3-19-2021

Influence of Cognitive Performance on Musculoskeletal Injury Risk: A Systematic Review

Jason M. Avedesian
University of Nevada, Las Vegas

Warren Forbes
University of Nevada, Las Vegas

Tracey Covassin
University of Nevada, Las Vegas

Janet S. Dufek
University of Nevada, Las Vegas, janet.dufek@unlv.edu

Repository Citation

Avedesian, J., Forbes, W., Covassin, T., Dufek, J. (2021). Influence of Cognitive Performance on Musculoskeletal Injury Risk: A Systematic Review. *American Journal of Sports Medicine* 1-9.
http://dx.doi.org/10.1177/0363546521998081

The Influence of Cognitive Performance on Musculoskeletal Injury Risk: A Systematic Review

Background: While a large number of studies have investigated the anatomical, hormonal, and biomechanical risk factors related to musculoskeletal injury risk, there is growing evidence to suggest that cognition is also an important injury contributor in the athletic population. A systematic review of the available evidence regarding the influence of cognitive performance on MSK injury risk has yet to be published in the sports medicine literature.

Purpose/Hypothesis: To determine the effects of cognition on 1) musculoskeletal biomechanics during sports-specific tasks, and 2) musculoskeletal injury occurrence in the athletic population. It was hypothesized that athletes with lower cognitive performance would demonstrate biomechanical patterns suggestive of musculoskeletal injury risk and that injured athletes perform worse on baseline measures of cognition compared to non-injured counterparts.

Study Design: Systematic review.

Methods: PubMed and SPORTDiscus were searched from January 2000 to January 2020. Manual searches were performed on the reference lists of the included studies. A search of the literature was performed for studies published in English that reported musculoskeletal biomechanics as a function of cognitive performance and musculoskeletal injury occurrence following baseline measures of cognition. Two independent reviewers extracted pertinent study data in accordance with PRISMA guidelines and assessed study quality using the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies from the National Institutes of Health. A meta-analysis was not performed due to the heterogenous nature of the included study designs.

Results: 10 studies (4 cognition-musculoskeletal biomechanics, 6 cognition-musculoskeletal injury) met inclusion criteria. All four of the included cognition-musculoskeletal biomechanics studies demonstrated that worse performance on measures of cognition was associated with lower extremity musculoskeletal biomechanical patterns suggestive of greater risk for musculoskeletal injury. The majority of the included cognition-musculoskeletal injury studies demonstrated that injured athletes significantly differed on baseline cognition measures versus matched controls, or that cognitive performance was a significant predictor for subsequent musculoskeletal injury.

Conclusion: Although the literature exploring cognitive contributions to musculoskeletal injury risk is still in its infancy, it is suggested that sports medicine personnel conduct baseline assessments of cognition (in particular, reaction time and working memory) to identify which athletes may be at elevated risk for future musculoskeletal injury.

Keywords: cognition; reaction time; lower extremity injury; musculoskeletal biomechanics

What is known about the subject: Injuries that temporarily impair cognitive function, such as sports-related concussion, have been recently associated with greater risk for subsequent musculoskeletal injuries. Baseline cognitive assessments are common in the sports medicine field for concussion management, however, recent evidence suggests additional clinical utility for identifying athletes at future risk for other sports-related injuries. Given that dynamic sporting environments impose temporal and space constraints on competitors, adequate cognitive functioning (i.e., reaction time, working memory) is imperative for proper decision-making to avoid injurious situations.

What this study adds to existing knowledge: Presently, the sports medicine literature has yet to systematically review the influences of cognitive performance on musculoskeletal injury risk in competitive athletes. We sought to identify whether cognition, measured through clinical assessments, offer utility for identifying athletes at risk for musculoskeletal injury through biomechanical assessments and injury occurrence investigations. The results of this systematic review suggest that common clinical measurements of cognitive performance are useful for determining high risk biomechanical loading patterns and subsequent musculoskeletal injury.

Introduction

Musculoskeletal (MSK) injuries are common occurrences worldwide, particularly to active adolescents and adults participating in physical activity and sport.[23] While the broad field of sports medicine has been able to identify mechanisms contributing to MSK injury, the incidence rate for these injury types are increasing steadily.[30] For example, multiple epidemiologic studies suggest the rate of anterior cruciate ligament (ACL) reconstructions in adolescents increase by 2–3% annually.[6,15] Significant health burdens are associated with MSK injury that may impact daily life and predispose athletes to further injury. Prior lower extremity MSK injury has been extensively linked to future injury at the ankle, knee, and hamstrings.[11] Female athletes with a previous ACL injury history are 16 times more likely to re-injure the ACL versus healthy controls.[25] MSK injuries also pose significant health care costs for injured athletes. In a single metropolitan area over a 7-year study period, the estimated direct hospital costs for sports injury was $265 million, with lower extremity and knee injuries accounting for nearly one-third of total costs.[10] In addition, ACL injuries in particular are a substantial economic burden, as the estimated 250,000 ACL injuries that occur annually in the United States represent $2 billion in costs related to surgical procedures and rehabilitation.[5] Given the prevalence and outcomes associated with MSK injury, identifying athletes at high risk for MSK injury is crucial for sports medicine personnel.

Prior studies have focused on anatomical, hormonal, and biomechanical risk factors for MSK injury with varying degrees of success.[26] However, it appears that cognition is also an important contributor to MSK injury risk.[33] Athletes under high cognitive demands during sporting maneuvers demonstrate biomechanical patterns (e.g., increased landing forces and frontal plane knee motion) suggestive of greater risk for MSK injury versus tasks that do not impose constraints on reaction time (RT) and decision-making.[2] Recent investigations have demonstrated that athletes who sustain injuries associated with a temporarily altered cognitive state, such as sports-related concussion, are at an approximately two times greater risk for MSK injuries in spite of medical clearance to participate in sport.[20]

The majority of cognitive research in sports medicine has focused on management and outcomes related to concussive injury events. Concussed athletes may undergo a variety of computer and/or pencil-and-paper assessments that measure RT, visuomotor speed, working memory, response inhibition, and attentional processes.[28] These tools are utilized to determine if cognitive disturbance has occurred and whether an athlete has returned to pre-injury performance levels.[3] Recently, several investigators have postulated that cognitive performance, even in the absence of a sports-related brain injury, is an important contributor to future injury risk.[2,31,33] Athletes who are unable to rapidly and accurately process environmental stimuli while simultaneously preplanning correct motor sequences may not be able to produce protective muscular forces, thus imparting high impact loads on MSK tissues that result in injury.[33] Therefore, it would be pertinent to assess whether specific measures of cognition utilized by sports medicine personnel are associated with MSK injury risk. While it appears cognition is an important contributor to MSK injury, the current literature has not systematically assessed the influence of cognitive performance on MSK injury risk in the athletic population. Thus, the primary aims of this systematic review were two-fold: (1) determine how cognition influences MSK biomechanics during sport-specific tasks (cognition-MSK biomechanics); and (2) compare baseline cognitive performance between subsequently injured and non-injured athletes (cognition-MSK injury). We focused specifically on studies that evaluated differences in baseline cognitive performance between subsequently injured and non-injured athletes, as well as investigations that measure MSK biomechanics as a function of cognition. It was hypothesized that athletes with lower cognitive performance will demonstrate biomechanical patterns suggestive of MSK injury risk and that injured athletes perform worse on baseline measures of cognition compared to non-injured counterparts.

Methods

Protocol

This systematic review was written in accordance with the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA).[21] The project was registered prospectively on PROSPERO, and at the time of this submission was awaiting confirmation of acceptance.

Search Strategy

The computerized search was conducted by the study investigators. Electronic searches in PubMed and SPORTDiscus were performed to identify relevant articles utilizing Medical Subject Headings (MeSH) terms with two concepts: Concept 1, "cognition," "brain," "baseline cognition," "memory," "reaction time"; Concept 2, "musculoskeletal injury," "athletic injury," "knee injury," "ankle injury." Concepts were linked with the "AND" operator. Additionally, we performed a manual search of the reference lists for each included study to identify all relevant studies. All results from the two databases were downloaded and examined for duplicates. Duplicate records were removed. Results of the literature search are shown in Figure 1.

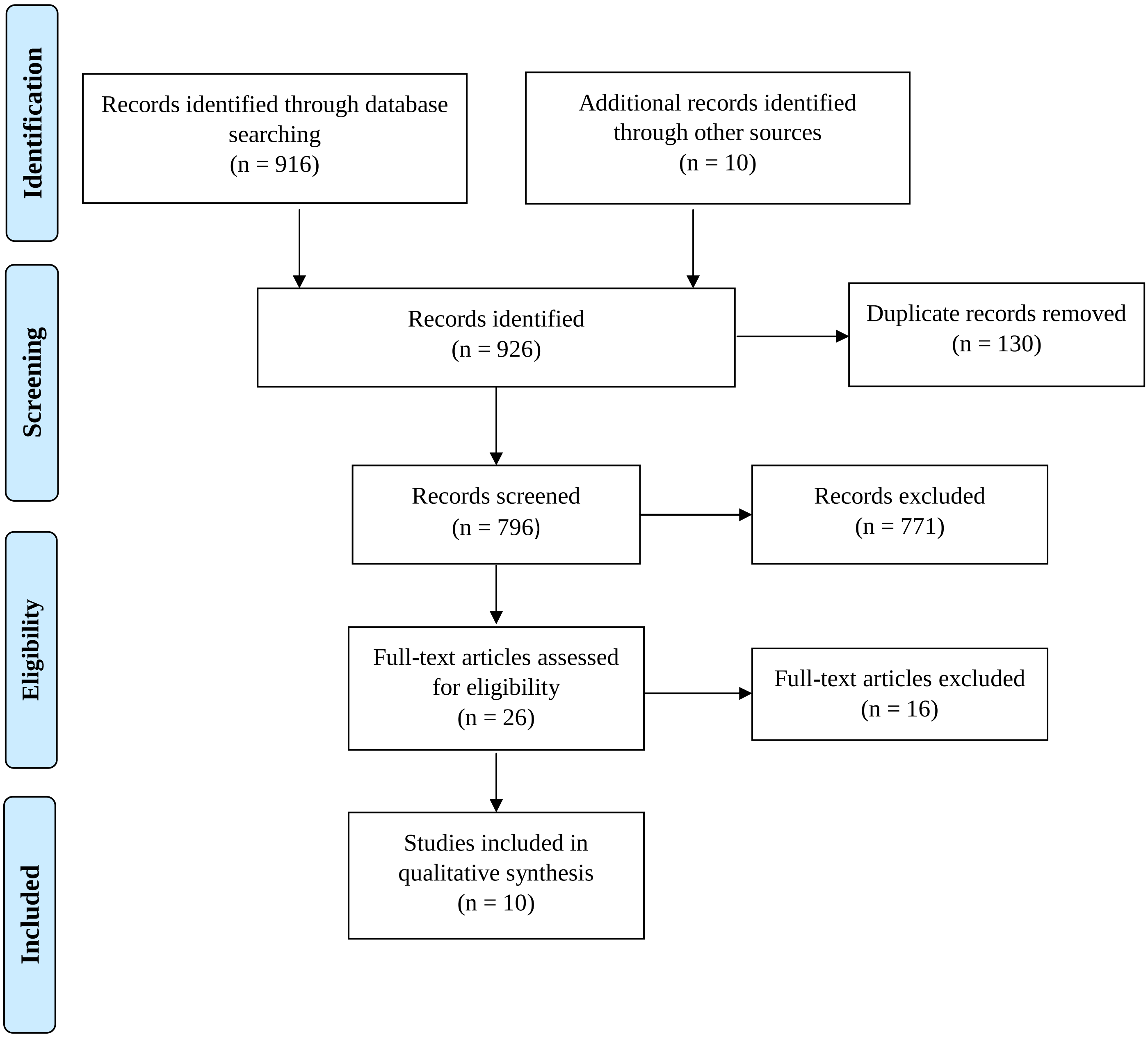

Figure 1. Article selection in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2009 flow diagram.

Selection Criteria

Observational and cross-sectional studies were included in this review if they met the following criteria: (1) published between January 2000 and January 2020, (2) published in English, (3) participants were athletes at any level of competition, (4) MSK biomechanics were reported along with measures of cognition, and (5) MSK injuries were reported after measures of cognition. Review articles were excluded. Two authors independently reviewed titles, abstracts, and full text articles. If a disagreement regarding inclusion occurred, a third author reviewed the article in question, and the decision was made by the majority vote. All studies which met the inclusion criteria were included in this review.

Quality Assessment

The Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies from the National Institutes of Health was used to assess methodological quality for each included study.[27] This tool is composed of 14 items to provide a qualitative description of the study characteristics. All included studies were independently scored by two reviewers and decisions for the final score of each article were determined through consensus of the two scores. If a disagreement regarding scoring occurred, a third author reviewed the article in question, and the decision was made by majority vote. For all items in the assessment, the independent variable of interest was measured cognitive performance. For item 7, a period of 365 days or 1–2 competitive seasons following the cognitive assessment was deemed a sufficient timeframe to determine the association between cognition and MSK injury.

Data Extraction and Synthesis

Studies were divided into two categories based on the protocols and outcomes of each study: MSK biomechanics and MSK injury occurrence. The primary outcome of interest for MSK biomechanical studies were measured kinematic and kinetic variables associated with musculoskeletal injury (e.g., vertical ground reaction force) during sport-specific tasks (e.g., jump-landing) based upon differences in cognitive performance (i.e., group stratification between low and high cognitive performance, correlational analysis). For MSK injury occurrence studies, the primary outcome of interest was group differences in cognitive performance between subsequently injured and non-injured athletes. All pertinent data were extracted from the included studies, including participant demographics, cognitive measurements, MSK biomechanical parameters, and MSK injury occurrence.

Results

A total of 926 studies were identified from the databases and additional sources. Following the review of potential articles, 26 were full-text screened, of which 10 articles (4 cognition-MSK biomechanics, 6 cognition-MSK injury) were included in the qualitative analyses (Tables 1 and 2). Due to the heterogeneous nature of the included study designs, we were unable to perform a quantitative meta-analysis for the present review. Therefore, our review presents a qualitative assessment of the available literature, as well as individual study characteristics and results. Included studies were prospective, retrospective, or cross-sectional designs, indicating that they were level 3 and 4 evidence studies.

TABLE 1. Cognition-MSK Biomechanics Study Characteristics[a]

Study	Participants (n, sex, age, specific sport if applicable)[b]	Quality Checklist Score	Cognitive Assessment(s)	Biomechanical Variables Assessed	Key Findings
Almonroeder (2017)	n = 13 with fast reaction time, age = 20.8 ± 1.8 n = 15 with slow reaction time, age = 21.7 ± 1.8 Recreationally active females with experience in landing and cutting sports (basketball, soccer, tennis)	7	ImPACT - reaction time	Kinematics - Hip flexion, knee flexion, knee abduction initial contact angle and range-of-motion Kinetics - Peak knee abduction moment and vertical ground reaction force	The slow reaction time group displayed higher peak vertical ground reaction forces for pre-planned (2.22 BW vs 1.90 BW) and unanticipated (2.26 BW vs 1.88 BW) conditions
Giesche (2020)	n = 20, age = 27.1 ± 4.2 Recreationally active males with a minimum counter-movement jump height of 30 cm	7	Trail-Making-Test A CogState detection and identification task Stroop color-word test: reading and writing Trail-Making-Test B Stop Signal Task Stroop color-word interference test Digit spans forward and backward test	Kinematics - Time to stabilization Kinetics - Center of pressure, vertical ground reaction force Number of standing errors, number of landing errors	Association between more errors on Stroop color-word interference test and decreased center of press path length Association between increased landing errors and worse performances on Trail Making Test B and Digit Spans Forward and Backward test Association between increased standing errors and

					better performances on Trail-Making-Test B and Digit spans forward and backward test
Herman (2016)	n = 20 (10 F, 10 M) with high cognitive performance, age = 21.1 ± 1.5 n = 17 (9 F, 8 M) with low cognitive performance, age = 20.8 ± 1.7 Recreationally active athletes with experience in jumping and cutting sports (basketball, soccer, volleyball, lacrosse)	6	Concussion Resolution Index (CRI) - Simple reaction time, complex reaction time, processing speed	Kinematics - Trunk flexion, trunk lateral bending, hip flexion, hip abduction/adduction, knee flexion, knee abduction/adduction Kinetics - Peak vertical ground reaction force, peak proximal anterior tibial shear force, knee abduction/adduction moment	Low performance group demonstrated 31% increase in peak vertical ground reaction force (1.81 BW vs 1.38 BW) and 26% increase in peak anterior tibial shear force (0.91 BW vs 0.72 BW) versus high performance group Low performance group demonstrated increased knee abduction moment (0.47 BW x BH vs 0.03 BW x BH) and knee abduction angle (6/1 deg vs 1.3 deg) versus high performance group

Monfort (2019)	n = 15, age = 20.7 ± 2.0 Collegiate club male soccer athletes	5	ImPACT - Verbal memory, visual memory, visuomotor speed, reaction time	Kinematics - Peak knee abduction angle Kinetics - Peak knee abduction moment Dual-task change scores for peak knee abduction angle and moment	Worse performance on the visual memory composite score was associated with an increase in peak knee abduction angle during ball-handling tasks when compared to non-ball handling tasks

[a]F, female; male.

[b]Data are reported as mean ±SD

TABLE 2. Cognition-MSK Injury Study Characteristics[a]

Study	Participants (n, sex, age, specific sport if applicable)[b]	Quality Checklist Score	Cognitive Assessment(s)	Injuries Tracked	Injury Tracking Period	Key Findings
Buckley (2020)	n = 30 (18 F, 12 M) with no MSK injury, age = 20.1 ± 1.2 n = 36 (17 F, 19 M) with MSK injury, age = 19.9 ± 1.0 NCAA Division 1 football, volleyball, soccer, basketball, lacrosse, track & field, softball/baseball, field hockey, tennis, cheerleading, crew	7	Standard Assessment of Concussion (SAC) - immediate memory, concentration, delayed memory recall ImPACT - verbal memory, visual memory, visuomotor speed, reaction time Clinical Reaction Time (CRT)	Acute LE MSK injury; tracked through electronic medical record	365 days from the day of RTP or occurrence of a new LE MSK injury	There were no predictors from the clinical cognitive assessments for subsequent LE MSK injury

Faltus (2016)	n = 41 (39 F, 2 M) with no MSK injury, age = 14-17 n = 93 (51 F, 42 M) with MSK injury, age = 14-17 Adolescent alpine skiing, freestyle skiing, snowboarding	8	ImPACT - verbal memory, visual memory, visuomotor speed, reaction time, cognitive efficiency index	Acute LE & UE MSK injury; tracked through local ski and snowboard club via paper and electronic records	7 months (Oct-Apr) during 2009-2012 competitive seasons	ImPACT scores did not differ between MSK injury groups Reaction time was 5.8% higher in males with injury Motor speed was 14.4% lower in males with injury
McDonald (2019)	Season 1: n = 72 with no MSK injury, age not reported n = 41 with MSK injury, age not reported Season 2: n = 54 with no MSK injury, age not reported n = 58 with MSK injury, age not reported NCAA Division 1 football	11	ImPACT - verbal memory, visual memory, visuomotor speed, reaction time	Acute LE or core sprain or strain; tracked by athletic training staff	1-2 years from the time of preparticipation screening to injury	Season 1: Reaction time (≥685 milliseconds) was one of four factors that demonstrated predictive power for MSK injury Season 2: Reaction time (≥800 milliseconds) and motor speed (≤28) were two of four factors that demonstrated predicative power for MSK injury Of players who sustained a Season 1 injury, reaction time (≥560 milliseconds) and verbal memory (≤87) demonstrate predictive power for MSK injury

Swanik (2007)	n = 80 with no non-contact ACL injury, age not reported n = 80 (45 F, 35 M) with non-contact ACL injury, Female age = 20.6 ± 1.7, Male age = 20.8 ± 1.1 NCAA Division 1, 2, 3, NAIA, and NCCAA football, soccer, lacrosse, basketball, volleyball, field hockey, gymnastics, softball, fencing	8	ImPACT - verbal memory, visual memory, motor speed, reaction time	Non-contact ACL injury; tracked through form at each participating institution	Not specified; injured groups were compared based upon preseason baseline ImPACT scores	ACL injured group demonstrated slower reaction time and motor speed, as well as worse performance on verbal and visual memory scores versus non-injured controls
Wilkerson (2012)	n = 53 with no LE MSK sprain or strain injury, age not reported n = 23 with LE MSK sprain or strain injury, age not reported NCAA Division 1 football	9	ImPACT - reaction time	LE MSK sprain or strain; injury tracking system not specified	11 game (approx. 3 month) football season	Athletes with a reaction time ≥545 milliseconds were more than twice as likely to sustain an in-season LE MSK sprain or strain
Wilkerson (2017)	n = 43 with no LE MSK injury, age not reported n = 33 with LE MSK injury, age not reported NCAA Division 1 football	9	Dynavision D2 System - Visuomotor reaction time	MSK sprain or strain; injury tracking system not specified	16.5 weeks	Athletes with a visuomotor reaction time ≥705 milliseconds were more than twice as likely to sustain an in-season MSK sprain or strain

[a]F, female; male.

[b]Data are reported as mean ±SD

Quality Assessment: Cognition-MSK Biomechanics

The quality assessment indicated that included cognition-MSK biomechanics studies ranged from 5 to 7 out of a possible 14 total items. All of the included studies were cross-sectional designs,[1,12,14,22] thus limiting the ability to analyze cognitive and MSK biomechanical behavior over time as it relates to MSK injury risk. All included studies analyzed lower extremity MSK biomechanics during jump-landing maneuvers.[1,12,14,22] Two of the included studies did not report a sample size justification,[12,22] while two of the four studies did not report effect size estimates.[12,14] Two studies utilized between-group statistical comparisons (i.e., high versus low cognitive performance),[1,14] one study performed correlational analysis,[12] and one study applied a regression model to predict MSK biomechanics as a function of cognitive performance.[22] All four studies were conducted on recreational or club sport athletes, however, the age-range for participating athletes was inconsistent across studies (ages 18–40). Two studies assessed cognition with the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT; ImPACT Applications, Inc., Pittsburgh, PA, USA) battery,[1,22] one study utilized multiple assessments (e.g., Trail-Making-Test A/B, Stoop color-word),[12] and one study measured cognitive performance with the Concussion Resolution Index (HeadMinder, Inc., New York, NY, USA).[14] Some authors cautioned against the generalizability of their results to athletes of higher skill[14,22] and noted relatively small sample sizes.[12,22] Sample sizes varied among studies, ranging from 15 athletes[22] to 37 athletes.[14]

Quality Assessment: Cognition-MSK Injury

The quality assessment indicated that included cognition-MSK injury studies ranged from 7 to 11 out of a possible 14 total items. Four of the included studies prospectively assessed cognitive measures and longitudinally tracked MSK injuries over a single year[7] or competitive season(s),[19,35,36] while two studies were retrospective chart reviews of injured versus non-injured athletes as a function of baseline cognitive performance.[9,34] Sample sizes ranged from 66 athletes[7] to 160 athletes,[34] however, none of the included studies provided a sample size justification. Three studies dichotomized cognitive performance measures to determine optimal cut-points between injured versus non-injured athletes,[19,35,36] two studies examined between-group differences based on injury status,[9,34] and one study utilized a sole regression-based model to predict MSK injury.[7] The majority of studies were conducted on collegiate athletes,[7,19,34–36] three of which were specific to football,[19,35,36] and one study assessed adolescent skiing and snowboarding athletes.[9] Most studies measured cognitive performance with ImPACT[7,9,19,34,35] and one study utilized a smartboard-based device.[36] One study assessed the predictability of cognitive measures for subsequent MSK injury in recently concussed athletes,[7] while the other investigations were conducted on athletes free from a recent sports-related concussion.[9,19,34–36] Three studies tracked lower extremity MSK injuries,[7,34,35] two studies tracked lower and upper extremity MSK injuries,[9,36] and one study tracked lower extremity and trunk MSK injuries.[19] Several authors cautioned against the generalizability of their findings to non-collegiate sporting populations,[7,35] as well as citing possible limitations relating to the reliability of the implemented cognitive assessments.[7,9,19]

Individual Study Results: Cognition-MSK Biomechanics

All four of the included cognition-MSK biomechanics studies demonstrated, to some degree, that worse cognitive performance was associated with lower extremity MSK biomechanical patterns suggestive of greater risk for MSK injury (Table 1). In a study of recreationally active female athletes, participants classified as 'slow' (>0.59 sec) or 'fast' (<0.52 sec) performers on the ImPACT RT module completed jump-landing maneuvers under anticipated and unanticipated conditions.[1] While there were no group differences in kinematic landing parameters, it was determined that participants in the 'slow' RT group experienced significantly greater landing forces during both anticipatory conditions.[1] Additionally, Herman and Barth[14] found that male and female recreational athletes with slower RT and processing speed, measured via the Concussion Resolution Index, performed unanticipated drop-jump landings with greater ground reaction force, anterior tibial shear force, knee abduction moment, and knee abduction angle versus a cohort with better RT and processing speed. The investigators,[14] along with Almonroeder,[1] concluded that their cohorts with slower RT were at greater risk for ACL injury during landing maneuvers. While no significant associations between cognition and landing force were present during anticipated or unanticipated landing conditions for recreationally active males, Giesche et al[12] reported a significant association ($r = 0.48$) between decreased landing stability (center-of-pressure pathlength) and the number of errors during a test of inhibitory control (Stroop color-word interference task). The number of landing errors (landing on the wrong limb or both limbs during unplanned landings) were significantly associated with worse short-term memory ($r = -0.55$) and working memory ($r = 0.54$) on the Digit Spans Forward and Trail Making Test B tasks, respectively.[12] Furthermore, the number of standing errors (landing on the correct limb but touching the ground with the contralateral limb, touching the ground with the hands, or leaving the force platform) was associated with better verbal short-term memory (r = 0.50) and working memory (r = -0.48) on the Digit Spans Backward and Trail Making Test B tasks, respectively.[12] When performing a dual-task ball handling maneuver, worse visual memory score on ImPACT was the only cognitive measure significantly associated with increased knee abduction angle (r = 0.69) in collegiate club male soccer athletes.[22] For every 10 unit decrease in visual memory score, there was an expected 2.1 degree increase in knee abduction angle.[22] While not statistically significant, the investigators noted that visual memory score was also the strongest predictor of knee abduction moment (r = 0.46) during the same ball handling task.[22]

Individual Study Results: Cognition-MSK Injury

Among the six included studies, two investigations[7,9] failed to determine group differences in cognitive performance between subsequently injured and non-injured athletes. The remaining four studies demonstrated that injured athletes significantly differed on baseline cognition measures versus matched controls,[34] or that cognitive performance was a significant predictor for subsequent MSK injury (Table 2).[19,34–36] In a study of collegiate athletes, Buckley et al[7] found that recently concussed athletes were 1.8 times more likely to sustain a subsequent MSK injury in the year following a concussive injury versus healthy controls. The investigators performed regression modeling and found that clinical cognitive assessments (ImPACT, Standard Assessment of Concussion, and Clinical Reaction Time) were not significant predictors for subsequent MSK injury in the previously concussed athlete cohort.[7] Relatedly, Faltus et al[9] found no main effects between injured and non-injured skiing/snowboarding adolescent athletes on baseline ImPACT scores. However, significant sex by injury interactions were found for reaction time and visuomotor speed scores; injured males demonstrated a 5.8% increase in RT and 14.4% decrease in visuomotor speed score compared to non-injured males.[9] A limitation with these findings is the small sample size of non-injured males (n = 2) versus injured males (n = 42).[9] In the three studies on collegiate football athletes, cognitive performance on the ImPACT[19,35] and Dynavision D2 System (Dynavision International, Chester Township, OH, USA)[36] were prospectively associated with MSK injury over the course of a competitive season(s). Using receiver operating characteristics and multiple regression models of injured versus non-injured athletes, McDonald et al[19] determined that ImPACT RT (season 1: ≥0.69 sec; season 2: ≥0.80 sec) and motor speed (season 2: ≤28) were among a multiple factor model that predicted MSK injury (odds ratio = 4.11 and 2.60 for season 1 and season 2, respectively). Furthermore, for athletes who sustained a season 1 MSK injury, RT (≥0.56 sec) and verbal memory (≤87) were among the significant predictors for MSK injury in season 2 (odds ratio = 4.45).[19] A prior investigation also demonstrated that baseline ImPACT RT (≥ 0.55 sec) was able to differentiate between college football athletes who sustained an in-season lower extremity sprain or strain versus non-injured controls (odds ratio = 2.94).[35] Utilizing a visuomotor RT task, Wilkerson et al[36] demonstrated that an in-season MSK injury was experienced by 52% of 'slow' performers (RT ≥ 0.71 sec) versus 32% of 'fast' performers (RT ≤ 0.71 sec), with an odds ratio = 2.30. A study of collegiate athletes who sustained a non-contact ACL injury demonstrated significantly worse baseline performance on all components of ImPACT versus matched controls.[34] Interestingly, RT for the ACL-injured cohort (RT = 0.57 sec)[34] was similar to the football athletes in subsequent investigations who experienced an in-season MSK injury (RT = 0.55–0.56 sec).[19,35]

Discussion

A systematic review of the literature was conducted to determine the influence of cognitive performance on MSK injury risk via assessments of MSK biomechanical performance and MSK injury occurrence. Our hypotheses were supported in that athletes with worse cognitive performance demonstrated biomechanical patterns suggesting greater risk for MSK injury and that subsequently injured athletes performed worse on baseline cognitive assessments compared to non-injured athletes. Based upon the available evidence, the results of this review demonstrate that cognition is an important contributor to MSK injury risk from both a biomechanical and injury occurrence standpoint. Of the 10 included studies, nine demonstrated that cognitive performance is related to higher risk lower extremity biomechanical patterns[1,12,14,22] or increased rate of MSK injury.[9,19,34–36] Furthermore, it appears that cognition has an influence on MSK injury risk for both male[12,14,19,34–36] and female[1,14,34] collegiate-age athletes.

Lower extremity injuries, particularly to the ACL, represent a major epidemiological concern to the sports medicine field. While prior biomechanical studies have identified athletes at risk for future ACL injuries,[16] it appears that an individual's cognitive performance is a contributor to these high risk loading patterns, and to an extent, ACL injury risk.[1,14,22] All four of the included cognition-MSK biomechanics studies noted the elevated risk for ACL-specific injuries in individuals with worse cognitive performance.[1,12,14,22] While the nature of the tasks varied slightly amongst the studies, high risk knee loading patterns such as increased vertical ground reaction force,[1,14] greater knee abduction angle,[14,22] and decreased landing stability[12] were associated with low scores on measures of cognition relative to better performers. A strength of all four of the included MSK-biomechanical studies was the analysis of sport-specific tasks that stress cognitive resources such as perception, visuomotor processing speed, and working memory. Monfort et al[22] tasked individuals with performing a 45 degree ball-handling maneuver at maximum speeds, while the other three studies assessed jump-landing performance under unanticipated conditions.[1,12,14] The temporal and space constraints implemented within these studies are realistic to a sporting environment in which performers are tasked with completing complex motor maneuvers under high cognitive loads. From these studies, it appears that clinical measures of reaction time[1,14] and working memory[12,22] are pertinent to determining individuals at risk for lower extremity MSK injury. Given that biomechanical performance during high-impact loading tasks are predictive of future MSK injury,[16] it is suggested that future research continue to determine which attributes of cognition are associated with high-risk MSK biomechanics.

Of the six included cognition-MSK injury studies, five demonstrated that cognitive performance was associated (to varying degrees) with subsequent MSK injury occurrence. The lone study that did not determine cognition as a significant predictor/differentiator for MSK injury was conducted in recently concussed athletes.[7] While Buckley et al[7] determined that post-concussion MSK injury risk was 1.8 times higher versus non-concussed controls, ImPACT and other clinical measures of cognition failed to predict at-risk athletes. These results are in opposition to other investigations, as ImPACT[19,35] and assessments of visuomotor reaction time[36] have demonstrated that worse baseline cognitive performance results in a higher likelihood for subsequent MSK injury. Specific to the ACL, collegiate athletes who sustained a non-contact ACL injury performed significantly worse on all ImPACT components.[34] It should be noted that Buckley et al[7] hypothesized that cognitive performance would be predictive of MSK injury in their concussed cohort, therefore, it is presently unclear as to why the study results did not align with this hypothesis. Nonetheless, it appears there is clinical utility in utilizing cognitive assessments for prospectively identifying athletes at future risk for MSK injury. Athletes with worse performance on reaction time[9,19,34–36] and visuomotor speed[19,34] assessments were more likely to sustain MSK injuries, therefore it is suggested that valid and reliable testing batteries specific to these cognitive measures be conducted prior to a competitive season.

Clinical Implications

Sports medicine personnel typically administer cognitive assessments as part of a concussion management program to monitor recovery trajectories and determine when it is appropriate for a recently concussed athlete to initiate a return-to-sport protocol.[18] The results of this systematic review suggest that cognitive performance on common clinical assessments can identify athletes at risk for future MSK injury. The literature to date examining lower extremity MSK biomechanics suggests that worse cognitive performance is associated with high-risk joint loading patterns,[1,12,14,22] while MSK risk factor studies have retrospectively[9,34] and prospectively[19,35,36] determined that cognition is a significant contributor to subsequent MSK injury. While experienced clinicians may be able to identify low baseline cognitive performance, testing batteries such as ImPACT include normative data to make appropriate age- and sex-comparisons[17] for identifying athletes that demonstrate low percentile performance compared to peers. From our findings, it may be that clinical cognitive assessments serve dual purposes for both concussion and MSK injury risk management in the athletic setting.

While most injury prevention research has emphasized anatomical, hormonal, and biomechanical risk factors, the results of this systematic review suggest that cognition must be considered as a contributor to MSK injury risk. Although the sports medicine field is in the early stages of identifying specific cognitive risk factors, it does appear that slow cognitive performance is modifiable through training interventions. For example, Wilkerson et al[36] demonstrated that visuomotor RT performance improved by 28% over the course of a six week training period utilizing the Dynavision D2 vision training system. One such training strategy that may enhance cognitive performance is stroboscopic visual training, in which athletes are subjected to motor tasks while wearing eyewear that partially obstructs vision by modifying opaqueness conditions.[13] Recent evidence suggests that visual obstruction training may improve important cognitive skills such as anticipation,[32] visual reaction time,[37] and visual working memory.[4] In theory, processing visual information faster would allow an athlete adequate time to initiate an appropriate and protective motor response within the temporal and space constraints of a dynamic sporting environment, thus leading to maneuvers that do not impart high impact loads on MSK tissues.[33] Novel visual training modalities such as stroboscopic devices may allow for neuroplastic alterations in the brain that lead to enhanced neuromuscular control and reduced risk for future MSK injury.[13] Other training systems such as FITLIGHT (FITLIGHT Corp., Miami, FL, USA) and the Senaptec Sensory Station (Senaptec LLC., Beaverton, OR, USA) offer athletes the ability to improve cognitive attributes such as visuomotor reaction time and working memory, however, the efficacy of these tools to reduce MSK injury has not yet been investigated by the current literature.

Limitations and Future Research Directions

Although the findings of the present systematic review offer novel information pertaining to the influence of cognition on MSK injury risk, several limitations must be addressed in order to strengthen future investigations. All of the included cognition-MSK biomechanics studies were cross-sectional research designs, limiting our understanding of the potential longitudinal changes in cognitive performance and its relationship to MSK biomechanics. Preliminary evidence suggests that training interventions are effective for specific cognitive indices such as visuomotor reaction time,[36] therefore, future studies should consider how high risk MSK loading patterns change as a result of improved cognitive performance over time. Although sample sizes within the included cognition-MSK biomechanics investigations were relatively small, it should be noted that each study determined cognition to be a significant factor as it relates to lower extremity MSK biomechanical patterns.[1,12,14,22] However, future research should continue to investigate larger cohorts to improve the generalizability of these preliminary findings. Given that the present cognition-MSK biomechanics literature is limited to recreational athletes,[1,12,14,22] future studies should consider the analysis of adolescent and competitive collegiate athletes, as both populations are at relatively high risks for lower extremity MSK injuries.[24,29]

While there appears to be clinical utility in examining baseline measures of cognition for identifying subsequent MSK injury occurrence, the included cognition-MSK injury studies are not without limitations. Future research should consider examining sex differences as it relates to the relationship between cognitive performance and future risk of MSK injury. Aside from Faltus et al,[9] none of the remaining cognition-MSK injury studies explicitly explored whether baseline cognition influences future MSK injury in female athletes, even though sex differences have been noted in previous cognitive performance literature.[8] Furthermore, more attention should be focused towards the adolescent sporting population to examine the relative contributions of cognition to MSK injury risk. These findings may assist in the future development of MSK injury prevention programs that incorporate cognitive assessments and intervention strategies. Lastly, the varied statistical analyses conducted in the included cognition-MSK injury studies limited our ability to perform a meta-analysis and obtain a summary estimate of the effect of cognitive performance on subsequent MSK injury risk.

Conclusion

The results of this systematic review suggest that cognitive performance adversely influences MSK biomechanics and future MSK injury risk. Sports medicine personnel should consider implementing baseline cognitive screenings specific to measures of reaction time and working memory for identifying athletes at greater risk for MSK injury occurrence.

References

1. Almonroeder TG. Cognitive contributions to anterior cruciate ligament injury risk [Doctoral dissertation, University of Wisconsin-Milwaukee]. 2017.

2. Almonroeder TG, Kernozek T, Cobb S, Slavens B, Wang J, Huddleston W. Cognitive demands influence lower extremity mechanics during a drop vertical jump task in female athletes. *J Orthop Sports Phys Ther*. 2018;48(5):381-387. doi:10.2519/jospt.2018.7739

3. Alsalaheen B, Stockdale K, Pechumer D, Broglio SP. Validity of the Immediate Post Concussion Assessment and Cognitive Testing (ImPACT). *Sports Med*. 2016;46(10):1487-1501. doi:10.1007/s40279-016-0532-y

4. Appelbaum L, Erickson G. Sports vision training: A review of the state-of-the-art in digital training techniques. *Int Rev Sport Exerc Psychol*. 2016;11:1-30. doi:10.1080/1750984X.2016.1266376

5. Bates NA, McPherson AL, Rao M, Myer GD, Hewett TE. Characteristics of inpatient anterior cruciate ligament reconstructions and concomitant injuries. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(9):2778-2786. doi:10.1007/s00167-014-3478-3

6. Beck NA, Lawrence JTR, Nordin JD, DeFor TA, Tompkins M. ACL tears in school-aged children and adolescents over 20 years. *Pediatrics*. 2017;139(3). doi:10.1542/peds.2016-1877

7. Buckley TA, Howard CM, Oldham JR, Lynall RC, Swanik CB, Getchell N. No clinical predictors of postconcussion musculoskeletal injury in college athletes. *Med Sci Sports Exerc*. 2020;52(6):1256-1262. doi:10.1249/MSS.0000000000002269

8. Covassin, Sachs M, Kendrick Z, et al. Sex differences in baseline neuropsychological function and concussion symptoms of collegiate athletes. *Br J Sports Med*. 2006;40(11):923-927. doi:10.1136/bjsm.2006.029496

9. Faltus J, Huntimer B, Kernozek T, Cole J. Utilization of ImPACT testing to measure injury risk in alpine ski and snowboard athletes. *Int J Sports Phys Ther*. 2016;11(4):498-506.

10. Finch CF, Kemp JL, Clapperton AJ. The incidence and burden of hospital-treated sports-related injury in people aged 15+ years in Victoria, Australia, 2004-2010: a future epidemic of osteoarthritis? *Osteoarthr Cartil*. 2015;23(7):1138-1143. doi:10.1016/j.joca.2015.02.165

11. Fulton J, Wright K, Kelly M, et al. Injury risk is altered by previous injury: a systematic review of the literature and presentation of causative neuromuscular factors. *Int J Sports Phys Ther*. 2014;9(5):583-595.

12. Giesche F, Wilke J, Engeroff T, et al. Are biomechanical stability deficits during unplanned single-leg landings related to specific markers of cognitive function? *J Sci Med Sport*. 2020;23(1):82-88. doi:10.1016/j.jsams.2019.09.003

13. Grooms D, Appelbaum G, Onate J. Neuroplasticity following anterior cruciate ligament injury: a framework for visual-motor training approaches in rehabilitation. *J Orthop Sports Phys Ther*. 2015;45(5):381-393. doi:10.2519/jospt.2015.5549

14. Herman, Barth JT. Drop-jump landing varies with baseline neurocognition: implications for anterior cruciate ligament injury risk and prevention. *Am J Sports Med*. 2016;44(9):2347-2353. doi:10.1177/0363546516657338

15. Herzog MM, Marshall SW, Lund JL, Pate V, Mack CD, Spang JT. Incidence of anterior cruciate ligament reconstruction among adolescent females in the United States, 2002 through 2014. *JAMA Pediatr*. 2017;171(8):808-810. doi:10.1001/jamapediatrics.2017.0740

16. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492-501. doi:10.1177/0363546504269591

17. Lovell M. ImPACT 2007 (6.0) Clinical interpretation manual. Pittsburgh, PA: ImPACT Applications Inc; 2007.

18. McCrory P, Meeuwisse W, Dvorak J, et al. Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med*. 2017;51(11):838-847. doi:10.1136/bjsports-2017-097699

19. McDonald AA, Wilkerson GB, McDermott BP, Bonacci JA. Risk factors for initial and subsequent core or lower extremity sprain or strain among collegiate football players. *J Athl Train*. 2019;54(5):489-496. doi:10.4085/1062-6050-152-17

20. McPherson AL, Nagai T, Webster KE, Hewett TE. Musculoskeletal injury risk after sport-related concussion: A systematic review and meta-analysis. *Am J Sports Med*. 2019;47(7):1754-1762. doi:10.1177/0363546518785901

21. Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med*. 2009;6(7):e1000097. doi:10.1371/journal.pmed.1000097

22. Monfort SM, Pradarelli JJ, Grooms DR, Hutchison KA, Onate JA, Chaudhari AMW. Visual-spatial memory deficits are related to increased knee valgus angle during a sport-specific sidestep cut. *Am J Sports Med*. 2019;47(6):1488-1495. doi:10.1177/0363546519834544

23. Öztürk S, Kılıç D. What is the economic burden of sports injuries? *Eklem Hastalik Cerrahisi*. 2013;24(2):108-111. doi:10.5606/ehc.2013.24

24. Patel DR, Yamasaki A, Brown K. Epidemiology of sports-related musculoskeletal injuries in young athletes in United States. *Transl Pediatr*. 2017;6(3):160-166. doi:10.21037/tp.2017.04.08

25. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med*. 2012;22(2):116-121. doi:10.1097/JSM.0b013e318246ef9e

26. Pfeifer CE, Beattie PF, Sacko RS, Hand A. Risk factors associated with non-contact anterior cruciate ligament injury: A systematic review. *Int J Sports Phys Ther*. 2018;13(4):575-587.

27. Quality assessment tool for observational cohort and cross-sectional studies. https://www.nhlbi.nih.gov/health-pro/guidelines/in-develop/ cardiovascular-risk-reduction/tools/cohort. Published March 2014.

28. Register-Mihalik JK, Kontos DL, Guskiewicz KM, Mihalik JP, Conder R, Shields EW. Age-related differences and reliability on computerized and paper-and-pencil neurocognitive assessment batteries. *J Athl Train*. 2012;47(3):297-305.

29. Rosa BB, Asperti AM, Helito CP, Demange MK, Fernandes TL, Hernandez AJ. Epidemiology of sports injuries on collegiate athletes at a single center. *Acta Ortop Bras*. 2014;22(6):321-324. doi:10.1590/1413-78522014220601007

30. Shaw L, Finch CF, Bekker S. Infographic: Trends in paediatric and adolescent ACL injuries. *Br J Sports Med*. 2019;53(4):228. doi:10.1136/bjsports-2017-098504

31. Smith JD, Shields WE, Washburn DA. The comparative psychology of uncertainty monitoring and metacognition. *Behav Brain Sci*. 2003;26(3):317-339; discussion 340-373. doi:10.1017/s0140525x03000086

32. Smith TQ, Mitroff SR. Stroboscopic training enhances anticipatory timing. *Int J Exerc Sci*. 2012;5(4):344-353.

33. Swanik. Brains and sprains: The brain's role in noncontact anterior cruciate ligament injuries. *J Athl Train*. 2015;50(10):1100-1102. doi:10.4085/1062-6050-50.10.08

34. Swanik, Covassin T, Stearne DJ, Schatz P. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. *Am J Sports Med*. 2007;35(6):943-948. doi:10.1177/0363546507299532

35. Wilkerson GB. Neurocognitive reaction time predicts lower extremity sprains and strains. *Int J Ath Ther Train*. 2012;17(6):4-9. doi:10.1123/ijatt.17.6.4

36. Wilkerson GB, Simpson KA, Clark RA. Assessment and training of visuomotor reaction time for football injury prevention. *J Sport Rehabil*. 2017;26(1):26-34. doi:10.1123/jsr.2015-0068

37. Wilkins L, Nelson C, Tweddle S. Stroboscopic visual training: A pilot study with three elite youth football goalkeepers. *J Cogn Enhanc*. 2018;2(1):3-11. doi:10.1007/s41465-017-0038-z