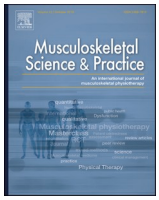
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Think fast, stay healthy? A narrative review of neurocognitive performance and lower extremity injury

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ABSTRACT

Background: Lower extremity (LE) injury has been problematic in athletic populations. While previous research has identified biomechanical and neuromuscular risk factors, more recent efforts have determined that neurocognitive performance (NP) may influence LE injury risk.
Objectives: To describe the present findings pertaining to the relationship between NP and LE injury. This review described potential cerebral neural mechanisms underpinning LE injury with a particular emphasis on the role of vision in sensorimotor integration. Lastly, newer technology such as stroboscopic eyewear, smartboards, and virtual/augmented reality were discussed for their utility in assessing and training NP.
Methods: Narrative review that described NP and LE injury, as well as plausible mechanisms and training interventions.
Results: NP appears to influence both LE biomechanics and LE injury risk. Athletes with worse NP demonstrated decreased knee flexion and increased frontal plane knee loading compared to better performing athletes. Most studies determined an association between NP and LE injury risk. Visual motor reaction time, processing speed, and working memory appear to be useful NP measures for identifying athletes at risk for LE injury. Various brain regions including the precuneus and lingual gyrus may be implicated as neural signatures for LE injury. While recently developed technology offer promise, far-transfer effects to LE injury risk reduction have yet to be substantially investigated.
Conclusions: NP should be considered an important component for identifying LE injury risk. Sports scientists and clinicians may consider a variety of assessments and interventions to quantify and train NP in conjunction with previously established protocols.

1. Introduction

The fields of sports science and sports medicine have invested significant resources into mitigating lower extremity (LE) injury risk in adolescent and adult athletes. LE injury represents the most common musculoskeletal injury type in both populations (Patel et al., 2017; Sheu et al., 2016) and is often associated with significant financial costs for rehabilitation and return-to-sport. Previous research has attempted to identify various risk factors for LE injury, including neuromuscular strength imbalances (Simonson et al., 2023; Delahunt and Remus, 2019), aberrant joint motion (Mausehund and Krosshaug, 2024), athlete preparation strategies (Sadigursky et al., 2017), and biological differences (Patel et al., 2021). Even with technological advancements in biomechanics, physiology, and wearables, LE injury rates in athletes continue to increase. For example, the incidence of anterior cruciate ligament (ACL) injuries has risen 2–3% annually over the last two decades (Kooy et al., 2023; Beck et al., 2017), while non-contact ankle sprains have also significantly increased over this period (Kerr et al., 2022). These injuries are associated with significant risk for re-injury, as prior research suggests approximately 1 in 5 athletes will re-injure the ACL or develop chronic ankle instability after an ankle sprain (Webster and Feller, 2016; Al-Mohrej and Al-Kenani, 2016). LE injury risk identification and subsequent intervention remains problematic for sports scientists and clinicians, necessitating further research and clinical translation.

Neurocognitive performance (NP) has emerged as a relatively new area of study that may have significant implications for LE injury risk in athletes. While the definition of NP may vary considerably, herein it is referred to as *cerebral neural functions contributing to cognition during physical task execution in a given context*. Athletes are required to

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complete complex maneuvers under significant spatiotemporal constraints that influence NP processes such as impulse control, working memory, visual attention, and reaction time (Avedesian et al., 2022a). Previous research suggests that athletes may be at greater risk for LE injury during unanticipated movements compared to anticipated conditions (Hughes and Dai, 2023). Biomechanical research has demonstrated greater ground reaction forces, reduced LE joint flexion, and decreased postural stability during unanticipated jump-cutting and jump-landing tasks (Almonroeder et al., 2015, 2018, 2019). Non-contact ACL injury events are often associated with NP errors, as athletes demonstrate poor inhibitory control and attentional errors during pressing actions when responding to deceiving actions from opposition (Gokeler et al., 2024). When athletes are immersed in environments that constrain decision-making and divided attention, less attentional resources are allocated to safe movement strategies and may lead to greater load on the LE (Hughes and Dai, 2023).

Work from our previous systematic review determined that all included studies demonstrated an association between worse NP performance and LE biomechanics suggestive of greater injury risk, as well as an association with actual LE injury occurrence in most included studies (Avedesian et al., 2022a). While this research indicates that NP influences LE injury risk, there remains a paucity of evidence that describe successful clinical translation and intervention for at-risk athletes. Newer technologies such as stroboscopic eyewear, smartboards, and virtual reality (VR)/augmented reality (AR) offer opportunities for sports scientists and clinicians to quantify NP and determine appropriate training interventions. However, successful implementation of these technologies require multiple features, including discrimination between athlete skill levels (e.g., novice versus expert), targeted skill improvement through training, and transfer of skill improvement to enhanced on-field performance (Hadlow et al., 2018). Furthermore, specific NP abilities that are strongly associated with LE injury must be determined to tailor technology and training modalities to at-risk athletes.

LE injury risk reduction remains problematic for athletes of all skill levels. While previous research has identified a relationship between NP and LE injury, there remains gaps in the current literature elucidating which NP abilities influence injury risk and how practitioners can implement NP training with their athletes. The primary aim of this narrative review is to describe the previous literature examining the relationship between NP and LE injury in athletic populations. Additionally, this paper will attempt to provide a rationale for the neurophysiological mechanisms of NP underpinning high-risk LE biomechanics and injury. Lastly, this review will discuss the available evidence for novel technologies and techniques to quantify and train NP, providing sports scientists and clinicians with a framework for adoption within their sport environment.

2. The relationship between NP and LE biomechanics

Examining the influence of NP on LE biomechanics associated with injury risk may identify mechanisms underlying this relationship and allow for clinicians to develop interventions specific to at-risk athletes. Previous research examining the relationship between NP and LE biomechanics have been performed in recreationally active individuals (Almonroeder, 2017; Fischer et al., 2021; Herman and Barth, 2016; Giesche et al., 2020), collegiate club athletes (Monfort et al., 2019), varsity collegiate athletes (Avedesian et al., 2021), and national-level university athletes (Shibata et al., 2018). All studies were cross-sectional investigations in which NP was assessed prior to LE biomechanical assessments. Studies included between 15 and 45 participants. NP was captured via computerized assessments (Almonroeder, 2017; Herman and Barth, 2016; Monfort et al., 2019; Avedesian et al., 2021), pen-and-paper tests (Shibata et al., 2018), or both (Fischer et al., 2021; Giesche et al., 2020). One study measured a task-specific visual motor reaction time, defined as the time taken to initiate a jump-cutting maneuver upon a presented visual stimulus (Avedesian et al., 2021). Computerized assessments measured indices of visual and verbal working memory, visual motor processing speed, reaction time, attentional control, multitasking, and inhibitory control (Almonroeder, 2017; Fischer et al., 2021; Herman and Barth, 2016; Monfort et al., 2019; Avedesian et al., 2021). Pen-and-paper tests assessed visual perception, attentional control, cognitive flexibility, and working memory (Giesche et al., 2020; Shibata et al., 2018). All NP assessments in these studies have been traditionally utilized for baseline and post-concussion evaluations. LE biomechanical tasks consisted of jump landings (Almonroeder, 2017; Fischer et al., 2021; Herman and Barth, 2016), sidestep cutting (Monfort et al., 2019; Avedesian et al., 2021; Shibata et al., 2018), and countermovement jumps (Giesche et al., 2020), in which kinematic and kinetic parameters previously associated with ACL and LE injury risk were quantified. Common kinematic measures included sagittal and frontal plane motion of the trunk, hip, and knee (Almonroeder, 2017; Fischer et al., 2021; Herman and Barth, 2016; Monfort et al., 2019; Avedesian et al., 2021; Shibata et al., 2018), while kinetic measures included frontal and sagittal plane moments about the hip and knee, as well as vertical ground reaction forces (Almonroeder, 2017; Fischer et al., 2021; Herman and Barth, 2016; Giesche et al., 2020; Monfort et al., 2019; Avedesian et al., 2021; Shibata et al., 2018). One study examined landing errors and the dual-task cost between planned and unplanned landings (Giesche et al., 2020). Various methodology and statistical analyses were conducted to assess the relationship between NP and LE biomechanics. In some investigations, individuals were dichotomized based on defined thresholds for “high” and “low” NP to detect whether group-based differences existed in LE biomechanics (Almonroeder, 2017; Herman and Barth, 2016; Shibata et al., 2018). Other investigations performed regression-based models or correlational analyses to determine the association between NP and LE biomechanics (Fischer et al., 2021; Giesche et al., 2020; Monfort et al., 2019; Avedesian et al., 2021).

2.1. Findings

Based on the findings from the included studies, it appears that NP influences LE biomechanics suggestive of greater injury risk, albeit to varying degrees. This is likely attributed to differences in study design, NP measures, task conditions, and athlete populations. Compared to the “high” NP group, individuals classified in the “low” NP group (i.e., slower reaction time and processing speed) demonstrated greater vertical ground reaction force, frontal plane knee moment and angle, and anterior knee shear force during bilateral and unilateral landing tasks (Almonroeder, 2017; Herman and Barth, 2016). Based on these findings, researchers concluded that athletes with worse NP were at greater risk for LE injury, specifically ACL injury, during landing tasks (Almonroeder, 2017; Herman and Barth, 2016). Although not statistically significant, the “low” NP group performed an unanticipated cutting task with approximately seven degrees less peak knee flexion than the “high” NP group (Shibata et al., 2018), which may still represent clinical significance given the measured effect size between groups ($d = 0.91$). During anticipated cutting maneuvers, researchers determined that worse visual memory performance was significantly associated with increased peak knee valgus ($r = 0.69$) in collegiate club soccer athletes (Monfort et al., 2019). Increased knee abduction moment was moderately correlated with decreased visual memory performance ($r = -0.54$) and increased reaction time ($r = 0.52$) during a reactionary jump-cut (Avedesian et al., 2021). There may also be utility in measuring task-specific NP, as researchers determined that slower reaction time to initiate a jump-cut was associated with reduced peak knee flexion during landing ($r = 0.51$; 25). While no significant associations were determined between NP and LE kinematics or kinetics during unplanned unilateral landings, worse inhibitory control ($r = 0.48$), short-term memory ($r = -0.55$), and working memory ($r = 0.54$) were significantly associated with decreased landing stability (Giesche et al., 2020).

NP was not associated with peak knee valgus or sagittal plane knee biomechanics during a dual-task jump-landing, in which the researchers speculate that secondary task conditions may modulate the relationship between NP and LE biomechanics (Fischer et al., 2021).

3. The relationship between NP and LE injury

While the relationship between NP and LE injury occurrence is relatively novel in the applied clinical setting, the first investigation of this topic was published nearly 17 years ago (Swanik et al., 2007). Subsequent studies have been performed in various athletic populations with a variety of NP batteries. Researchers have examined this relationship in collegiate (Swanik et al., 2007; Buckley et al., 2020; McDonald et al., 2019; Wilkerson, 2012; Wilkerson et al., 2017) and adolescent athletes (Faltus et al., 2016; Gureck et al., 2023; Avedesian et al., 2022b). One study attempted to identify predictors of LE injuries in collegiate athletes following a concussion injury (Buckley et al., 2020), while the remaining studies did not include athletes with a recent concussion history. In prospective studies, athletes performed baseline NP assessments and LE injury occurrence was subsequently tracked over the course of a single season (Wilkerson, 2012; Wilkerson et al., 2017) or multiple seasons (Swanik et al., 2007; McDonald et al., 2019). Researchers utilizing a retrospective study design gathered baseline NP and quantified subsequent LE injury occurrence over a single year (Buckley et al., 2020; Avedesian et al., 2022b) or multiple years of competition (Faltus et al., 2016; Gureck et al., 2023). NP was captured via computerized assessments (Swanik et al., 2007; Buckley et al., 2020; McDonald et al., 2019; Wilkerson, 2012; Faltus et al., 2016; Gureck et al., 2023; Avedesian et al., 2022b), smartboard technology (Wilkerson et al., 2017), and clinical measures (Buckley et al., 2020). Measurements related to reaction time, working memory, visual motor processing speed, and attention were captured in these investigations. Various LE injuries were reported, including ACL injury (Swanik et al., 2007; Gureck et al., 2023) and an aggregate of LE sprains and strains to the ankle, knee, and hip (Buckley et al., 2020; McDonald et al., 2019; Wilkerson, 2012; Wilkerson et al., 2017; Faltus et al., 2016; Avedesian et al., 2022b). LE injuries were specific to non-contact in three studies (Swanik et al., 2007; Gureck et al., 2023; Avedesian et al., 2022b), while the remaining five studies included non-contact and contact injuries (Buckley et al., 2020; McDonald et al., 2019; Wilkerson et al., 2017; Faltus et al., 2016Faltus et al., 2016). Studies included between 72 and 488 participants. Various statistical methods were implemented, with some researchers examining group-based differences between athletes who sustained a LE injury versus those who did not (Swanik et al., 2007; Buckley et al., 2020; Faltus et al., 2016; Gureck et al., 2023), while others sought to determine a "cut-point" for optimal discrimination between injured and non-injured athletes (McDonald et al., 2019; Wilkerson, 2012; Wilkerson et al., 2017; Avedesian et al., 2022b).

3.1. Findings

Among the eight included studies, five investigations demonstrated group differences in baseline NP between injured and non-injured athletes (Swanik et al., 2007; Avedesian et al., 2022b) or that NP predicted subsequent LE injury (McDonald et al., 2019; Wilkerson, 2012; Wilkerson et al., 2017; Avedesian et al., 2022b). The remaining three studies did not determine group differences in NP between injured and non-injured athletes (Buckley et al., 2020; Faltus et al., 2016; Gureck et al., 2023), although one study demonstrated a sex by injury status interaction effect (Faltus et al., 2016). Athletes who sustained a non-contact ACL injury demonstrated significantly slower reaction time, along with worse processing speed and working memory performance, during pre-season baseline testing when compared to matched controls (Swanik et al., 2007). Mean reaction time in the ACL injury cohort (0.57 s) was similar to the optimal "cut-point" for discriminating between injured and non-injured athletes in subsequent investigations utilizing the same NP testing battery (McDonald et al., 2019; Wilkerson, 2012). In collegiate football athletes, athletes with a reaction time greater than 0.55 s were nearly three times as likely to sustain an LE sprain or strain (Wilkerson, 2012). Investigators in a separate study found reaction time, processing speed, and working memory to be significant predictors of LE injury during two seasons of collegiate football (McDonald et al., 2019). Similar to computerized measures, baseline visual motor reaction time on a smartboard technology was able to discriminate between injured and non-injured football athletes (Wilkerson et al., 2017). Athletes with a visual motor reaction time greater than 0.71 s were more than twice as likely to sustain an LE injury versus faster performers (Wilkerson et al., 2017). In adolescent male football and female soccer athletes, every 10 ms increase in orienting network reaction time relative to a baseline reaction time condition was associated with a 15% increased risk for LE injury (Avedesian et al., 2022b). Athletes above a cut-point of greater than 32.8 ms for orienting network reaction time were 2.6 times more likely to sustain a non-contact LE injury (Avedesian et al., 2022b). However, other researchers have found that computerized NP measures could not differentiate between uninjured adolescent athletes and those who sustained ACL or LE injuries (Faltus et al., 2016; Gureck et al., 2023). The relationship between NP and LE injury in adolescents may be sex-specific, as skiing and snowboarding male athletes who sustained an LE injury demonstrated a 5.8% increased reaction time and 14.4% decreased working memory score compared to uninjured males (Faltus et al., 2016). In the same investigation, no differences in NP were detected in female athletes (Faltus et al., 2016). Although collegiate athletes with recent concussion were 1.8 times more likely to sustain a subsequent LE injury compared to controls, researchers determined that computerized and clinical measures of NP were not predictive of LE in this cohort (Buckley et al., 2020).

4. Cerebral neurophysiological mechanisms underpinning LE injury

As stated previously, NP is defined as *cerebral neural functions contributing to cognition during physical task execution in a given context*. During sport, various neural processes allow athletes to perceive environmental stimuli and subsequently predict the appropriate amount of muscle force and stiffness required to optimize LE joint stability during high-risk tasks (e.g., jump-cutting). Sensory information from the central nervous system (brain and spinal cord) must provide rapid and accurate efferent information to the peripheral musculature to avoid high external loads that lead to injury (Swanik, 2015). This process may be referred to as *sensorimotor integration* (Machado et al., 2010). Researchers have recently considered LE injury, particularly non-contact ACL injury, as an error in sensorimotor integration caused by a mismatch in perception-action coupling, or the continuous regulatory loop between perception and movement output (Swanik, 2015; Grooms et al., 2022a). Athletes perceive vast amounts of environmental information via visual attention, as approximately 70% of all sensory receptors are located in the eyes and 20–30% of the cerebral cortex is dedicated to vision (Van Essen, 2004). As previous research has demonstrated that preparatory neural activity is initiated hundreds of milliseconds prior to actual movement (Swanik, 2015; Armstrong et al., 2018), athletes must utilize various visual strategies such as saccades, smooth pursuits, and convergence to predict task relevant and irrelevant stimuli that regulates motor output (Klostermann et al., 2019). It is believed that disruptions in visual processing or attending to complicated visual information leads to altered neuromuscular activity and reduced LE joint stiffness (Swanik, 2015). For example, knee stiffness and electromyographical activity of the quadriceps and hamstrings were significantly reduced during visuospatial tasks compared to a control condition (Kim et al., 2016). This reduction in neuromuscular control is commonly seen in sport-specific scenarios when athletes must visually attend to various stimuli while performing high-risk movements (Hughes and Dai, 2023). Various brain regions are implicated in

processing sensory information to guide neuromuscular control, including the thalamus, visual cortex, and prefrontal cortex (Grooms et al., 2022a). Visual information first passes through the thalamus, which acts to relay sensory information to the cerebral cortex (Huff et al., 2024). The visual cortex, in particular the lingual gyrus and Area V5, process complex visual information and are crucial for the perception of tracking motion such as opponents, teammates, and other sport-related objects (Zeki, 2015). Interestingly, individuals who sustained an ACL injury demonstrate neuroplastic alterations within the visual cortex, as researchers have demonstrated increased activity in these brain regions during motor tasks when compared to controls (Criss et al., 2020; Grooms et al., 2017). The prefrontal cortex acts to filter visual information that enables executive control of planning, decision-making, and inhibitory control prior to movement initiation (Libedinsky and Livingstone, 2011; Krämer et al., 2013). While the extent of the contributions of the central nervous system to sensorimotor integration are still unknown, it is believed that visual processes play a critical role in LE injury risk (Swanik, 2015).

The disruption in sensorimotor integration leading to LE injury may be attributed to inefficiencies in cerebral neural functions during high-risk tasks. Preliminary findings suggest a potential neural correlate to ACL injury risk, as athletes who sustained an ACL injury demonstrated reduced pre-season connectivity between brain areas responsible for sensorimotor control when compared to uninjured controls (Diekfuss et al., 2019, 2020a). Recently, researchers have utilized functional magnetic resonance imaging to quantify brain activity during knee flexion-extension tasks and determine its relationship to LE biomechanics during sport-specific scenarios (Grooms et al., 2022b; Culiver et al., 2023). In adolescent athletes, increased activity in the precuneus and lingual gyrus was associated with greater frontal plane knee moment during a drop vertical jump (Grooms et al., 2022b). After ACL injury, increased activity in the precuneus and superior parietal lobe was associated with greater peak knee extension moment during a change-of-direction task with visual perturbation (Culiver et al., 2023). Taken together, these findings suggest a neural basis for sensorimotor dysfunction in brain areas responsible for perception-action coupling and motor control. It must be recognized that future research with larger study populations is necessary to confirm these findings, as well as determine how cerebral neural signatures moderate the relationship between NP and LE injury.

5. Can we train the brain to reduce LE injury? Technological and training considerations for NP enhancement

From the available evidence linking NP to LE biomechanics and injury risk, it can be inferred that athletes must possess a requisite level of NP to safely perform their sport. In theory, improvements in NP, such as decreased reaction time and faster visual motor processing, would allow athletes more time to initiate appropriate neuromuscular forces that protect the LE during high loading maneuvers (Swanik, 2015). Training interventions targeting perceptual and/or neuropsychological skills, typically referred to as *perceptual-cognitive training* (PCT), have become more popular in applied athletics settings (Hadlow et al., 2018; Fransen, 2024). Some common PCT technologies include stroboscopic eyewear, smartboards, and VR/AR. The following sections will briefly describe each technology, along with a summary of the available evidence supporting its use for enhancing NP to reduce LE injury risk.

5.1. Stroboscopic eyewear

Stroboscopic eyewear utilizes liquid crystal lens technology that regulate visual information by alternating between clear and opaque states. Users are recommended to begin at the highest frequency (i.e., "blink rate") level and then progressively lower the strobe frequency to reduce the amount of visual information gained during sport-specific tasks. It is theorized that stroboscopic eyewear improves multiple processes important for sensorimotor control, including visual attention, efficiency, accuracy, and trajectory estimation (Wilkins and Appelbaum, 2020). Stroboscopic eyewear may also facilitate sensory re-weighting to increase contributions from proprioceptive and vestibular inputs, an important considerations for athletes post-ACL injury who demonstrate an overreliance on vision for LE motor control (Grooms et al., 2017; Walker et al., 2021).

Current evidence indicates that stroboscopic eyewear training is generally associated with improvements in visual motor performance, however these improvements are typically seen in near-transfer, non-sport-specific tasks (e.g., laboratory-based assessments). Stroboscopic eyewear training has led to increased sensorimotor performance, such as more accurate response inhibition (Appelbaum et al., 2016), faster visual motor processing speed (Hülsdünker et al., 2021; Ellison et al., 2020; Wilkins and Gray, 2015), enhanced motion detection (Appelbaum et al., 2011), and improved short-term visual memory (Appelbaum et al., 2012). While positive far-transfer effects related to agility (Zwierko et al., 2024) and sport-specific performance (Mitroff et al., 2013; Hülsdünker et al., 2019) have been demonstrated, these findings are not consistently present in the literature (Fransen, 2024; Hülsdünker et al., 2021; Palmer et al., 2022).

Researchers have speculated that stroboscopic eyewear training may enhance rehabilitation from long-term injuries, such as ankle sprains or ACL injury (Grooms et al., 2017; Wohl et al.). Indeed, improvements in postural stability have been demonstrated following stroboscopic eyewear training in individuals with chronic ankle instability (Lee et al., 2022; Kim et al., 2021). However, there are currently no published studies regarding the effectiveness of stroboscopic eyewear training for LE injury risk mitigation, providing opportunities for future research in this area.

5.2. Smartboards

Smartboards are interactive touch screens for the assessment and training of various visual motor skills in which athletes typically respond to visual stimuli via upper extremity movements. Targeted outcomes include reaction time, multiple object tracking, and eye-hand coordination (Erickson, 2021). These measures have good test-retest reliability in college-aged individuals (Zynda et al., 2024; Wells et al., 2014). Prior research has demonstrated that training interventions with smartboards improve visual motor abilities (Feldhacker and Molitor, 2019) and sport-specific performance (Clark et al., 2012).

Presently, one study has examined the relationship between smartboard performance and LE injury risk (Wilkerson et al., 2017). Collegiate football athletes classified as "slow" performers based on visual motor reaction time were significantly more likely to sustain an LE injury compared to "fast" performers. Furthermore, the researchers demonstrated that a 6-week post-season training intervention utilizing the smartboard improved visual motor reaction time by 28% in high-compliance athletes (Wilkerson et al., 2017). While this provides optimism for the utility of smartboard technology in training sensorimotor abilities, substantially more evidence is required prior to adoption in a clinical setting.

5.3. Virtual/augmented reality

VR and AR have become more popular in athletic settings, allowing athletes complete control over their training environment and offering realistic sporting scenarios. VR places a user in a simulated environment that when paired with eye and pose tracking offer a fully immersive experience, while augmented reality supplements the natural environment with digital elements that are often interactive with the user (Soltanabadi et al., 2023). Researchers and clinicians have particular interest in both technologies during injury rehabilitation, as athletes can undergo cognitively challenging tasks without incurring unnecessary physical stress in early stages. Recent investigators have utilized VR as a

supplemental therapy to improve pain and subjective knee function following ACL injury (Gsangaya et al., 2023) and may restore LE biomechanics to pre-injury status (Gokeler et al., 2016). Preliminary findings in AR indicate that bio-feedback driven AR training may improve knee control during jump-landings that is modulated by increased brain functional connectivity in sensorimotor areas (Diekfuss et al., 2020b).

While these emerging technologies have been found to improve performance through positive sensorimotor adaptations (Richlan et al., 2023), few studies to date has examined VR training interventions for mitigating LE injury risk (Reneker et al., 2019, 2020). In both investigations, collegiate male and female soccer athletes underwent a 4-week (Reneker et al., 2019) and 6-week (Reneker et al., 2020) training intervention in which VR was used to train oculomotor control, visual acuity, and sensory perception-action. Researchers in the first study observed a 27% reduction in injury rate compared to the prior season (Reneker et al., 2019), although this was not statistically significant. In the second study, no differences in season-long injury rate were found between the experimental and control groups (Reneker et al., 2020). Future research is necessary to confirm these findings in healthy athletes and those returning from previous injury.

6. Conclusion

The purpose of this narrative review was three-fold: 1) describe the evolving literature on the relationship between NP and LE injury risk; 2) discuss the underlying cerebral neurophysiological mechanisms of NP underpinning high-risk LE biomechanics and injury; and 3) present novel technologies for training NP. Athletes perform complex multi-joint maneuvers under strict spatial-temporal constraints, requiring quick and efficient sensory processing to guide motor output that allows for safe movement (Swanik, 2015). Quantifying and training NP may supplement previously described LE injury risk reduction programs that are concentrated on neuromuscular or biomechanical outcomes (Avedesian et al., 2022a). The present literature suggests that worse NP is associated with LE biomechanics suggestive of greater injury risk, particularly at the knee (i.e., decreased sagittal plane motion). Furthermore, NP appears to influence LE injury outcomes, as measures of reaction time, processing speed, and working memory differ at baseline between injured and non-injured athletes (Swanik et al., 2007; Avedesian et al., 2022b) or predicted subsequent LE injury (McDonald et al., 2019; Wilkerson, 2012; Wilkerson et al., 2017; Avedesian et al., 2022b). Visual performance may be the most important NP indicator, as vision predominantly guides sensorimotor integration during movement. Various brain regions implicated in visual processing indicate a neural signature to LE injury (Diekfuss et al., 2019; Grooms et al., 2022b;

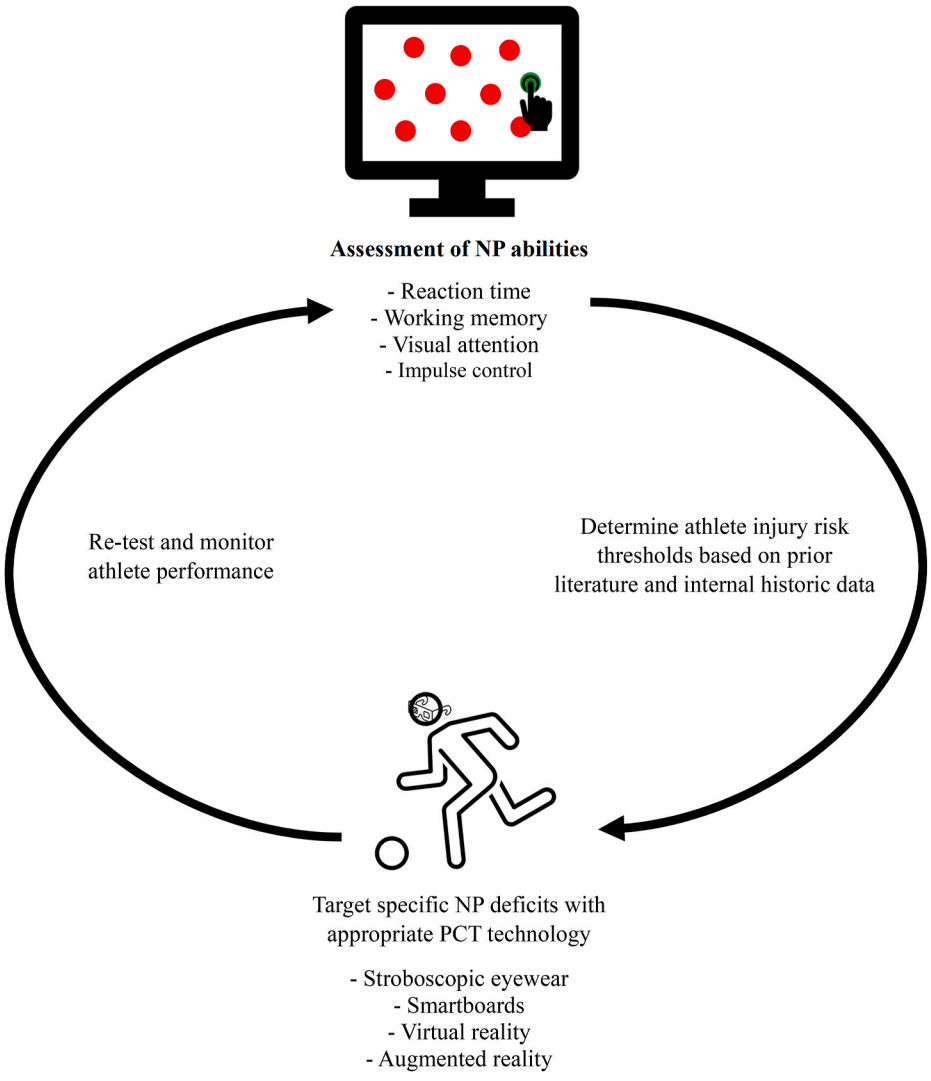


Fig. 1. NP assessment and training strategy to identify at-risk athletes and determine appropriate interventions.

Culiver et al., 2023), suggesting that sensorimotor interventions emphasize visual motor deficits to reduce injury risk. While recently developed PCT technology such as stroboscopic eyewear, smartboards, and VR/AR offer promise for improving NP and LE stability, far-transfer effects to LE injury risk reduction have yet to be substantially investigated. Fig. 1 describes how sports scientists and clinicians can monitor assess NP, determine athlete injury risk thresholds, and determine appropriate training interventions with the previously described PCT technology.

Limitations must be acknowledged when interpreting the findings of this review. A systematic review was not performed, suggesting the effect of NP on LE biomechanics and injury, as well as the effect of PCT on relevant outcomes, may require further interpretation. Future research should conduct a systematic review and meta-analysis on these topics. Additionally, this review primarily focused on the study of healthy athletes, although NP and related training interventions may be particularly relevant in the rehabilitation of injured populations. All three areas of study in this review share a common theme in that more research is required to offer definitive conclusions for how NP may be incorporated within applied clinical settings. However, it is the hope that this review orients the reader with the current knowledgebase of the relationship between NP and LE injury to influence future research and practice.

CRediT authorship contribution statement

Jason M. Avedesian: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Data curation, Conceptualization.

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