics During Cutting in Female Athletes	Dual Task	Good	Prospective Cross-Sectional Study
9	Almonroeder, et al. (2017). The Utility of a 2D ACL Injury Risk Screen Measure to Assess Changes in Landing Mechanics Related to Cognitive Task Demands	Dual Task	Good	Prospective Cross-Sectional Study
10	Almonroeder, et al. (2018). Cognitive Demands Influence Lower Extremity Mechanics During a Drop Vertical Jump Task in Female Athletes	Dual Task	Good	Prospective Cross-Sectional Study
11	Biese, et al. (2019). Preliminary Investigation on the Effect of Cognition on Jump-Landing Performance Using a Clinically Relevant Setup	Dual Task	Good	Prospective Quasi-Experimental Study
12	Dai, et al. (2018). The Effect of a Secondary Cognitive Task on Landing Mechanics and Jump Performance	Dual Task	Good	Prospective Quasi-Experimental Study
13	Ross, et al. (2008). Procedural Reaction Time and Balance Performance During a Dual or Single Task in Healthy Collegiate Students	Dual Task	Good	Prospective Quasi-Experimental Study
14	Schnittjer, et al. (2017). The Effects of a Cognitive Dual Task on Jump-Landing Mechanics	Dual Task	Fair	Prospective Quasi-Experimental Study
15	Simon, et al. (2019). Neurocognitive Challenged Hops Reduced Functional Performance Relative to Traditional Hop Testing	Dual Task	Good	Prospective Cross-Sectional Study
16	Shinya, et al. (2011). The Effects of Choice Reaction Task on Impact of Single Leg Landing	Dual Task	Fair	Prospective Quasi-Experimental Study
17	Talarico, et al. (2016). Static and Dynamic Single Leg Postural Control Performance During Dual Task Paradigms	Dual Task	Good	Prospective Cross-

No.	Paper	Category	Appraisal	Design
				Sectional Study
18	Fino, et al. (2016). Decreased High-Frequency Center-of-Pressure Complexity in Recently Concussed Asymptomatic Athletes	Concussion + Dual Task	Good	Prospective Quasi-Experimental Study
19	Howell, et al. (2017). The Utility of Instrumented Dual Task Gait and Tablet-Based Neurocognitive Measurements After Concussion	Concussion + Dual Task	Good	Prospective Cohort Study
20	Howell, et al. (2018). Worsening Dual-Task Gait Costs after Concussion and Their Association with Subsequent Sport-Related Injury	Concussion + Dual task	Good	Prospective Longitudinal Cohort Study
21	Lynall, et al. (2016). Functional Movement Deficits in Relation to Sport-Related Concussion	Concussion + Dual Task	Good	Prospective Quasi-Experimental Study
22	Aggelou, et al. (2017). Concussion as a Risk Factor for Lower Extremity Musculoskeletal Injury in Collegiate Athletes	Concussion + Risk Prediction	Good	Retrospective Matched Cohort Study
23	Brooks, et al. (2016). Concussion Increases Odds of Sustaining a Lower Extremity Musculoskeletal Injury After Return to Play Among Collegiate Athletes	Concussion + Risk Prediction	Good	Retrospective Matched Cohort Study
24	Burman, et al. (2016). Concussed Athletes are More Prone to Injury Both Before and After their Index Concussion: A Data Base Analysis of 699 Concussed Contact Sports Athletes	Concussion + Risk Prediction	Fair	Retrospective Cohort Study
25	Cross, et al. (2015). Professional Rugby Union Players have a 60% Greater Risk of Time Loss Injury After Concussion: A 2-season Prospective Study of Clinical Outcomes	Concussion + Risk Prediction	Good	Prospective Longitudinal Cohort Study
26	Fino, et al. (2019). Effects of Recent Concussion and Injury History on Instantaneous Relative Risk of Lower Extremity Injury in Division I Collegiate Athletes	Concussion + Risk Prediction	Good	Retrospective Cohort Study
27	Gilbert, et al. (2016). Association Between Concussion and Lower Extremity Injuries in Collegiate Athletes	Concussion + Risk Prediction	Fair	Retrospective Cross-Sectional Study
28	Harada, et al. (2019). Multiple Concussions Increase Odds and Rate of Lower Extremity Injury in National Collegiate Athletic Association Athletes After Return to Play	Concussion + Risk Prediction	Good	Retrospective Cohort Study
29	Herman, et al. (2016). Concussion may Increase the Risk of Subsequent Lower Extremity Musculoskeletal Injury in Collegiate Athletes	Concussion + Risk Prediction	Good	Retrospective Cohort Study
30	Houston, et al. (2018). Sex and Number of Concussions Influence the Association Between Concussion and Lower Extremity Injury	Concussion + Risk Prediction	Fair	Retrospective Cross-Sectional Study
31	Howard, et al. (2018). Relationship Between Concussion Factors and Lower Extremity Injury Rates in Collegiate Athletes	Concussion + Risk Prediction	Fair	Retrospective Cohort Study
32	Kardouni, et al. (2018). Risk for Lower Extremity Injury After Concussion: A Matched Cohort Study in Soldiers	Concussion + Risk Prediction	Good	Retrospective Matched Cohort Study
33	Koperna, et al. (2018). Sport-Related Concussion and Lower Extremity Musculoskeletal Injuries in High School Athletes	Concussion + Risk Prediction	Good	Retrospective Cross-Sectional Study
34	Krill, et al. (2018). Effect of Concussions on Lower Extremity Injury Rates at a Division I Collegiate Football Program	Concussion + Risk Prediction	Good	Prospective Observational Cohort Study
35	Lynall, et al. (2015). Acute Lower Extremity Injury Rates Increase After Concussion in College Athletes	Concussion + Risk Prediction	Good	Retrospective Cohort Study

No.	Paper	Category	Appraisal	Design
36	Lynall, et al. (2017). Lower Extremity Musculoskeletal Injury Risk After Concussion Recovery in High School Athletes	Concussion + Risk Prediction	Fair	Retrospective Cohort Study
37	Nordstrom, et al. (2014). Sports Related Concussion Increases the Risk of Subsequent Injury by About 50% in Elite Male Football Players	Concussion + Risk Prediction	Good	Prospective Cohort Study
38	Pietrosimone, et al. (2015). Concussion Frequency Associates with Musculoskeletal Injury in Retired NFL Players	Concussion + Risk Prediction	Fair	Retrospective Cross-Sectional Study
39	De Beaumont, et al. (2011). Persistent Motor System Abnormalities in Formerly Concussed Athletes	Concussion + Testing	Good	Prospective Quasi-Experimental Study
40	Dorrien, et al. (2015). History of Concussion and Current Functional Movement Screen Scores in a Collegiate Recreational Population	Concussion + Testing	Good	Prospective Cross-Sectional Study
41	DuBose, et al. (2017). Lower Extremity Stiffness Changes Following Concussion in Collegiate Football Players	Concussion + Testing	Good	Prospective Observational Cohort Study
42	Gagnon, et al. (2004). Visuomotor Response Time in Children with a Mild Traumatic Brain Injury	Concussion + Testing	Good	Prospective Cohort Study
43	Gagnon, et al. (2004). Children Show Decreased Dynamic Balance After Mild Traumatic Brain Injury	Concussion + Testing	Good	Prospective Cohort Study
44	Gearhart, et al. (2002). Consistency of Concussed Athletes on a Battery of Motor Performance and Computerized Neuropsychological Tests	Concussion + Testing	Fair	Prospective Matched Cohort Study
45	Maxwell, et al. (2005). Effects of Postural Stability and Neurocognitive Function in Sports Concussion Injuries	Concussion + Testing	Good	Prospective Cohort Study
46	Merritt, et al. (2017). Concussion History and Time Since Concussion Do Not Influence Static and Dynamic Balance in Collegiate Athletes	Concussion + Testing	Fair	Prospective Cross-Sectional Study
47	Myashita, et al. (2017). Correlation of Head Impacts to Change in Balance Error Scoring System Scores in Division I Men's Lacrosse Players	Concussion + Testing	Good	Prospective Longitudinal Cohort Study
48	Shiflett, et al. (2015). The Effects of Subconcussive Impacts on Postural Stability	Concussion + Testing	Poor	Prospective Longitudinal Cohort Study
49	Hunzinger, et al. (2020). Diagnosed Concussion is Associated with Increased Risk for Lower Extremity Injury in Community Rugby Players	Concussion + Risk Prediction	Fair	Retrospective Cross Sectional Study
50	Giesche, et al. (2019). Are Biomechanical Stability Deficits During Unplanned Single-leg Landings Related to Specific Markers of Cognitive Function	Dual Task	Good	Prospective Cross Sectional Study
51	Monfort, et al. (2019). Visual-spatial Memory Deficits are Related to Increased Knee Valgus Angle During a Sport-specific Sidestep Cut	Dual Task	Fair	Prospective Cross Sectional Study
52	Murray, et al. (2020). Baseline Postural Control and Lower Extremity Incidence Among Those with a History of Concussion	Concussion + Risk Prediction	Good	Prospective Cohort Study
53	Biese, et al. (2021). Association of Lower Extremity Injuries and Injury Mechanism with Previous Concussion History in Adolescent Athletes	Concussion + Risk Prediction	Fair	Prospective Cross Sectional Study
54	Ha, et al. (2020). Can Neurocognitive Function Predict Lower	Concussion	Good	Prospective

No.	Paper	Category	Appraisal	Design
	Extremity Injury in Male Collegiate Athletes?	+ Risk Prediction		Cohort Study
55	McDonald, et al. (2019). Risk Factors for Initial and Subsequent Core and Lower Extremity Sprain or Strain Among Collegiate Football Players	Concussion + Risk Prediction	Good	Prospective Cohort Study
56	Wilke, et al. (2020). Increased Visual Distraction Can Impair Landing Biomechanics	Dual Task	Good	Prospective Cross Sectional Study



**Figure 2. Methodological quality of studies across content areas.**

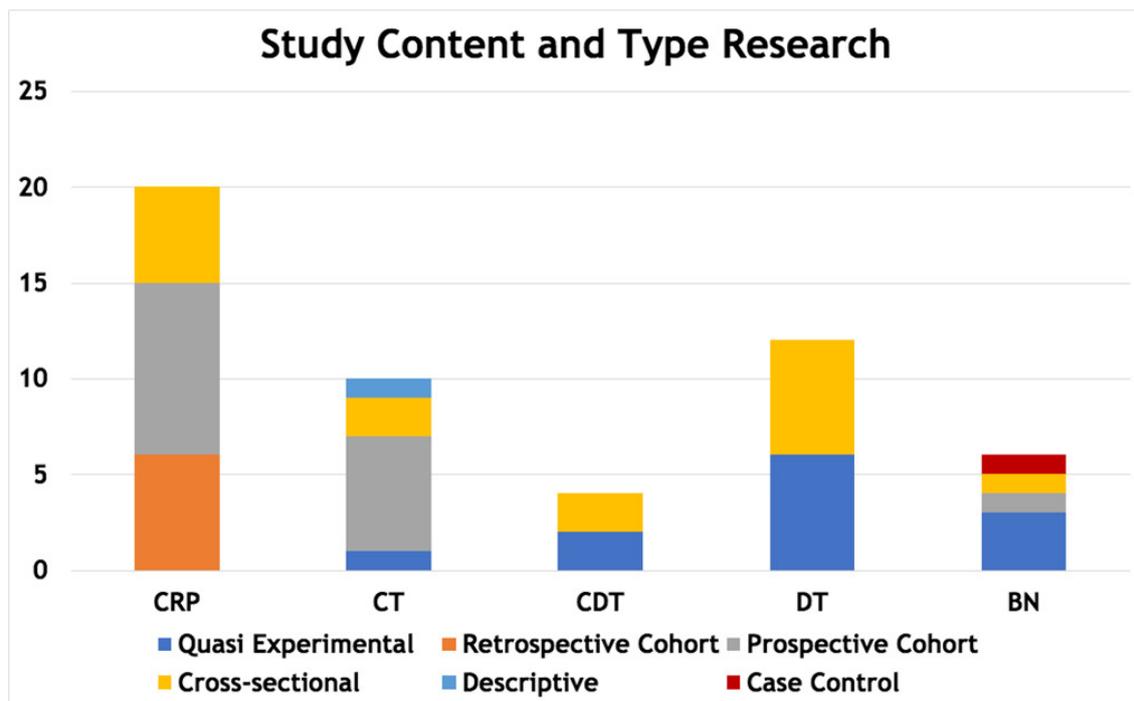
Abbreviations: Concussion and Risk Prediction (CRP); Concussion and Testing (CT); Concussion and Dual Task (CDT); Dual Task in Healthy Athletes (DT); Baseline Cognition in Healthy Athletes (BN).

*THE EFFECT OF COGNITIVE LOAD ON LOWER EXTREMITY MOVEMENT IN HEALTHY ATHLETES*

**Dual Task Activities.** While one approach to determine the role of cognitive ability on lower extremity injury risk is to measure natural baseline function, it may not consider the additional resources needed in game time situations. Another approach is to add a second cognitive operation in addition to performing a motor task. The use of single motor tasks to assess athletic performance, such as a drop vertical jump, balance measures, and reaction time have not been specific enough to determine which athletes would ultimately sustain a lower extremity injury.<sup>19</sup> Single motor tasks may not be challenging enough from a cognitive perspective and do not replicate the full demands of sport participation. Dual task paradigms explore the impact on performance when a cognitive task, such as trail making, serial 7's, word spelling, or reciting months in reverse order, is combined with a physical task, such as maintaining postural stability during perturbations, walking, balancing, or

cutting activities. The addition of a cognitive demand, and thus the utilization of dual-task paradigms, has shown increases in the incidence of more risky lower extremity mechanics.<sup>20</sup> The decrease in cognitive or physical performance during dual task paradigms compared to performance during single physical tasks is termed *dual-task cost*.<sup>21</sup>

Ten articles in this category utilized jump landing tasks to examine participants' ability to maintain controlled lower extremity mechanics to decrease injury risk.<sup>4,12,19,20,22-27</sup> Five utilized a similar method of introducing cognitive demand, including counting, math, memorization, and visual distractions,<sup>4,23-25,27</sup> while the other five articles<sup>12,19,20,22,26</sup> used decision-making and sport activities (cutting, passing, overhead goal, dribbling a soccer ball) to increase cognitive demand. In all cases, the ten studies demonstrated that when a second simultaneous task was added, lower extremity mechanics changed including increased number of failed trials,<sup>4,19</sup> decreased overall jump height,<sup>4,23</sup> higher peak vertical ground reaction



**Figure 3. Distribution of experimental designs across content areas.**

Abbreviations: Concussion and Risk Prediction (CRP); Concussion and Testing (CT); Concussion and Dual Task (CDT); Dual Task in Health Athletes (DT); Baseline Cognition in Healthy Athletes (BN).

force,<sup>12,24,28</sup> decreased knee flexion,<sup>12,22,28</sup> decreased postural stability,<sup>25</sup> and increased knee valgus.<sup>22,26</sup> These altered lower extremity mechanics are classified as “risky” mechanics leading to increased lower extremity injury risk.

Three included articles took a different approach to quantify athlete’s ability to maintain safe mechanics during activities other than jump landings, such as balance assessments<sup>29,30</sup> and repeated hop tests.<sup>31</sup> These three articles introduced additional cognitive demand through the use of more reactive tasks such as the Auditory Procedural Reaction Time (APRT) test and the Procedural Reaction Time Throughput (PRTT) test,<sup>29</sup> modified Stroop test and the Brooks Spatial Memory Test,<sup>30</sup> and reaction to color identifying initiation of hopping task.<sup>31</sup> The APRT and PRTT increase cognitive demand through the participant reacting to auditory (APRT) or visual (PRTT) stimuli to assess reaction time. The Stroop test increases cognitive demand through higher level processing to report the color of the work presented which is typically also a color (the word ‘red’ presented in blue font). The Brooks Spatial Memory Test involves a person describing a set of numbers on a grid to a participant and the participant must then report the order of the numbers on a grid from memory, increasing cognitive load during other tasks. Under dual task conditions, reaction time decreased,<sup>29,31</sup> mechanics were modified to maintain stability,<sup>29,30</sup> and athletes had more difficulty maintaining balance control,<sup>30</sup> potentially leading to increased injury risk compared to single task conditions.

#### *THE EFFECT OF COGNITIVE ABILITY AND COGNITIVE LOAD ON LOWER EXTREMITY MOVEMENT IN CONCUSSED ATHLETES*

In recent years, a considerable number of studies have addressed the impact of a concussive event on lower extremity injury risk and the presence of altered lower extremity mechanics post-concussion. These authors focused on the effect of concussion itself on injury risk. A slightly different perspective on this patient population can be taken. Rather than focusing on the diagnosis of concussion, these studies were included as concussions lead to short-term cognitive deficits<sup>32,33</sup> and potentially represent lower cognitive ability. However, due to the transient nature and significant variability of concussive effects,<sup>34,35</sup> the results of these articles were summarized separately from the other categories.

**Concussion and Dual Task Performance.** Four articles<sup>21,36–38</sup> examined the effect a positive history for concussion on participant performance during dual task paradigms. These studies included division I collegiate athletes<sup>21,36</sup> and recreational athletes.<sup>37,38</sup> Cognitive tasks included the Standard Assessment of Concussion (SAC) test, Trail Making A and B, processing speed tasks, spelling five letter words backwards, subtracting by serial 7s from a randomly presented 2-digit number, and reciting the months of the year in reverse order. Participants performed these cognitive tasks while maintaining postural stability, performing an 8- or 10-meter walk test and performing tandem gait tests, functional movement tasks such as jump landing tasks and cutting tasks.<sup>39</sup> Three studies<sup>21,37,39</sup> explored the dual task cost when cognitive assessment tasks

were performed simultaneously during gait tasks while one study examined dual task during quiet stance.<sup>36</sup> All four papers found a decreased level of performance in the recently concussed cohort compared to healthy controls.<sup>21,36,37,39</sup> Participants with a recent concussion not only reported more symptoms, but also walked significantly slower during dual task conditions and responded with slower simple reaction times. Although the differences were less significant during functional tasks, the control group displayed better reaction time than the concussed group during the anticipated cutting and the concussed group displayed greater trunk flexion while cutting.<sup>39</sup> Recently concussed athletes exhibited less postural stability compared to healthy controls, even when tested 6-weeks post-concussion and beyond the resolution of symptoms.<sup>36</sup>

**Concussion and Risk Prediction.** Twenty-two articles<sup>10,11,36,38,40–57</sup> examined the influence of concussion on lower extremity injury rates. Researchers across these studies examined participant data longitudinally and included a wide variety of participant characteristics: both male and female participants, recreational, university, and professional athletes, soldiers, high school-aged athletes, retired professional athletes, participants from multiple countries, and participants across many sport activities. All twenty-two studies reported an increased risk of lower extremity injury after experiencing one or more concussive events. A history of concussion can increase the risk of sustaining a lower extremity injury between 1.60 times<sup>42</sup> to 7.37 times.<sup>40</sup> Injury rates remained increased far beyond the resolution of symptoms and even remained increased following an appropriate return to play (RTP) protocol. A 38% greater risk of lower extremity injury up to two years post-concussion has been reported.<sup>47</sup> Time to lower extremity injury after RTP, was significantly shorter in concussion groups than in control groups.<sup>36,52</sup> Lastly, multiple concussions were often associated with higher incidence or greater odds of sustaining a lower extremity injury,<sup>38,45,48,51,52</sup> with one study reporting a 34% increase in odds of sustaining a lower extremity injury for every previous concussive event.<sup>38</sup>

**Concussion and Baseline Testing.** Ten papers<sup>58–67</sup> examined the effect that a history of concussion has on motor performance. Tests in this category included rapid alternating movement,<sup>58</sup> the Bruininks-Oseretski Test of Motor Proficiency (BOTMP),<sup>61,62</sup> the modified Romberg test on foam,<sup>65</sup> the Balance Error Scoring System (BESS), the Y-balance test,<sup>63,64,67</sup> balance tasks<sup>66</sup> and the functional movement screen (FMS).<sup>59,67</sup> Participants varied in age range and participation level, including children aged 7–16 years old,<sup>61,62</sup> high school athletes,<sup>65,66</sup> recreationally active college students,<sup>59,66</sup> and Division I collegiate athletes.<sup>58,63,64,67</sup>

Five of the ten articles reported significant test performance deficits by participants who had a history of at least one concussive event. Performance test deficits included greater inhibition of the primary motor cortex during a balance task,<sup>58</sup> altered lower extremity stiffness during landing,<sup>60</sup> decreased performance on the BOTMP,<sup>61,62</sup> and increased errors on the BESS test.<sup>67</sup> The remaining five

articles did not find statistically significant differences between concussed and non-concussed groups when examining performance during testing.

## DISCUSSION

Cognition most likely contributes to lower extremity injuries when the system is taxed beyond capacity. Exceeding cognitive limits can occur either due to limited cognitive ability or to increased task demands. Articles addressing both components of cognitive function (ability and demand) were included in this scoping review to assess the robustness of any cognitive contributions to LE injury risk. No constraints were placed on sport, gender or experience level for the same reason. Additionally, studies that directly measured both the predictive ability of cognitive function on lower extremity rates and ones measuring biomechanical factors known to lead to ACL injury were included to cast a wide net. Consistent across participant demographics, tasks, and dependent measures, fifty-one of fifty-six assessed articles concluded that decreased cognitive ability or increased cognitive load led to risky LE mechanics or a direct increase in non-contact LE injury risk. The six studies that did not support the previous statement had some commonalities: four of six had fair or poor methodological quality and five of six fell under the concussion and baseline testing category. Limitations of these latter five articles included: investigating sub-concussive events,<sup>64</sup> fair methodological quality,<sup>63,65</sup> poor methodological quality due to non-matched cohorts,<sup>64</sup> club level athletes as participants,<sup>59</sup> and small sample size.<sup>64</sup>

The results from the 51 papers provide some insight on how clinicians might further consider how to optimize current injury prevention and return-to-sport protocols. A cognitive component contributing to decreased reaction time, decreased attentional resources, and altered LE mechanics leading to increased risk of non-contact injury has largely been ignored in both research and clinical practice settings. Dual task conditions, which are common in sport, challenge cognitive reserve which then results in decreased physical and cognitive performance during biomechanical tasks in both healthy and previously concussed populations.<sup>21</sup> Further research is needed to evaluate the effectiveness of novel prevention and intervention programs that address cognitive functional deficits in addition to biomechanical considerations. Future studies should include methods to quantify the risk associated with altered cognitive function.

## LIMITATIONS

In such a broad, scoping review, decisions for article inclusion to increase the robustness of the findings also created some limitations. The intent of the present study to uncover cognitive contributions to lower extremity non-contact injury risk led to casting a wide net by including athletes with impaired cognitive function (concussion), athletes with a natural variance in typical cognitive function and also athletes undergoing tasks with higher cogni-

tive load (dual-task paradigms). Cognition is impacted both by an individual's cognitive capacity and the cognitive demands of a task. In sport, the cognitive demands are typically high in sports where most non-contact ACL injuries occur (e.g., soccer, basketball). Add to that diminished cognitive ability, either through a natural baseline or through brain injury, an athlete might be at higher risk of injury. It is explicitly for this reason, populations with differences in cognitive ability and populations undergoing tasks with higher cognitive loads were included to determine if both cognitive ability and cognitive demands had a similar impact on injury risk. Far more research exists on the effect of concussion on injury risk than typical baseline function, so this population was included in the present scoping review. These cases of concussion were intentionally evaluated separately in case the results deviated from healthy individuals, which ended up not being the case.

Attempting to define cognitive ability (whether natural variance or after brain injury) is difficult. In this manuscript, the definition provided by Herman and Barth<sup>7</sup> was used, which includes multiple domains presumed not to affect motor function (social interactions, intelligence) and others that do (reaction time, attention, working memory). The findings of this manuscript do not allow the reader to identify the specific cognitive domains most critical for efficient lower extremity function. Future work is needed to pinpoint domains most ripe for intervention to prevent injury.

Studies investigating actual risk (AKA reporting injury rates in sub-populations) and studies measuring lower extremity mechanics thought to lead to non-contact ACL injury were included in the present scoping review. It is important to distinguish between the two. Research evaluating actual risk were confined to the categories of baseline cognitive function and athletes who have experienced concussion, whereas at least one paper in each category included in this scoping review evaluated changes in lower extremity mechanics based on cognition (either cognitive capacity or task cognitive load). Caution must be taken in the interpretation of changes in mechanics as it may not directly lead to injury.

Although 56 articles were included in the present scoping review, not enough articles existed to allow any conclusions to be made specific to gender, age, or level of sport. Interestingly, in spite of the significant variation in researched sport, level of competition and gender, the results were surprisingly consistent that cognition did appear to play a factor. An interesting line of future research would be to explore any one of these categories relative to cognition and injury risk.

Some may consider another limitation of the present scoping review is that of including eleven doctoral dissertations, although others would not. While these documents would have not gone through blinded peer-review, they would have been extensively reviewed by a dissertation committee that would presumably consist of experts in the research area. The methods of the dissertations were reviewed in the same manner as the published articles to

ensure methodological quality using the NIH checklist. None of them exhibited poor or fair quality.

Overall, the literature is dominated by concussion studies, and more research needs to focus on cognitively typical populations. Of the studies that do study cognitive function and dual tasks, large variability exists in the objective measures used to demonstrate decreased cognitive function, allowing for limited capability in comparing measures among studies. Future research will need to determine cut-off scores for cognitive tests and dual task performance tests to better define what constitutes an at-risk athlete based on cognitive performance.

#### CLINICAL IMPLICATIONS

Determining the impact of cognitive function on non-contact LE injury will guide rehabilitation professionals to develop innovative, evidence-based prevention strategies to decrease risk of non-contact LE injury in a wide variety of populations that may have a cognitive component to injury risk. Training cognitive factors may serve as the missing link in highly effective and robust injury prevention programs and warrants further study.

#### CONCLUSIONS

Results of this scoping review demonstrate decreased cognitive function and increased cognitive load related to task demands are associated with increased lower extremity injury risk via decreased attentional resources, slowed reaction time, and altered LE mechanics. Further investigation is needed to understand how cognitive function can be improved to decrease the risk of future non-contact LE injury, address these deficits and to better understand how baseline cognition and dual task conditions can impact and improve functional rehabilitation protocols. Additionally, it will be important to determine how functional rehabilitation protocols can maximize performance in individuals with a history of concussive event(s) or otherwise lower cognitive function.

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Authors have nothing to report.

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**Appendix 2. Summary of study demographics, methods, and results.**

No.	Participants	Task	Dependent measures	Results / Conclusions
1	Recreationally active females aged 18-25 (n=45) competing in sports involving landing and cutting (basketball, soccer, tennis)	ImPACT and biomechanics testing including a forward jump with pre-planned and unplanned conditions. Unplanned conditions included: (1) lateral cut from non-dominant limb (2) single leg landing on non-dominant limb without subsequent cut (3) bilateral landing and vertical jump. Participants unaware of which maneuver would be performed until after initiation of the trial. Planned trials included only the lateral cut stimulus.	ImPACT reaction time; hip, knee, ankle joint angles and net joint moments; hip flexion, knee flexion and knee abduction initial contact angles and range of motion (ROM= peak angle-angle at initial contact); peak knee abduction moments and peak vGRFs.	Participants with slower reaction times demonstrated higher peak vGRFs compared to participants with faster reaction times, regardless of cognitive demands. Landing with higher vGRFs may increase injury risk.
2	134 athletes (93 with injury, 41 without) aged 14-17 in local ski and snowboard club in 2009-2012 seasons	ImPACT scores (administered prior to each competitive season) and injury records.	Components of ImPACT and each sub-component score including reaction time (RT), verbal memory, visual memory, visual motor speed (VMS), and cognitive efficiency index and injury rates.	No significant difference between non-injured and injured females or males in RT and VMS. RT for injured females was 4.7% faster while males without injury had a 5.8% slower reaction time. Females with injury had a 4.1% higher mean VMS score while males without injury had a 14.4% higher VMS score.
3	Recreational athletes 18-30 years (n=28) who (1) participate in jumping or squatting sports at least 3 times a week or (2) participate in jump/squatting sports at least once per month and participated at the high school varsity or collegiate club levels.	Concussion Resolution Index (CRI). Based on CRI scores, subjects were placed into high performers (n=14) and low performers (n=14) groups. Task consisted of a forward jump onto a force plate with an immediate rebound to a second target that was assigned 250 ms before landing on the force plate.	Three-dimensional kinematic and kinetic data of the dominant limb were collected while performing an unanticipated jump-landing task	The low performers group demonstrated significantly altered neuromuscular performance during the landing phase of the jump-landing task, including significantly increased peak vGRF, peak anterior tibial shear force, knee abduction moment, knee abduction angle, and decreased trunk flexion angle.
4	Physically active university-aged males (n=41) (14 with no history of ankle sprain, 13 with history of 1 ankle sprain, 14 with chronic ankle instability [CAI])	CNS Vital Signs computer-based neurocognitive tests (verbal memory, visual memory, finger tapping, symbol digit coding, Stroop, and shifting attention)	CNS Vital Signs score	CAI group had significantly lower composite memory, visual memory, and simple attention compared to control group. Single ankle sprain group demonstrated poorer visual memory compared to controls.
5	Female athletes (n=15) (age 20.1 +/- 1.3 years) who engage in university athletic club	Symbol Digit Modalities Test (SDMT) and unanticipated cutting tasks. Participants were asked to fill out 110 boxes under symbols	Joint angles and moments measured muscle activity of dominant leg during unanticipated cutting task using a	Subjects with a lower SDMT score had significantly increased quadriceps activity before and after ground contact and decreased co-contraction ratio only after ground contact. Dominant quadriceps activity has been

No.	Participants	Task	Dependent measures	Results / Conclusions
	jumping or cutting sports.	with the corresponding number within 90 seconds, referring to a key on top of the test form to identify which number goes with each symbol. Experimental tasks were three unanticipated cutting tasks: (1) sidestep (2) single leg landing and (3) forward step.	3-dimensional motion analysis system and surface EMG.	reported to increase the load on the ACL, increasing the risk of ACL injury.
6	160 athletes (80 noncontact ACL injuries, 80 controls) from 18 universities. Of the 80 non-contact ACL Injury (NCAACL) athletes, 45 women (age 20.6 +/- 1.7 years) and 35 men (age 20.8 +/- 1.1 years). Control group was randomly matched based on similar characteristics.	Participants completed the 4 subtests of the ImPACT version 2.0 and injury data.	Pre-season ImPACT score results from ImPACT subtests, including verbal memory, visual memory, processing speed, and reaction time	Statistical differences were found between the non-contact ACL-injury group and the matched controls on all 4 neurocognitive subtests. Non-contact ACLs are associated with errors in coordination. Neurocognitive differences identified between groups may predispose athletes to non-contact injuries.
7	NCAA-FCS collegiate football players (n=76) (19.8 +/- 1.5 years) participating in the 2011 pre-season practice sessions	Pre-season ImPACT test results and injury data	ImPACT test score results and injury statistics	Participants with increased RT were at increased risk of sustaining a LE injury. Thus, athletes who exhibit slower neurocognitive reaction time, as determined by computer-based testing, may derive the greatest benefit from activities designed to enhance responsiveness to visual stimuli.
8	Recreational college females (n=20) age 18-25 with experience in organized basketball	Landing jump plus lateral cutting trials conducted in 3 different conditions (1) pass: while carrying a basketball and execute a chest pass immediately upon landing, (2) ball: carrying a basketball with no chest pass, (3) cut: lateral cut without hold ball or performing chest pass	Peak vGRFs for the plant limb; angles of hip flexion and peak knee abduction at initial contact for plant or landing limb; hip flexion ROM, knee flexion ROM and knee abduction ROM. (ROM measured by the difference between peak joint angle and the angle at initial contact for each trial). Knee abduction infers a 'valgus collapse' of the knee, characterized by the knee moving medially while the distal end of the shank angles away from the midline of the body.	Participants landed with less knee flexion and greater knee abduction (valgus) when required to focus attention on a chest pass following a cut. Requiring participant to focus attention on performing a chest pass resulted in a landing pattern that would likely increase demands on the ACL.
9	Recreational college females (n=20) age 18-25 with experience in	Drop vertical jump (DVJ) task with 4 conditions (1) without decision making or overhead goal, (2) with	2D and 3D knee ankle (KA) ratio measure (KA: horizontal distance between knee joint centers divided by	Participants demonstrated decrease in the KA ratio, indicating increased knee valgus, when the overhead goal condition is added to a DVJ, relative to the baseline. Including an overhead

No.	Participants	Task	Dependent measures	Results / Conclusions
	organized basketball	decision making but no overhead goal, (3) without decision making with an overhead goal, (4) with both decision making and overhead goal.	horizontal distance between ankle joint centers).	goal has the potential to influence landing mechanics. Landing in this manner may place an individual at high-risk for ACL injury since it corresponds with valgus collapse of either one or both knees.
10	Recreational college females (n=20) age 18-25 with experience in organized basketball	(1) Standard DVJ without decision-making or overhead goal (2) DVJ without decision-making but with an overhead goal (3) DVJ with decision-making but without overhead goal and (4) DVJ with both decision-making and overhead goal.	Initial contact and peak knee flexion and abduction angles, peak knee abduction moments, peak vGRFs, vertical jump height, and stance time	Including a DVJ + overhead goal results in higher peak vGRFs and lower peak knee flexion angles compared to standard DVJ. Also, including an overhead goal and/or decision-making resulted in greater peak knee abduction angles compared to standard DVJ. Imposing additional cognitive demands during DVJ task influences lower extremity mechanics in a way that suggests increased loading to the ACL.
11	Recreationally active males (n=11) and females (n=9) aged 20-23 who play one of five sports: basketball, football, rugby, soccer, or lacrosse	Tasks were randomized for each participant: Jump landing tasks with no concurrent cognitive task, jump landing task with dual task condition consisting of: Stroop Color Word Test (SCWT), Symbol Digits Modalities Test (SDMT), and Brooks Visuospatial Task (BVT)	(1) LESS score, (2) Reaction time in sec, (3) Speed and % error performance of cognitive variables (SCWT, SDMT, BVT)	Movement quality, as assessed by LESS, did not change during dual task conditions. Gross RT was slower during dual-task conditions. Cognitive task completion speed INCREASED during dual task conditions. Test accuracy decreased (more errors) for all cognitive dual task conditions (SCWT, SDMT, BVT) compared to baseline testing. Increased number of failed trials in SCWT, SDMT and BVT dual task conditions compared to baseline trials. Participants sacrificed reaction time and accuracy on the cognitive task to produce a consistent movement pattern. Increased cognitive task speed during dual task conditions compared to baseline can be explained by increase in attention during dual task conditions.
12	Recreationally active athletes (n=38) who play sports involving jump landings	Drop jump task lateral to 50% standing height followed by a maximum vertical jump. Three reps performed solo, counting backwards by 1, and counting backwards by 7.	First 100 ms of first landing: knee kinematics, vGRF, knee valgus, posterior GRF, jump height, stance time.	Participants demonstrated decreased knee flexion angles at initial contact for the counting by 1 s condition compared with the no counting condition. Participants showed increased peak posterior GRF and vGRF during early landing and decreased jump height for the counting by 1s and counting by 7s conditions compared with the no counting condition. The authors had minimal criteria for counting trials, and the number of trials that had to be performed to get a 'correct' trial increased with the increased demands of the task.
13	Healthy, physically active 18-25 (20.43 +/- 1.33) year old males (n=14) and females (n=16)	Participants completed the Sensory Organization Test (SOT), Balance Error Scoring System (BESS), Procedural Reaction Time Throughput (PRTT), and Auditory Procedural Reaction Time (APRT) in both single and dual task conditions.	Scores on SOT, BESS, PRTT, APRT, and cost to balance and auditory (% change in performance from single task to dual tasks on SOT and BESS)	Balance performance on the BESS (14.236 ± 31.003) showed a greater percentage cost compared to balance performance on the SOT (1.993 ± 4.873) during a dual task. Combining a cognitive test aimed at processing speed and attention with the BESS and SOT has the potential to be a more sensitive test than these same measures performed during a single task.

No.	Participants	Task	Dependent measures	Results / Conclusions
14	10 male, 10 female age 22.4+/-1.314 years who participated in exercise at least 3 hours a week	Participants completed a tuck-jump trial over 3 cognitive conditions (control, easy, difficult). The easy cognitive task consisted of digit recall of a string of 5 numbers and the difficult task consisted of use of arithmetic of a string of 5 numbers.	Overall tuck jump score; peak vertical ground reaction force	There was a significant increase in tuck jump score from baseline to easy cognitive task and baseline to difficult cognitive task, but no significant increase from easy to difficult. There were no significant differences in mean vGRF; it may be possible that the easy and difficult cognitive tasks may have been distracting enough to decrease jump height, resulting in a decrease in vGRF.
15	9 male, 13 females aged 20.9 +/- 2.5 years who were healthy and active for 3 days/week with no LE injury or surgery within the past 6 months.	Four single-leg (SL) hops (traditional condition): (1) SL hop for distance (2) 6-m SL hop for time (3) SL cross-over hop for distance and (4) SL triple hop for distance. Participants also performed the four types of SL hops with a neurocognitive condition implemented using the FitLight system with colors indicating when to hop.	Quickest reaction time, maximum hop distance.	The crossover hop, triple hop and 6-m were statistically different between traditional and neurocognitive conditions. No significant difference between SL hops traditional or neurocognitive condition.
16	Healthy male subjects (n=12) age 24.4 +/- 3.0 years	Participants stood on a force platform holding button switches marked for left and right directions. There was a choice reaction task, a landing task, and a dual task. In the choice reaction, participants responded to a left or right LED light and were instructed to push the corresponding button as fast as possible. In the landing task, participants made a small vertical jump as soon as possible. The dual task was a combination of choice reaction and landing tasks.	vGRF and RT	Greater vGRF and acceleration was observed during SL landing under the conditions in which the participants were required to react to visual stimuli. High impact during landing is known to be related to sprains. Results suggest that athletes are exposed to higher impact forces in a real sport environment than during a controlled landing task, in which they can cognitively focus on absorbing the impact.
17	Convenience sample of healthy college students. 22 female, 8 male; age 20.8 +/- 1.6 years	SL stance and SL squat tasks on a force plate individually (single task) and concurrently (dual task) with two cognitive assessments, a modified Stroop test and the Brooks Spatial Memory Test.	Center of pressure speed, 95% confidence ellipse, squat depth, and speed and cognitive test measures.	Not all dual task paradigms have the same effect on postural control. Squat performance is compromised during dual task conditions. RT is slowest during dynamic movement with a dual task added. Individuals alter their biomechanics during dual task conditions to maintain stability and correctly complete the cognitive assessments.
18	6 recently concussed NCAA DI athletes, 25 healthy athletes with no concussion history, 25 healthy physically active	Concussed and healthy participants stood barefoot with feet together on a force platform and instructed to stand still for 2 minutes. Three additional quiet standing trials with additional instructions	Center of pressure (COP) displacement, COP oscillation regularity, motor execution speed, long-interval intracortical inhibition, cortical silent period	Concussed athletes exhibited less postural stability complexity compared to healthy athletes, providing evidence that postural stability complexity remains affected by concussive deficits 1-6 weeks post-concussion. Post-concussion postural deficits persist beyond the recovery of clinical signs and symptoms. Non-athlete participants demonstrated an increase

No.	Participants	Task	Dependent measures	Results / Conclusions
	non-athletes with no concussion history.	were then performed randomly: (1) co-contraction (2) cognitive task of counting and (3) with control of body sway undetectable to outside observer. Concussed athletes were tested weekly for 6 weeks post-concussion.		in postural stability complexity during co-contraction task. This study did not find an effect of an added cognitive task on postural complexity.
19	Division 1 collegiate athletes with recent concussion and larger matched control group (18 tested within 5 days of concussion, 41 tested as part of a baseline examination)	Participants completed the Standard Assessment of Concussion (SAC), Trails A and B Test, a processing speed task (Symbol Digit Modalities, simple reaction time task, choice reaction time task, dynamic visual acuity test, and dual task conditions) for a 10-meter walk as follows: (1) spelling a five-letter word backwards, (2) subtracting by 6s or 7s from a randomly presented 2-digit number, or (3) reciting months of the year in reverse order starting from a randomly chosen month.	SAC score, Trail Making A time, Trail Making B time, processing speed with number of correct answers, simple reaction time, choice reaction time, visual acuity line difference, and average gait speed.	Participants with concussion reported significantly more severe symptoms, walked significantly slower during dual-task conditions, and responded with significantly slower simple reaction times.
20	Recreational athletes with subsequent injury (n=15) and with no subsequent injury (n=27) that sustained a concussion were evaluated for dual task gait outcomes within 3 weeks and after recovery	Post-Concussion Symptom Scale (PCSS) evaluated symptom severity and dual task conditions during an 8-meter walk test as follows: (1) spelling a five-letter word backwards, (2) subtracting by 6s or 7s from a randomly presented 2-digit number, or (3) reciting the months in reverse order starting from a randomly chosen month and calculated dual task cost between no task and dual task conditions.	Dual-task gait cost	Significant dual-task gait cost worsening throughout concussion recovery was associated with time-loss injuries during sport performance in the year after a concussion.
21	Recreational athletes with recent concussion and matched controls (concussion n=15, control n=15)	Tandem gait with varied conditions: (1) eyes open, no distraction (2) eyes closed, no distraction (3) eyes open, with cognitive distraction (Brooks Visuospatial Task), and (4) eyes closed, with cognitive distraction. Joint kinematics and reaction time data	COP data, joint kinetics and kinematics, velocity on tasks, and reaction time	The recently concussed group demonstrated slower velocity during tandem gait compared to the control group. Greater dual-task cost was observed for COP speed, such that the concussion group reduced their COP speed to a greater extent than the control group during the eyes closed dual-task condition as compared to the eyes closed, no cognitive task condition. There were no between-group differences in reaction time

No.	Participants	Task	Dependent measures	Results / Conclusions
		during jump-landing, anticipated-cut, and unanticipated cut.		during cutting tasks, but the control group displayed better reaction time cost than the concussed group during anticipated cutting. The concussed group displayed greater trunk flexion compared to the control group during anticipated cut towards the non-dominant side.
22	NCAA D1 athletes; 116 males, 48 females. 82 recently concussed athletes (58 males, 24 females) were randomly matched with one non-concussed subjects by sex, sport, position, calendar year, and BMI.	Medical records pertaining to any documented LE musculoskeletal injury that had occurred in the 90-day period prior to the concussed subjects' sport-related concussion and in the subsequent 180-day period after the concussed athlete returned to play was collected and analyzed and compared to matched controls. All athletes performed ImPACT testing.	Documented musculoskeletal injury data	The frequency of LE musculoskeletal injury during the 180-day observation window following return to play was greater in concussed athletes (62.2%) when compared with matched controls (25.6%). The odds for an athlete with a history of concussion, sustaining a LE musculoskeletal injury after returning to play following a concussion is 7.37 times greater in the same period compared to athletes who have not sustained a LE injury.
23	58 male and 17 female athletes with 87 total cases of concussion participating in NCAA DI football, soccer, hockey, softball, basketball, wrestling, or volleyball from 2011-2014 matched with 182 control athletes without a history of concussion in the previous year.	Concussion diagnosis, onset, return-to-play date and MS injury diagnosis and onset were collected through the SIMS database. During the 90-day-period after return-to-play for each case was reviewed for LE MS injury as well as the year before enrollment to account for previous injury history and was compared with the same 90-day period in up to 3 control athletes.	Lower extremity injury incidence rate	Concussed athletes have increased odds (17%) of sustaining an acute lower extremity MS injury during the 90-day return to play than non-concussed matched controls (9%). No difference in time to lower extremity injury in controls and concussed athletes.
24	Participants were athletes who suffered a concussion (n=4,961) aged 15-35, and played either ice hockey, football (soccer), floorball, and handball in the data base of the University Hospital in Umea, Sweden during the years 1993-2009. Control group of athletes (n=1,259) with	Injury data from 24 months before and 24 months after the index injury (concussion for study group; ankle sprain for control group) were analyzed.	Injury data	Athletes with concussion had higher risk for injury both before and after the index injury, compared with the control group (OR 1.98 before and 1.72 after). Athletes with concussion suffered two or more times the number of injuries before and after concussion compared with control group. No significant increase in overall number of injured individuals after the concussion compared with before. Athletes who sustained concussion were more injury prone, in general.

No.	Participants	Task	Dependent measures	Results / Conclusions
	ankle sprain, obtained from the same data base and played the same sports.			
25	First-team players in 12 highest level club rugby teams in England (n=810)	Incidence of concussions and 24-hour time-loss injuries recorded by medical personnel	Incidence rate for injury before concussion and following RTP from concussion	Of 810 players in study, 150 reported 181 concussions. Following a concussion, players were 1.6 times more likely to suffer a match injury of any type than players who had not sustained a concussion. Pre-concussion incidence for injury not significantly different between groups.
26	76 male and 34 female NCAA D1 athletes with average age 20.1 years that were matched with non-concussed controls.	Medical records reviewed on 110 concussed athletes and 110 matched controls for LE injuries within the year before and year after concussion.	Previous injury in last year, time from concussion to LE injury.	The concussed group had a 67% greater instantaneous relative risk of LE injury compared with controls after adjusting for the presence of a previous LE injury.
27	College athletes (n=335) (17 different NCAA and NJCAA member institutions) from 13 sports at the end of their athletic career	Self-report questionnaire indicating total number of reported, unreported, and potentially unrecognized concussions as well as LE injuries including ankle sprains, knee injuries, and muscle strains.	LE injury data	Significant associations found between concussion and lateral ankle sprain, concussion and knee injury, and concussion and LE muscle strain.
28	NCAA DI athletes (n=48) from one institution who sustained multiple concussions between 2001-2016.	Athletes with multiple concussions (MC) were matched with athletes with single concussion (SC) and to athletes with no concussion history (NC). Incidence of time to and location of injury were recorded after RTP from first reported concussion until completion of collegiate career.	LE injury data (rate to injury and odds of future injury) after RTP.	Incidence of LE injury after RTP was significantly greater in MC cohort than SC and NC athletes. Odds of LE injury were significantly greater in the MC cohort than in SC and NC athletes. Time to LE injury was significantly shorter in the MC group compared with matched controls.
29	NCAA DI athletes from M football, W basketball, W soccer, and W lacrosse with in-season concussion between 2006-2013. (52 males, 21 females)	Injury surveillance data from the University of Florida Athletic Association	LE injury data	LE musculoskeletal injuries occurred at a higher rate in concussed athletes than in non-concussed athletes. Odds of sustaining a musculoskeletal injury were 3.39 times higher in concussed athletes.
30	NCAA DI and DIII athletes (n=468)	Retrospective self-report questionnaire reporting concussion, knee, and ankle sprains.	Concussion and LE injury history	Females with concussion history had greater odds of reporting an ankle sprain or knee injury compared to females with no concussion history. No difference found for males with or without concussion. Athletes reporting multiple concussions had the greatest odds of ankle sprain or knee injury history.

No.	Participants	Task	Dependent measures	Results / Conclusions
31	NCAA DI athletes with sport-related concussion (n=24) compared with matched control concussion (n=27).	Electronic medical record review for concussion and LE injuries	Number and type of musculoskeletal injuries sustained after concussion	Participants with concussion were 2.95 times more likely than non-concussion group to sustain a LE musculoskeletal injury within 1 year of sport participation clearance. Participants with concussion were 2.9 times more likely to sustain any type of LE injury and 2.25 times more likely than the control group to sustain a non-contact injury within one year of RTP.
32	Active-duty US Army soldiers from 2005 to 2011 that sustained a concussion (n=11,522) and matched control that did not have a concussion (n=11,522).	Retrospective review of medical records following concussion identifying ICD-9 codes for lower extremity injury following a concussion	LE musculoskeletal injuries sustained after initial concussion and during same time period for matched controls	Within 2 years of concussion, the hazard of LE injury was 38% greater in concussed compared to control soldiers, while the 15-month hazard was 45% greater.
33	US high school athletes with concussion, ankle sprain, or knee sprain (n=1,613)	Retrospective review using AT-PBRN database for knee sprains, ankle sprains, and concussions	LE musculoskeletal injury data consisting of knee or ankle sprain	Sport related concussions, and the number of concussions, were associated with increased knee and ankle sprains.
34	NCAA DI male collegiate football athletes, 12 of which sustained a concussion, 50 without concussion	Cohort analysis of collegiate football athletes over a 5-year period to track incidence of concussion and lower extremity injury	LE injury data	No significant difference in LE injury rates between the athletes post-versus pre-concussion or between the post-concussion and no concussion (control) athletes. There was an increased LE injury risk beyond 12 months in the post-concussion group compared with the no concussion group. Line position players had an increase in LE injuries after a concussion compared with linemen with no concussion.
35	College athletes with concussion (n = 44) and matched non-concussed college athletes (n = 58).	Compared acute LE musculoskeletal injury rates before and after concussion in athletes with concussion and their matched control over a 2-year period.	Musculoskeletal injury rates 90, 180, and 365 days post-concussion for both study cohorts. Risk ratios were calculated for all time periods.	Within one year after concussion, the group with concussion was 1.97x more likely to have experienced an acute LE injury after concussion than before concussion and 1.64x more likely to have experienced an acute LE injury after concussion than their matched non-concussed cohort over the same time period. Up to 180 d after concussion, the group with concussion was 2.02x more likely to have experienced an acute LE injury after concussion than before concussion.
36	High School athletes (n=18,216)	Retrospective analysis of National Athletic Treatment, Injury and Outcomes Network	(1) any LE injury, (2) a time-loss LE injury, or (3) a non-time-loss LE injury after concussion	For every previous concussion, the odds of sustaining a subsequent time-loss LE injury increased 34% (odds ratio [OR] = 1.34). The number of previous concussions had no effect on the odds of sustaining any subsequent LE injury (OR = 0.97) or a non-time-loss injury (OR = 1.01).
37	Senior professional male football (soccer) players (n=1,665) from	Analysis of exposure to and occurrence of concussions and LE injuries.	LE risk following injury	During the follow-up period, 66 players sustained concussions and 1,599 players sustained other injuries. Compared with the risk following other injuries, concussion was

No.	Participants	Task	Dependent measures	Results / Conclusions
	10 European countries (mean age of 26 +/- 1 years) were followed prospectively for 172 team-seasons			associated with a progressively increased risk of subsequent injury in the first year.
38	Former NFL players (n=2,429) who retired between the years of 1930 and 2001 part of the Health Survey of Retired NFL Players.	Participants completed a survey detailing their injury history while participating in the NFL.	History of concussions and musculoskeletal injuries	Nearly 61% of participants who responded had experienced a concussion while competing in the NFL. Compared with players who did not sustain a concussion, players who did sustain concussion were more likely to have sustained various musculoskeletal injuries. A history of concussions was associated with higher odds of reporting musculoskeletal injuries.
39	University level football players (age 19-26) who sustained concussion (n=21), who had not sustained concussion (control n=15)	Rapid alternating-movement task on force platform	COP displacement, COP oscillation regularity, motor excursion speed, long-interval intracortical inhibition, cortical silent period	Previously concussed athletes demonstrated persistently lower COP oscillation randomness, normal performance on a rapid alternating-movement task, and more M1 intracortical inhibition. Results demonstrate neurophysiologic and behavioral evidence of lasting, subclinical changes in motor system in concussed athletes.
40	55 male (n=38) and female (n=17) healthy collegiate club sport athletes aged 20 +/- 1.49 years active in M/W rugby, M lacrosse, ultimate frisbee and cheerleading.	11 item health questionnaire assessed current and past health history. Functional Movement Screen (FMS) includes 7 tests: deep squat, hurdle step, inline lunge, shoulder mobility test, active SLR, trunk stability test, rotary stability test. FMS performance was compared with concussion history.	FMS composite score	No difference in composite FMS score in those with or without a history of concussions, nor were individual FMS tests correlated with concussion history. After controlling for BMI and age, the hurdle step did have a small significant correlation to history of concussion.
41	NCAA DI male football players during competitive seasons 2007-2011. 13 with concussion matched with 26 uninjured players with no history of concussion	Motion Capture System recorded subject jumping on one limb from a 25.4 cm high step onto a force plate. Hip, knee, and ankle joint stiffness were calculated from initial contact to peak joint flexion using the regression line slopes of the joint moment versus joint angle plots. Both limbs were tested, and participants were tested both pre-season and post-season.	Joint moments, peak flexion angles at initial contact, peak external flexion moments (kg) for hip, knee, and ankle.	At pre-season, there were no differences in stiffness measures between groups. From pre- to post-season, the concussion group showed an increase in hip stiffness, a decrease in knee and leg stiffness, and no change in ankle stiffness. The concussion group demonstrated altered stiffness from pre-season to post-season when compared to the uninjured group. Decreased hip peak moments and increased hip angular excursion at post-season testing may result in increased hip flexion, thus increasing hamstring activation while decreasing quadriceps activation.
42	76 children aged 7 to 16 years, n=38 in each group. Children with mTBI who were considered	Bruininks-Oseretski Test of Motor Proficiency (BOTMP)	Response time using the response speed subtest of the Bruininks-Oseretski Test of Motor Proficiency (BOTMP)	BOTMP raw score revealed no statistically significant differences between the groups across all testing sessions although a strong tendency could be observed. The mTBI children performed than those non-injured only at 1-week post-injury. The injured

No.	Participants	Task	Dependent measures	Results / Conclusions
	normal neurologically at the time of hospital discharge in experimental group. Control group were friends of those with mTBI.			children presented with lower scores in the first week when compared to those of the fourth and of the 12th week.
43	76 children aged 7 to 16 years, n=38 in each group. Children with mTBI who were considered normal neurologically at the time of hospital discharge in experimental group. Control group were friends of those with mTBI.	Balance subtest of BOTMP, Pediatric Clinical Test of Sensory Interaction for Balance (P-CTSIB), and the Postural Stress Test (PST)	Scores on BOTMP balance subtest, PTST, and P-CTSIB	Children with mild TBI performed significantly worse than the non-injured group on the BOTMP balance subtest, PST, and the eyes-closed conditions in the P-CTSIB tandem position.
44	High school athletes (n=12 concussion, n=12 control)	Subjects performed four randomized tests: Automated Neuropsychological Assessment Metrics (Simple Reaction Time, Matching to Sample, Continuous Performance, and Stanford Sleepiness Scale), Standardized Assessment of Concussion, Trail Making A & B, and Modified Romberg on foam.	Scores on testing	Test measures were unable to detect differences between groups; however, the injured groups' scores were initially lower and remained lower over the course of the study
45	20 subjects recruited from high schools, colleges, and universities in Pennsylvania, n=10 healthy control, n=10 mild head injury.	Descriptive study that analyzed relationship between concussion, neurocognitive function, and postural stability (single leg standing with eyes open/closed conditions)	Neurocognitive function within 7 days of the injury using ImPACT test. Postural stability was measured using a 3D kinematic motion analysis system and a force platform.	There were no significant differences in postural stability or neurocognitive function between groups. No relationship existed between postural stability and neurocognitive function. There may be trends to suggest that visual memory and reaction time are different between groups.
46	NCAA DI collegiate athletes Concussed participants included 23 males, 22 females (n=45) age 19 +/- 1.3 y, controls (n=45) were matched by gender, sport, and age.	Participants completed a static (Balance Error Scoring System) and dynamic (Y-Balance Test) balance assessment	Scores on the BESS and Y-Balance	Static and dynamic balance performance did not significantly differ between groups.
47	Division I men's lacrosse players	Participation in one lacrosse season (15	BESS scores	The number of errors from pre- to post-season increased during the

No.	Participants	Task	Dependent measures	Results / Conclusions
	(n=34) age 19.56 +/- 1.44 years	games, 45 practices). Pre and post season BESS performance; linear acceleration, head injury criteria, and Gadd Severity Index scores were recorded using Warrior Sports Regulator II helmets instrumented with a GForce Tracker sensor internally fixed to the crown of the helmet.		double leg stance on foam, tandem stance on foam, on total numbers of errors on a firm surface, and on total number of errors on a foam surface. There were significant correlations only between total errors on a foam surface and linear acceleration, head injury criteria, and Gadd Severity Index.
48	15 NCAA DI football athletes that were diagnosed with concussion and 13 non-contact athletes	The effects of concussion on postural stability in NCAA DI athletes using BESS pre- and post-season	BESS scores	No clinically significant deficits in postural stability were measured over the course of a single season.
49	59.0% male, (612/1037), age: 31.6 ± 11.3 years, rugby players (10.1 ± 8.1 years played)	85 item health questionnaire, 55 of them from the reliable Gilbert injury history questionnaire. 30 questions were demographic.	ankle sprain, multiple ankle sprain, knee injury, fractured LE bone, LE muscle strain, ACL injury, LE-MSI	significant association found between concussion and LE-MSI for both males and females. Significant association for specific LE-MSI outcomes except ACL injury.
50	male sex, age between 20 and 40 years, engagement in regular physical activity, a minimum of 12 school years (= at least upper secondary education), and a minimum counter-movement jump (CMJ) height of 30 cm (corresponding to a flight time of about 500 ms).	participants did 70 counter movement jumps with planned and unplanned single leg landings. The planned or unplanned nature was received from the participant by visual stimulus, they then landed on a pressure plate to test cognitive function and unplanned landing costs.	time to stabilization (TTS), center of pressure (COP-path length) and the vertical peak ground reaction force (pGRF)	no significant difference in landing stability or error counts observed, thus, no substantial fatigue or learning affects. Unplanned landing jumps had significantly lower flight time than planned. Unplanned landing had higher COP path length and significantly more standing errors. No difference for TTS and pGRF.
51	current members of a men's collegiate club outdoor soccer team or had been members in the past 2 months. No history of traumatic knee or ankle injury in the past 3 months that limited their participation in soccer. Required to have a score 7 on the Tegner Activity Scale and a score 12	Kinetic and kinematic data taken from non-dominant leg during single task non-ball handling and dual task ball handling. These were done while running and cutting at a 45-degree angle in a single step. They also completed the ImPACT cognitive assessment.	approach speeds, exit speed, ImPACT composite score for visual memory, verbal memory, processing speed and reaction time	Greater pKVA values were associated with worse visual spatial memory. BH had a significant group effect on pKVA.

No.	Participants	Task	Dependent measures	Results / Conclusions
	on the Marx Activity Scale. No concussion in the past 10 weeks.			
52	division one student athletes between the ages of 18-25 currently involved in a university sport	injury records were looked at following the athletic season. The participants did 3 trials of eyes open and eyes closed upright quiet stance during baseline testing.	documented injury, postural control	association between concussion history and injury was significant.
53	adolescent athletes between the ages 12-15 playing on youth club sports teams in the sports of volleyball, baseball, soccer, softball, basketball, track and field, lacrosse, swim, and ice hockey.	A survey with a comprehensive injury history was filled out. Then subjects with concussions were matched with those who did not have concussions and a statistical analysis was done on the data from the two groups.	LE injury data	History of concussion in the athletes was associated with LE injuries but was different between males and females.
54	male elite college athletes. 14 basketball, 22 rugby, 11 baseball, 15 ice hockey, 15 soccer. No orthopedic acute injury or concussion in the past 6 months. Participate in training and competition.	First the Korean version of SAC was used for the neurocognitive evaluation. It consisted of a mental test, memory test, concentration test, and a delayed memory test. Then postural control of the lower extremities was evaluated using LESS, BESS, and SEBT. The data was then analyzed and assessed for correlations.	test results	weak to moderate correlation between SAC and SEBT. SAC, LESS, BESS and SEBT do not influence the occurrence of lower extremity injuries.
55	National Collegiate Athletic Association Division I Football Bowl Subdivision football players from two consecutive seasons. Season 1 players 113 (age= 19.7 + or - 1.4 years, height = 188.0 + or - 6.8 cm, mass = 106.9 + or - 22.7 kg), and season 2 players totaled 112 (age = 19.7 + or - 1.4 years, height = 187.2 + or - 6.8 cm, mass = 108.3 +	The athletes started by doing a preparticipation screening that classified them as low risk or high risk for injuries in the upcoming season based on how they scored on a neurocognitive test and a plank test. Then data was collected over the next two seasons on who was injured.	Injury data	players with increased risk of injury were proven to score FPH less than or equal to 120 seconds, verbal memory score less than or equal to 87, composite reaction time greater than or equal to 560 milliseconds, and starter status. Players with 2 or more of the 4 risk factors demonstrated 44% sensitivity and 91% specificity.

No.	Participants	Task	Dependent measures	Results / Conclusions
	or - 22.3 kg)			
56	students from the university's sports science Bachelor's and Master's programs. Most participants were involved in either soccer, basketball, or handball.	Participants used a capacitive pressure platform to do 30 bilateral counter movement jumps. After each jump the participants measured how long they could maintain a stable one-legged landing position. During the jumps there were varying degrees of visual demand to add a visual distraction.	flight time, landing errors, recall errors, peak ground force reaction, time to stabilization, and center of pressure trace lengths.	as the amount and degree of visual distraction increases, recall precision and landing biomechanics decrease.

LE=lower extremity, vGRF=vertical ground reaction force, RT=reaction time, VMS=visual motor speed, CAI=Chronic Ankle Instability, SDMT= Symbol Digit Modalities Test, DVJ=Drop Vertical Jump, SCWT=Stroop Color Word Test, BVT=Brooks Visuospatial Task, LESS=Landing Error Scoring System, SOT=Sensory Organization Test, BESS=Balance Error Scoring System, PRTT=Procedural Reaction Time Throughput, APRT=Auditory Procedural Reaction Time, SL=Single Leg, COP=Center of Pressure, SAC=Standard Assessment of Concussion, PCSS=Post-Concussion Symptom Scale, RTP=Return to Play, M=Men's, W=Women's, FMS=Functional Movement Screen



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## APPENDICES

APPENDIX 1. SPECIFIC ELECTRONIC SEARCHES USED IN PUBMED, EBSCO – CINAHL, SPORTDISCUS AND GOOGLE SCHOLAR.

“neurocog\*” AND (“lower extremity injury” OR “leg injury”)

    (“concussion” OR “mTBI”) AND “impact testing” AND “lower extremity injur\*”

    (“neurocognitive deficits” OR “mTBI”) AND “lower extremity injury”

    (“neuropsychological function” OR “neurocog\*” OR “neuropsych\*”) AND (“lower extremity injury” OR “lower extremity” AND injur\*)

    (“leg injur\*” OR “lower extremity injur\*”) AND (“neuropsych\*” OR “neurocog\*”)

    (“concussion” OR “mTBI”) AND “impact testing” AND “lower extremity injur\*”

    (“lower extremity” AND “injur\*”) AND (“neurocog\*” OR “neuropsych\*”)

    (“Lower Extremity injur\*”) AND (“Brain Concussion” OR “mTBI”),