EXAMINING THE ROLE OF COGNITION IN THE RISK OF LOWER EXTREMITY MUSCULOSKELETAL INJURIES AND CONCUSSIONS AMONG ELITE ATHLETES

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Abstract

Risk factors for lower extremity musculoskeletal (LEMSK) injury and concussion have largely been examined in isolation. This thesis sought to elucidate the associations between cognition, concussion, and LEMSK injury. Cognition was measured by the Vienna Test System (VTS) and injuries (LEMSK and concussions) were documented prospectively among elite athletes. Study 1 ($N = 58$) assessed the test-retest reliability (9-21-month period) and temporal stability of the VTS. Across cognitive tests, reliability ranged from poor to good (0.34-0.83). Cognition significantly changed across time points, most notably in cognitive flexibility. Study 2 ($N = 145$) explored cognition and concussion history as risk factors of injury. Concussion history and slower reaction time on a working memory test significantly predicted LEMSK injury. Concussion history and cognition did not significantly predict concussion. Moreover, no cognitive measures mediated the relationships between concussion history and subsequent injury. Therefore, future research should explore alternative mechanisms that underly these associations.

Keywords*:* Concussions, musculoskeletal injuries, cognition, computerized neuropsychological testing, athletes

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List of Abbreviations

ACL	Anterior cruciate ligament
ADHD	Attention-deficit/hyperactivity disorder
ANOVA	Analyses of variance
CI	Confidence interval
ICC	Intraclass correlation coefficient
ImPACT	Immediate Post-Concussion Assessment and Cognitive Testing
LEMSK	Lower extremity musculoskeletal
MSK	Musculoskeletal
OR	Odds ratio
RCI	Reliable change index
RT	Reaction time
SAC	Standardized Assessment of Cognition
SCAT	Sport Concussion Assessment Tool
SWC	Smallest worthwhile change
VTS	Vienna Test System

Chapter 1.

Introduction

Musculoskeletal (MSK) injuries and concussions are common occurrences among athletes (Gimigliano et al., 2021; Khurana & Kaye, 2012). Beyond physical repercussions, injuries are also associated with psychosocial and psychological consequences (Houston et al., 2016; Putukian, 2016) and may increase an athlete's risk of future injuries (Abrahams et al., 2014; Fulton et al., 2014). Therefore, injury prevention is fundamental for athlete health and success (Drew et al., 2017). Identifying risk factors for MSK injuries and concussions is critical for developing primary prevention strategies. The majority of research that has explored risk factors for injury have primarily focused on biological, biomechanical, and environmental factors, such as age, sex, level of competition, and playing surface (Abrahams et al., 2014; Hewett et al., 2005; McPherson et al., 2019; D. F. Murphy et al., 2003; Myer et al., 2009). There is also evidence to suggest that concussion history is a risk factor for subsequent concussion and MSK injury (Abrahams et al., 2014; Howell, Lynall, et al., 2018; McPherson et al., 2019; Ramirez et al., 2022; Reneker et al., 2019). Cognition as a potential risk factor for concussion and MSK injury has emerged as a relatively new area of research (Avedesian, Forbes, et al., 2022). This thesis aims to better understand the potential roles of concussion history and cognition as risk factors for MSK injuries and concussions.

Concussions

Concussion is a type of mild traumatic brain injury that occurs as a result of biomechanical forces being induced on the brain (Meaney & Smith, 2011; Tierney, 2024). Sport-related concussions often occur due to direct blows to the head, either by contact with a surface, another player, or sports equipment (Noble & Hesdorffer, 2013). Concussion signs and

symptoms may include somatic (e.g., headaches), cognitive (e.g., difficulty concentrating), or emotional (e.g., lability) symptoms, physical signs (e.g., loss of consciousness), balance impairment (e.g., postural instability), behavioural changes (e.g., irritability), cognitive impairment (e.g., slowed reaction time), and sleep-wake disturbances (Khurana & Kaye, 2012; McCrory et al., 2017). Concussion signs and symptoms are typically acute in nature, with most symptoms resolving within 7 to 14 days in adults or around four weeks in children and adolescents (Bleiberg et al., 2004; Macciocchi et al., 1996; McCrory et al., 2017).

The 2022 consensus statement on concussion in sport (Patricios et al., 2023) provides guidelines on the evaluation and management of sport-related concussions. Any player who demonstrates concussion signs or symptoms following a potential injury should be removed from play and given a sideline evaluation that includes a brief cognitive assessment. For athletes with a suspected concussion, a more comprehensive off-field multimodal evaluation of signs and symptoms, balance, gait, neurological, and cognitive changes is recommended. Since signs and symptoms evolve acutely following a concussion, re-evaluation of the concussion in the coming hours or days should take place. At this point, neuropsychological or computer-based cognitive tests can be administered. Ultimately, a diagnosis of a concussion is based on clinical judgement from all of the available evidence. Following a concussion, athletes are recommended a brief period of relative rest for approximately 24 to 48 hours, followed by a gradual increase in physical activity levels (Leddy et al., 2023). Clinical recovery from a concussion is determined when symptoms are absent at rest and during activity, and cognitive abnormalities or other relevant clinical factors of the athlete’s current concussion (e.g., balance) are resolved. Therefore, cognitive testing also assists return-to-sport decisions. After clinical recovery, athletes start by participating in non-contact training drills, followed by full contact practice, and finally, full

return to sport. Taken together, cognitive testing following a concussion is a critical component for the assessment and management of concussion in athletes.

Cognitive Testing in Sport and Concussions

Measuring cognitive abilities in athletes is important given the role of cognition in both sport performance and concussion. Sports are cognitively demanding activities. Athletes must coordinate motor actions with a rapidly changing environment, under stressful conditions while challenging their physical limits (Williams & Ericsson, 2005). Consider a wide receiver in American football. While running at full speed, a receiver must concentrate on the trajectory of the ball, remember the position of opposing players, and react quickly if the ball were to change direction unexpectedly. Further, there is evidence to suggest that cognitive performance is associated with physical activity (Erickson et al., 2015; Esteban-Cornejo et al., 2015). Given cognitive and physical demands of sport, it is unsurprising that research has found that athletes demonstrate superior cognitive abilities compared to non-athletes (Logan et al., 2023; Voss et al., 2010). Sport expertise is also associated with higher cognitive performance, as evidenced by meta-analyses comparing elite athletes to lower-performance athletes (Kalén et al., 2021; Scharfen & Memmert, 2019). Cognitive abilities may also show different patterns according to sport type (J. Jacobson & Matthaeus, 2014; Yongtawee et al., 2022).

Given that cognition may be influenced by sport expertise, sport type, and individual pre-existing factors (e.g., sex, age, education level), pre-season cognitive testing is important to establish a baseline for which post-concussion cognitive performance can be compared (Cottle et al., 2017; Dougan et al., 2014; Echemendia et al., 2013; French et al., 2019; Roebuck-Spencer et al., 2013). For example, an elite athlete with superior baseline cognitive performance may perform in the average range on post-concussion cognitive testing, which may be misinterpreted

as normal cognitive functioning. In contrast, comparing post-concussion cognitive performance to baseline functioning could indicate a cognitive abnormality due to a concussion. Conversely, pre-season cognitive testing also allows clinicians to differentiate between pre-existing cognitive difficulties (e.g., attention-deficit/hyperactivity disorder [ADHD]) and cognitive deficits due to a concussion (Cottle et al., 2017).

When comparing pre-season and post-concussion cognitive performance, it is also important to consider that an athlete may show normal variation in their performance on a cognitive test over time. Test-retest reliability informs us about the temporal stability of cognitive performance on a cognitive test. In other words, it measures how cognitive performance on a test is expected to change over a given time period. This helps to determine whether post-concussion cognitive disparities are due to measurement error of the cognitive test or whether it is attributable to the concussion itself. Reliable change indices (RCIs) can be calculated from the cognitive test's reliability to classify whether change on a cognitive measure is clinically significant (i.e., above and beyond what is expected based on normal variation). In contrast to studies on test psychometrics that often report test-retest reliability across short time periods (e.g., one week), long-term reliability (i.e., greater than three months) is usually more meaningful for sport-related concussions since the length of time between pre-season and post-concussion cognitive testing could be several months (Mayers & Redick, 2012). Common concussion assessment measures and their long-term test-retest reliability are outlined below.

Concussion Assessment Measures

Cognitive abnormalities that are typically detected in post-concussion cognitive testing span attention, processing speed, reaction time, memory, and executive functions (Baillargeon et

al., 2012; Johnson et al., 2011; Khurana & Kaye, 2012). Concussion assessment measures aim to assess these different domains.

The Sport Concussion Assessment Tool (SCAT) is the most common screening measure of post-concussion symptoms, cognition, neurological functioning, and balance (Echemendia et al., 2023). The SCAT's Standardized Assessment of Cognition (SAC) measures general orientation (e.g., "what is the day of the week?"), immediate and delayed memory of a word list, and concentration for recalling digits in the backwards order. Studies that have assessed the test-retest reliability of the SAC over a one-to-two-year period report stability coefficients ranging from 0.29 to 0.52 (Bailey et al., 2022; Broglio et al., 2018; Bruce et al., 2014, 2022). This suggests that the SAC has poor test-retest reliability. The SAC was also designed as a fast cognitive screening measure that can be used as a sideline assessment of concussion and may not be sensitive enough to detect subtle cognitive impairments among athletes. Therefore, computerized testing may provide additional value in the assessment and management of concussions (Farnsworth et al., 2017; Resch et al., 2013).

Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT; ImPACT Applications, Inc., Pittsburgh, PA) was developed to be a more comprehensive cognitive screening measure for concussion (Schatz et al., 2006). ImPACT is one of the most widely used computerized neuropsychological testing batteries for concussion. It includes composites of verbal and visual memory, processing speed, and reaction time. Even though ImPACT has widespread use, there are some psychometric concerns that have been raised in the literature (Alsalaheen et al., 2016; Mayers & Redick, 2012). Long-term test-retest reliability of ImPACT composite scores range from 0.21 to 0.85, with processing speed showing the highest reliability with a range of 0.72 to 0.85 (Broglio et al., 2018; Bruce et al., 2014; Elbin et al., 2011; Schatz,

2010; Tsushima et al., 2016). CogState (CogState Ltd, Melbourne, Australia) is another computerized neuropsychological assessment used for sport-related concussions that includes processing speed, attention, learning, and working memory domains (Collie et al., 2003). Broglio and colleagues (2018) measured the one-year test-retest reliability of CogState and found it to have poor-to-moderate reliability (0.49-0.59). Moreover, along with some psychometric concerns, ImPACT and CogState do not extensively measure the breadth of executive functioning and attention difficulties that may occur following a concussion (Cristofori & Grafman, 2017; Howell, Osternig, Van Donkelaar, et al., 2013; McGowan et al., 2018, 2019).

The Vienna Test System (VTS; Schuhfried CmbH, Moedling, Austria) is an alternative computerized neuropsychological test battery that has been used to assess cognitive abilities in athletes (Ong, 2015; Schuhfried, 2013). Cognitive tests include measures of executive functioning (e.g., cognitive flexibility, inhibition, working memory, and planning ability) and attention (e.g., selective and sustained attention). Cognitive tests on the VTS have been deemed valid and reliable in non-athlete populations (Kaiser et al., 2019; Kaller et al., 2019; Schellig et al., 2011; Schelling, 2016; Schuhfried, 2017, 2019). A subset of cognitive tests from the VTS were also assessed in a small sample of wrestlers (Gierczuk & Ljach, 2018). The study concluded that the VTS was a valid instrument to assess coordinated motor abilities in wrestlers (Gierczuk & Ljach, 2018). However, psychometric properties of the cognitive tests from the VTS among athletes are very limited in comparison to studies using the SCAT SAC, ImPACT, and CogState. Specifically, the long-term test-retest reliability of the VTS has yet to be established.

Pre-season cognitive testing is not only useful in the assessment and management of concussions, but also in answering research questions regarding the associations between cognition, concussion, and MSK injury. Research has found that athletes who have recovered

from their concussion and returned to sport are at an increased risk of an MSK injury or another concussion (Abrahams et al., 2014; Howell, Lynall, et al., 2018; McPherson et al., 2019; Ramirez et al., 2022; Reneker et al., 2019). Cognitive testing may help in understanding the mechanisms that underlie these relationships. Research also provides evidence that worse pre-season cognitive performance may be associated with an increased risk of MSK injury (Avedesian, Forbes, et al., 2022; Swanik, 2015; Wilke & Groneberg, 2022). Concussion history and cognition as potential risk factors for MSK injury and concussion are outlined below.

Musculoskeletal Injury Risk

MSK injuries are damage to the bones, muscles, cartilage, tendons, ligaments, joints, and other connective tissues in the body (Bahr et al., 2020). Lower extremity MSK (LEMSK) injuries are the most common type of injury among athletes (Sheu et al., 2016). LEMSK injuries are MSK injuries to the hip/groin, thigh, knee, lower leg, ankle, or foot (Orchard et al., 2020). This may include injuries such as ankle sprains, hamstring strains, stress fractures, and anterior cruciate ligament (ACL) tears. Previous research suggests that risk of LEMSK injury may be greater in competition than training sessions, on artificial turf than grass or gravel, and following a previous injury with inadequate rehabilitation (D. F. Murphy et al., 2003). Other risk factors that have been explored include biomechanical characteristics (Hewett et al., 2005) and muscular strength (Myer et al., 2009). More recently, studies have explored the roles of concussion history and cognition as risk factors for subsequent LEMSK injury.

Concussion History as a Risk Factor for MSK Injury

Concussion history has been associated with a greater risk of subsequent MSK injury (Howell, Lynall, et al., 2018; McPherson et al., 2019; Ramirez et al., 2022). Considering that

MSK injuries to the lower extremities are the most common injury (Sheu et al., 2016), many studies have focused on examining LEMSK injuries specifically.

Ramirez and colleagues (2022) conducted a meta-analysis of five studies (Brooks et al., 2016; Fino et al., 2019; Harada et al., 2019; Herman et al., 2017; Murray et al., 2020) that investigated the risk of LEMSK injury among collegiate athletes with a history of concussion. The risk of sustaining an LEMSK injury was 1.58 times greater in athletes with a history of concussion compared to athletes without a history of concussion (Ramirez et al., 2022). Secondary analyses found that the risk of LEMSK injury was particularly elevated within the first 90 days following return to sport (risk ratio = 2.20), but not significantly elevated one year later (Ramirez et al., 2022). Other studies with collegiate athletes have also found a significant association between concussion history and subsequent LEMSK injuries (Buckley et al., 2020; Gilbert et al., 2016; Krill et al., 2018; Lutz et al., 2021; Lynall et al., 2015). This relationship has also been found in high school athletes (Biese et al., 2021; Lynall et al., 2017; Wilson et al., 2021) and professional athletes (Jildeh, Meta, Young, Page, Nwachukwu, et al., 2021; Nyberg et al., 2015; Wittrup et al., 2020). Notably, higher levels of competition, such as at collegiate and professional levels, have been associated with a greater risk of sustaining a subsequent LEMSK injury compared to high school students (Jildeh et al., 2022). That said, there are studies of collegiate and professional athletes that did not find an association between concussion history and subsequent LEMSK injury (Buckley, Browne, et al., 2023; Buckley, Chandran, et al., 2023, 2023; Jildeh, Meta, Young, Page, & Okoroha, 2021; Nyberg et al., 2015).

The association between history of *multiple* concussions and subsequent LEMSK injuries has also been explored. Harada et al. (2019) reported that athletes with a history of multiple concussions had significantly greater odds of sustaining an LEMSK injury compared to healthy

matched controls (odds ratio [OR] = 1.83) and athletes with a single concussion (OR = 3.06). In another study, the odds of sustaining a concussion were 2.56 times greater in athletes with a history of multiple concussions compared to athletes with no history of concussion, but it was not significantly greater than athletes with a history of a single concussion (Houston et al., 2018). When examining these associations separately for male and female athletes, Houston and colleagues (2018) also found that the odds of sustaining a subsequent concussion was especially elevated among female athletes with a history of multiple concussions compared to female athletes with no history of concussion (OR = 4.31).

Taken together, there is evidence to suggest that concussion history increases an athlete's risk of LEMSK injury. However, the underlying mechanism has yet to be elucidated. One mechanism that has been proposed to explain the association between concussion history and MSK injury risk is the existence of factors that increase an athlete's risk of concussion and MSK injury independently from each other. For instance, a study found that risk-taking behaviours were significantly higher in collegiate athletes with a history of multiple concussions than those without a concussion history (Beidler et al., 2017). Two studies also found that athletes who have sustained a concussion are more prone to injuries both before and after the concussion (Burman et al., 2016; Nordström et al., 2014). Injury rates also vary based on sport, whereby participation in a specific sport or position may put an athlete at an increased risk of MSK injury and concussion (Clay et al., 2013; Hootman et al., 2007; Pfister et al., 2016; Pierpoint & Collins, 2021). Therefore, individual characteristics may increase an athlete's risk of both concussions and LEMSK injuries, rather than concussion history itself increasing the risk of subsequent LEMSK injury.

Another proposed explanation for the association between concussion history and subsequent MSK injury is the presence of persistent concussion effects that extend beyond clinical recovery. Some studies have detected lingering deficits in neuromuscular control following a concussion, such as dual-task gait performance and postural control (Chmielewski et al., 2021; Howell, Lynall, et al., 2018; Martini & Broglio, 2018), which have independently been associated with an increased risk of MSK injury (Hewett et al., 2005; Read et al., 2016; Weiss & Whatman, 2015). Studies have also found that athletes with a concussion history show electrophysiological abnormalities related to working memory, attention, and visual processing even years after their concussion (Baillargeon et al., 2012; Broglio et al., 2009; Gosselin et al., 2012; Ledwidge & Molfese, 2016; Moore et al., 2014; Ozen et al., 2013). In contrast to this literature, findings of persisting cognitive deficits after a concussion are less established.

Athletes tend to recover from cognitive deficits within 7 to 14 days post-concussion (Belanger & Vanderploeg, 2005; McCrory et al., 2017). However, some studies have reported prolonged cognitive difficulties following a concussion (Howell, Osternig, Van Donkelaar, et al., 2013; Lempke et al., 2020; Martini & Broglio, 2018; McGowan et al., 2019; Taylor et al., 2018; Thoma et al., 2015). For example, a meta-analysis found that reaction time deficits persisted beyond concussion clinical recovery and were still present 21 to 59 days post-concussion (Lempke et al., 2020). Howell and colleagues (2013) also showed that two months following a concussion, adolescents showed slower reaction times on tests of executive functioning and attention compared to matched controls (Howell, Osternig, Van Donkelaar, et al., 2013). Inhibitory control deficits have also been shown to persist up to one month following return to sport (McGowan et al., 2019). These studies suggest that cognition may not truly be recovered by the time that an athlete is cleared to return to sport. Therefore, it could be the case that subtle

cognitive deficits that persist beyond concussion recovery and return to sport put athletes at an increased risk for future MSK injuries.

Cognition as a Risk Factor for MSK Injury

Cognition is not only a crucial component of sport, but it may also have a role in an athlete's ability to avoid injuries (Herman et al., 2015). Studies have found that worse performance on pre-season cognitive testing is associated with an increased risk of sustaining an MSK injury (Avedesian, Forbes, et al., 2022; Swanik, 2015; Wilke & Groneberg, 2022). One mechanism that may explain this relationship is that worse cognitive performance has been associated with biomechanical patterns associated with an increased risk of injury (Avedesian et al., 2021; Avedesian, Forbes, et al., 2022; Chou et al., 2023; Herman & Barth, 2016). One important limitation when interpreting the findings of low pre-season cognitive performance is the possibility that athletes intentionally perform worse at baseline with the hope of appearing less impaired at post-concussion testing, a term known as sandbagging (Erdal, 2012).

The first study to investigate the association between cognition and subsequent LEMSK injury was Swanik and colleagues (2007) in a sample of collegiate athletes. They found significant differences between athletes who sustained a non-contact ACL injury and matched controls on all four composites of ImPACT (Swanik et al., 2007). Specifically, athletes who later sustained an ACL injury demonstrated worse performance on tests of verbal and visual memory, and had slower reaction time and processing speed compared to controls (Swanik et al., 2007). Other studies with samples of collegiate athletes have found that slower reaction time, motor speed, and visuomotor response speed were associated with an increased risk of MSK injury (McDonald et al., 2019; Wilkerson, 2012; Wilkerson et al., 2017). Despite these findings, one study of collegiate athletes has reported that subsequent LEMSK injury was not predicted by pre-

season scores on ImPACT or the SCAT SAC (Buckley et al., 2020). The association between cognition and MSK injury risk among studies with adolescent athlete samples was also inconsistent (Avedesian, McPherson, et al., 2022; Faltus et al., 2016; Gureck et al., 2023). Slower reaction time on a computerized task of visuospatial selective attention was associated with an increased risk of LEMSK injury among adolescent American football and soccer athletes (Avedesian, McPherson, et al., 2022). However, two other studies that used ImPACT with samples of adolescent athletes did not find a significant difference between pre-season cognitive performance of injured and non-injured athletes (Faltus et al., 2016; Gureck et al., 2023). However, one of the studies only included ACL injuries (Gureck et al., 2023), while the other study included a wide range of injuries that included concussions (Faltus et al., 2016). Taken together, there is evidence to suggest that pre-season cognitive performance may be a predictor of subsequent LEMSK injury, but inconsistencies exist in the literature.

Concussion Risk

While there are variable findings for many risk factors for concussion, there is a consensus that concussions are more likely during match play compared to practice and among athletes with a history of concussion (Abrahams et al., 2014; Brett et al., 2018).

Concussion History as a Risk Factor for Concussion

Concussion history has been established as a risk factor for subsequent concussions (Abrahams et al., 2014; Castellanos et al., 2021; Reneker et al., 2019; Van Ierssel et al., 2021). In a systematic review by Abrahams and colleagues (2014), ten of the 13 studies that explored concussion history and risk of concussion reported an increased risk of concussion in athletes who sustained a least one previous concussion. A meta-analysis estimated that the odds of sustaining a concussion is 4.44 times greater in athletes with a history of concussion compared to

athletes with no history of concussion (Reneker et al., 2019). Among the individual studies, samples included high school, collegiate, and professional athletes, and ORs ranged from 1.88 to 7.83 (Delaney et al., 2000, 2001, 2002; Guskiewicz et al., 2000; Zemper, 2003). Reneker and colleagues (2019) also reported a pooled risk ratio across three studies (Guskiewicz et al., 2003; Hollis et al., 2009; Schulz, 2004), whereby athletes with a previous concussion were at a 1.97 greater risk of sustaining a subsequent concussion than athletes with no concussion history. A separate meta-analysis by Van Ierssel et al. (2021) investigated the association between concussion history and subsequent concussion in children and adolescent athletes. Across seven studies, the pooled risk of sustaining a concussion was 3.64 times greater among those with a previous concussion compared to those with no concussion history (Van Ierssel et al., 2021). Three studies included only athletes from American football (Chrisman et al., 2019; Kontos et al., 2006; Zemper, 2003), three studies included only ice hockey (Black et al., 2016; Emery et al., 2010, 2011), and one study explored the association in a variety of sports among middle and high school athletes (Tsushima et al., 2019). Taken together, there is strong evidence to suggest that concussion history is associated with subsequent concussion.

Cognition as a Risk Factor for Concussion

Less is known about the role of cognition in predicting the risk of concussion. Based on findings from the MSK injury risk literature, authors have hypothesized that worse cognitive performance would also predict subsequent concussion. However, preliminary evidence suggests that there is no association between pre-season cognitive testing and subsequent concussion among athletes (Caccese et al., 2020; Lopez-Flores et al., 2022; Putukian et al., 2021).

Caccese et al. (2022) found no significant differences on pre-season cognitive performance on ImPACT and the SCAT SAC between collegiate athletes with a future

concussion and matched controls. Lopez-Flores and colleagues (2022) used the processing speed composite from ImPACT to categorize youth soccer players (10-15 years old) into fast and slow processing speed groups. The odds of sustaining a concussion over a nine-year study period was not significantly predicted by processing speed group (Lopez-Flores et al., 2022). This finding was inconsistent with studies that found an association between the ImPACT processing speed composite as a continuous variable and MSK injury risk among collegiate athletes (Swanik et al., 2007; Wilkerson, 2012). Lastly, Putukian et al. (2021) found no significant differences in pre-season cognitive performance on ImPACT or the SCAT SAC between collegiate athletes with and without a subsequent concussion (Putukian et al., 2021).

Despite null findings, one study found that self-reported and parent-reported attention problems have been associated with an increased risk of concussion among youth ice hockey players (Gerschman et al., 2022). An increased incidence of concussions has also been detected among individuals with ADHD (Alosco et al., 2014; Biederman et al., 2015; Cook et al., 2022). While research in this area is still in its infancy, current evidence suggests that there is no relationship between pre-season cognitive performance and subsequent concussion, but limitations exist in the designs of these studies.

Gaps and Limitations of the Literature

Our current understanding of the relationship between cognition, concussion, and LEMSK injury has its limitations. While several studies have explored the association between cognition and LEMSK injury risk, very few studies have explored whether cognition may also predict subsequent concussion. Moreover, studies that have explored cognition as a risk factor for LEMSK injuries and concussion have often used cognitive batteries of tests that were designed as screening measures for post-concussion cognitive deficits (Avedesian, Forbes, et al.,

2022; Caccese et al., 2020; Lopez-Flores et al., 2022; Putukian et al., 2021). Therefore, these measures may not be sensitive enough to detect subtle pre-season cognitive disparities among healthy athletes which could be used to predict subsequent injuries. This could especially be relevant for the studies that have not found an association between cognitive performance and subsequent concussion risk.

Despite that the SCAT, ImPACT, and CogState are widely used cognitive measures for assessing concussion, they carry psychometric concerns in test-retest reliability (Broglio et al., 2018). Moreover, these measures do not extensively measure the breadth of executive functioning and attention difficulties that may occur following a concussion (Cristofori & Grafman, 2017; Howell, Osternig, Van Donkelaar, et al., 2013). While the VTS may be a suitable alternative computerized neuropsychological test battery, the long-term test-retest reliability of the VTS has yet to be established.

Moreover, while there is strong evidence to suggest that concussion history is associated with an increased risk of LEMSK injury and concussion (Abrahams et al., 2014; Howell, Lynall, et al., 2018; McPherson et al., 2019; Ramirez et al., 2022; Reneker et al., 2019), the mechanisms underlying these relationships have not been clearly elucidated. Authors have hypothesized that lingering effects of a concussion on neuromuscular control, neurophysiology, or cognition may increase an athlete's risk of injury (Avedesian et al., 2024; Avedesian, Forbes, et al., 2022; Chmielewski et al., 2021; Herman et al., 2015; Howell, Lynall, et al., 2018; Wilke & Groneberg, 2022). However, to the best of our knowledge, no study has investigated these potential mechanisms in mediation models. Additionally, research exploring concussion history and cognitive performance as risk factors for subsequent injuries have primarily investigated concussion history and cognition independently from one other.

Lastly, previous studies in these areas of research primarily focus on popular team sports (e.g., American football, hockey, soccer, and rugby). Studies have also included a relatively high proportion of males in their sample (Cowley et al., 2021; D'Lauro et al., 2022).

The present thesis addressed these gaps in the literature by assessing the test-retest reliability of the VTS and using the VTS to explore associations between cognition, concussion, and LEMSK injury. The thesis also investigated risk factors (concussion history and cognitive performance) concurrently and included a sample of male and female elite athletes across six different sports.

Current Research

The overall objective of this research was to better understand the relationship between cognition, concussion, and LEMSK injury among elite athletes. Specifically, this thesis aimed to better understand the potential roles of concussion history and cognition as risk factors for LEMSK injuries and concussions. This was accomplished across two studies. Study 1 aimed to establish the utility of the VTS in our sample of athletes for the purpose of then using the VTS as a measure of cognition when investigating the associations between cognition, concussion, and LEMSK injury in Study 2. Specific research objectives and hypotheses for Study 1 and Study 2 are outlined below.

Study 1

The objective of Study 1 was to examine the stability of cognitive performance on the VTS between sport seasons. Specifically, we aimed to assess the long-term test-retest reliability of the VTS, as well as changes in cognition at the group and individual level across pre-season cognitive testing sessions. We hypothesized that the VTS would show moderate test-retest

reliability, and that cognitive performance would be relatively stable across pre-season assessments.

Study 2

The objective of Study 2 was to better understand the roles of concussion history and cognition as risk factors for LEMSK injuries and concussions. Specifically, we aimed to explore the associations between (i) concussion history and cognition; (ii) concussion history and subsequent LEMSK injury; (iii) cognition and subsequent LEMSK injury; (iv) concussion history and subsequent concussion; and (v) cognition and subsequent concussion. We hypothesized that (i) concussion history would minimally predict cognition; (ii) concussion history would predict subsequent LEMSK injury; (iii) cognition would predict subsequent LEMSK injury; (iv) concussion history would predict subsequent concussion; and (v) cognition would predict subsequent concussion.

We also explored whether cognition mediated (vi) the relationship between concussion history and subsequent LEMSK injury; or (vii) the relationship between concussion history and subsequent concussion. We hypothesized that cognition would mediate (vi) the relationship between concussion history and subsequent LEMSK injury; and (vii) the relationship between concussion history and subsequent concussion.

Chapter 2.

Study 1

Pre-season cognitive testing is useful for both clinical and research purposes. Post-concussion cognitive performance can be compared to an athlete's baseline functioning to assist in the diagnosis of sport-related concussions (McCrory et al., 2017). However, poor test-retest reliability of a cognitive measure may limit a clinician's ability to determine whether post-concussion cognitive disparities are due to a possible concussion or whether they are attributed to test measurement error (K. R. Murphy & Davidshofer, 1998). Test-retest reliability over longer periods of time are often more meaningful in the field since concussions may occur several months following pre-season cognitive testing (Mayers & Redick, 2012). Concerns regarding the long-term test-retest reliability of the SCAT SAC, ImPACT, and CogState have been raised in the literature (Bailey et al., 2022; Broglio et al., 2018; Mayers & Redick, 2012). The Vienna Test System provides an alternative computerized neuropsychological testing battery, but the long-term test-retest reliability has yet to be established. The objectives of this study were to: (i) determine the long-term test-retest reliability of cognitive measures from the VTS; and (ii) explore cognitive changes on the VTS at the group and individual level across two and three time points. In alignment with studies that have investigated the test-retest reliability and cognitive stability of computerized cognitive testing batteries (Broglio et al., 2018; Bruce et al., 2014; Elbin et al., 2011; Schatz, 2010; Tsushima et al., 2016), we hypothesized the following: (i) the VTS would show moderate test-retest reliability; and (ii) cognitive performance on the VTS would remain relatively stable across seasons.

Methods

Participants

The sample was elite/international-level athletes from the Institut National du Sport du Québec (INS Québec), a non-profit organization that supports Canadian athletes competing at the national and international level. Athletes competed in one of five sports: artistic swimming, boxing, short-track speed skating, trampoline, or water polo. As part of INS Québec's concussion management program, all athletes in these sports were required to complete pre-season cognitive testing. Athletes were included in this study if they completed pre-season cognitive testing at two time points between 2018 and 2023. A sub-sample of athletes also had an additional third time point. Athletes were excluded from analyses if they sustained a concussion within six months of pre-season cognitive testing at any time point.

Measures

Cognitive performance was measured using tests from the VTS (Schuhfried CmbH, Moedling, Austria), a validated computerized neuropsychological test battery in sport psychology (Ong, 2015; Schuhfried, 2013). The cognitive battery of this study included six cognitive tests spanning executive functions (working memory, inhibition, cognitive flexibility, and planning) and attention (selective attention and sustained attention). For each cognitive test, variables for analyses were chosen to evaluate performance, specifically focusing on accuracy and/or reaction time. Cognitive tests and the variables of interest are described in detail below.

The *N-Back Non-Verbal* test measured working memory (Schellig et al., 2011). Participants had to identify whether the figure on the screen was the same as the figure from two positions earlier. The test was designed as a measure of visual working memory since the figures were abstract in nature and difficult to verbalize. The test took approximately nine minutes to

complete. The variables of interest were the number of correct responses and the mean reaction time for correct responses.

The *Response Inhibition* test measured inhibition (Kaiser et al., 2019), but also included a behavioural shift. Participants were required to press “5” for upward-facing triangles, which occurred frequently (i.e., standard stimuli), and “6” for downward-facing triangles, which occurred infrequently (i.e., shift stimuli). Participants also had to refrain from pressing any key when a circle appeared on the screen (i.e., no-go stimuli). The test took approximately seven minutes to complete. The variables of interest were the number of commission errors (i.e., pressing a key for no-go stimuli), the mean reaction time for correctly processed standard stimuli, and the mean reaction time for correctly processed shift stimuli.

The *Determination Test* measured cognitive flexibility (Schuhfried, 2019). Participants had to respond as quickly as possible using their hands (keyboard; Figure 1) and feet (pedals) to different types of visual and acoustic stimuli. Participants had to press the keyboard button that corresponded to the colour of the circle on the screen. They also had to press either the left or right foot pedal to match the location of a rectangular shape on the screen. Simultaneously, participants also heard auditory tones and had to press the black button on the keyboard for low tones and the grey button for high tones. The test measured the ability to react to multiple types of stimuli quickly and accurately, as well as reactive stress tolerance, described as the ability to react quickly and accurately under stressful conditions. The test utilized an adaptive stimulus presentation, whereby, the speed of stimulus presentation continuously adapted to the respondent’s pace and performance level. In other words, if a participant was working quickly and accurately, stimulus presentation became faster. The test took approximately six minutes to

complete. The variables of interest were the number of correct reactions and the median reaction time for correct reactions.

Figure 1

Response Panel for the Vienna Test System

The *Tower of London – Freiburg Version* measured planning ability (Kaller et al., 2019). Participants were shown a platform of three rods with beads of various colours inserted onto the rods in different configurations. Participants had to move the beads between the rods to convert the current configuration to a goal state model shown on the screen. Participants were instructed to complete the task in the fewest number of moves as possible. Therefore, participants had to mentally create solution possibilities and assess the consequences of their action before carrying it out. The test took approximately eight minutes to complete. The variable of interest was planning ability (i.e., the number of items solved in the minimum number of moves).

The *Movement Detection Test* measured selective attention (Schelling, 2016). The task involved detecting the movement of a small ball from the centre of the screen. The ball moved towards one of the four corners of the screen, which were denoted by a specific colour. Participants had to press the corresponding-coloured button on the keyboard (Figure 1) as quickly as possible. Therefore, along with measuring selective attention, the task also involved

decision speed and motor reaction speed. The test took approximately eight minutes to complete. The variable of interest was the median detection time (i.e., time between the start of the movement and the participant pressing the button).

The *Signal Detection* test measured sustained attention (Schuhfried, 2017). Dots were displayed over the entire screen. Pseudo-randomly, some of the dots would disappear and others would come into view. When four dots formed a square, participants had to press a button as quickly as possible. The test took approximately 15 minutes to complete. The variables of interest were the number of correct reactions and the median reaction time for detecting the critical stimulus (i.e., square formed by four dots).

Procedure

Cognitive testing was conducted in a quiet room by a sport neuropsychologist and took approximately one hour to complete, with breaks included. Cognitive testing was scheduled during the sport's pre-season evaluations. For winter sports (short-track speed skating), pre-season was between March and April. For summer sports (artistic swimming, boxing, trampoline, and water polo), pre-season was between September and October. The exact schedule of pre-season cognitive testing depended on whether it was an Olympic year and if testing occurred during the COVID-19 pandemic. Our secondary use of data was approved by the Human Participants Review Committee at the York University Office of Research Ethics.

Statistical Analyses

Long-term test-retest reliability of cognitive tests from the VTS was evaluated using intraclass correlation coefficients (ICCs). Two-way mixed effects models with absolute agreement were used to calculate ICCs for each cognitive variable (McGraw & Wong, 1996)

Based on ICCs, cognitive variables were interpreted as having poor ($ICC < 0.5$), moderate ($0.5 \leq ICC < 0.75$), good ($0.75 \leq ICC < 0.9$), or excellent ($ICC \geq 0.9$) reliability (Koo & Li, 2016).

Group-level changes in cognitive performance between the two pre-season cognitive testing sessions (i.e., Time 1 and Time 2) were evaluated using paired-samples *t*-tests or Wilcoxon signed-rank tests, when appropriate (Hollander et al., 2013). Wilcoxon signed-rank tests were used when the assumption of normality was violated, as determined by the Shapiro-Wilk test. Effect sizes of paired-sample *t*-tests were estimated using Cohen's *d* and categorized into small ($0.2 \leq d < 0.5$), moderate ($0.5 \leq d < 0.8$), and large ($d \geq 0.8$) effects, while effect sizes for Wilcoxon signed-rank tests were calculated with the *r*-estimate and classified into small ($0.1 \leq r < 0.3$), moderate ($0.3 \leq r < 0.5$), and large ($r \geq 0.5$) effects (Cohen, 1988). In sensitivity analyses, we repeated the paired-samples *t*-tests and Wilcoxon signed-rank tests after excluding athletes who sustained a concussion between Time 1 and Time 2.

Individual-level changes on cognitive variables between Time 1 and Time 2 were interpreted based on smallest worthwhile changes (SWCs). SWCs were calculated for each cognitive variable as 0.2 times the between-subject standard deviation at Time 1 (Buchheit, 2016; Hopkins et al., 2009) Individual-level changes that exceeded the threshold set by SWCs were considered meaningful. SWCs are commonly used in the sport literature and were opted to be used in this study in replacement of RCIs since four of the six cognitive tests from the VTS did not have a measure of short-term test-retest reliability, which was required for the calculation of the standard error of measurement in the RCI calculation (N. S. Jacobson & Truax, 1991). For the two cognitive tests with available test-retest reliability (*Determination Test* and *Movement Detection Test*), RCIs were computed along with SWCs.

Cognitive performance across the three time points (Time 1, Time 2, and Time 3) was compared using one-way repeated measures analyses of variance (ANOVAs) or Friedman's tests, when the assumption of normality was violated. The assumption of sphericity was assessed by Mauchly's test and if violated, the reported *p*-values were adjusted with the Greenhouse-Geisser correction. Effect sizes of ANOVA models were measured by generalized eta-squared (η^2) and classified into small ($0.01 \leq \eta^2 < 0.06$), medium ($0.06 \leq \eta^2 < 0.14$), and large ($\eta^2 > 0.14$) effects (Cohen, 1988). Effect size for Friedman's tests were calculated using Kendall's W test, which utilizes Cohen's interpretation guidelines (Tomczak & Tomczak, 2014). For significant ANOVA models, post-hoc pairwise comparisons with the Bonferroni Correction were conducted. For significant Friedman's tests, Wilcoxon signed-rank tests with Bonferroni Correction were used for post-hoc analyses. Individual-level changes on cognitive variables between the time points was interpreted based on SWCs. In sensitivity analyses, we repeated the ANOVA and Friedman's tests after excluding athletes who sustained a concussion between any of the three time points.

All analyses were conducted in R (version 4.3.1). For cognitive variables, outliers beyond 3 standard deviations of the mean were excluded. Reaction time was measured in milliseconds. Two-tailed alpha values of less than 0.5 were considered statistically significant.

Results

Test-Retest Reliability

The sample included 58 athletes across five sports (artistic swimming, boxing, short-track speed skating, trampoline, and water polo) who completed pre-season cognitive testing at two time points. The second pre-season cognitive testing session (Time 2) was 9-21 months following the first testing session (Time 1), depending on the sport's pre-season schedule (M = 15.13 months, SD = 3.47). The average age of athletes at Time 1 was 21.58 years (SD = 3.91,

range: 16.30-35.58). The sample was predominantly female (N_{female} = 42; % female = 72). Demographic characteristics of all participants stratified by sport are presented in Table 1.

Table 1

Baseline Demographic Characteristics for Study 1 (Two Time Points)

	All sports	Artistic swimming	Boxing	Short-track speed skating	Trampoline	Water Polo
N	58	14	8	22	3	11
Sex, *n* (%)						
Female	42 (72%)	14 (100%)	3 (38%)	12 (55%)	2 (67%)	11 (100%)
Male	16 (28%)	0 (0%)	5 (62%)	10 (45%)	1 (33%)	0 (0%)
Age, years						
Mean (SD)	21.58 (3.91)	20.32 (2.22)	24.51 (5.17)	19.36 (2.45)	20.23 (1.90)	25.83 (2.91)
Range	16.30-35.58	17.83-24.93	21.02-35.58	16.30-24.65	18.17-21.92	21.39-32.60

ICCs of cognitive variables of interest from the VTS ranged from 0.34 to 0.83 (Table 2). The test of cognitive flexibility, the *Determination Test*, had the best test-retest reliability of the six measures from the VTS. The median reaction time had good test-retest reliability (0.82), and the number of correct reactions had moderate reliability (0.67). ICCs were also classified as moderate on the *Signal Detection* test, with a slightly higher ICC on the measure of median reaction time (0.69) compared to the number of correct responses (0.56). Test-retest reliability of the *Response Inhibition Test* varied according to the cognitive variable. The number of commission errors had poor test-retest reliability (0.36), but the reaction time for correctly processed standard and shift stimuli had good (0.83) and moderate (0.72) reliabilities, respectively. Test-retest reliability was deemed poor for the *N-Back Non-Verbal test*, *Tower of London – Freiburg Version*, and the *Movement Detection* test (ICCs ranging from 0.34 to 0.46).

Table 2

Test-Retest Reliability of the Vienna Test System

Test Variable	*n*	Time 1 *M*	Time 1 *SD*	Time 2 *M*	Time 2 *SD*	ICC [95% CI]	Test Statistic	*p*-value
Executive functions								
N-Back Non-Verbal Test								
Number correct	57	9.21	2.73	9.91	2.54	0.43 [0.19, 0.62]	$F(56,56.7) = 2.53$	< .001***
Mean RT	56	838.24	178.69	783.29	140.36	0.37 [0.12, 0.57]	$F(55,51.9) = 2.26$	0.002**
Response Inhibition Test								
Number of commission errors	55	2.56	3.11	1.71	1.89	0.36 [0.11, 0.56]	$F(54,54.8) = 2.15$	0.003**
Mean RT (standard stimuli)	58	353.90	49.44	354.03	50.89	0.83 [0.73, 0.90]	$F(57,57) = 10.50$	< .001***
Mean RT (shift stimuli)	57	379.62	52.62	383.25	55.36	0.72 [0.57, 0.82]	$F(56, 57) = 6.19$	< .001***
Determination Test								
Number correct	57	266.56	28.96	284.52	28.83	0.67 [0.13, 0.85]	$F(56,5.68) = 8.38$	0.008**
Median RT	57	697.37	60.70	677.24	54.48	0.82 [0.54, 0.91]	$F(56,10.1) = 14.00$	< .001***
Tower of London – Freiburg Version								
Planning ability	58	6.48	2.60	7.00	2.05	0.34 [0.10, 0.55]	$F(57,58) = 2.07$	0.003**
Attention								
Movement Detection Test								
Median RT	58	520.84	42.60	540.11	50.91	0.46 [0.22, 0.64]	$F(57, 42.9) = 2.91$	< .001***
Signal Detection Test								
Number correct	57	71.33	5.78	72.76	6.25	0.56 [0.36, 0.72]	$F(56, 49.9) = 3.81$	< .001***
Median RT	58	817.10	119.03	801.03	104.89	0.69 [0.52, 0.80]	$F(57, 57.7) = 5.46$	< .001***

Note. Test-retest reliability over a period of 9-21 months was estimated using ICCs. CI = confidence interval; ICC = intraclass correlation coefficient; RT = reaction time (ms).
* $p < .05$. ** $p < .01$. *** $p < .001$

Cognitive Stability Across the Two Time Points

Group-level cognitive stability between Time 1 and Time 2, as calculated by paired-samples *t*-tests and Wilcoxon signed-rank tests, are presented in Table 3. Individual-level changes across cognitive variables as determined by SWCs can be found in Table 4.

The number of correct reactions on the measure of cognitive flexibility, the *Determination Test,* was significantly higher at Time 2 (M = 284.52, SD = 28.83) compared to Time 1 (M = 266.56, SD = 28.96), $t(56) = 7.08$, $p < .001$. The effect size was large (d = 0.94) and 81% of athletes showed a meaningful improvement at the individual level according to SWCs. From RCIs calculated with a test-retest value of 0.90 reported in Schuhfried (2019), 20 athletes (35%) showed reliable improvement in the number of correct reactions, 35 athletes (61%) showed trivial changes, and 2 athletes (4%) showed a reliable decline. Athletes also had a faster median reaction time on the *Determination Test* at Time 2 (Mdn = 675.00 ms, IQR = 77.50) compared to Time 1 (Mdn = 690.00 ms, IQR = 90.00), z = -4.40, $p < .001$, r = -0.66, suggesting a large effect. According to the SWC threshold of 12.14 ms, 53% of athletes were meaningfully faster at Time 2. According to RCIs, 9 athletes (16%) showed significantly faster reaction time at Time 2, while 48 athletes (84%) showed no reliable change in their reaction time.

Athletes had a significantly faster mean reaction time for correct responses on a test of working memory (*N-Back Non-Verbal* test) at Time 2 (M = 783.29 ms, SD = 140.36) compared to Time 1 (M = 838.24 ms, SD = 178.69), $t(55) = -2.46$, p = 0.02. The effect was deemed small (d = -0.33). Based on the SWC threshold of 35.74 ms, 54% of athletes had meaningfully faster reaction times on the *N-Back Non-Verbal test* at Time 2. The number of correct responses on the *N-Back Non-Verbal* test was not significantly different between Time 1 and Time 2 at the group

level ($p = 0.11$), however, 54% of athletes showed a meaningful improvement at the individual level.

Athletes had a significantly slower median reaction time on a measure of selective attention, the *Movement Detection* test, at Time 2 ($M = 540.11$ ms, $SD = 50.91$) compared to Time 1 ($M = 520.84$ ms, $SD = 42.60$), $t(57) = 3.09$, $p = 0.003$, $d = 0.41$, representing a small effect. Based on the SWC threshold of 8.52 ms, 60% of athletes were meaningfully slower on the task at Time 2, 14% showed trivial changes, and 26% showed meaningfully faster reaction times at Time 2. Shelling (2016) reported test-retest reliability of the *Movement Detection* test as 0.84, which was used to calculate RCIs across athletes. Based on these RCIs, 12 athletes (21%) had reliably slower reaction times at Time 2 compared to Time 1, 42 athletes (72%) had trivial changes, and 4 athletes (7%) had faster reaction times.

The number of correct responses on a test of sustained attention (*Signal Detection* test) was significantly higher at Time 2 ($M = 72.76$, $SD = 6.25$) compared to Time 1 ($M = 71.33$, $SD = 5.78$), $t(56) = 2.37$, $p = .02$. This was a small effect ($d = 0.31$). In terms of individual-level changes, 49% of athletes showed a meaningful improvement on the test at Time 2. The median reaction time for correct responses on the *Signal Detection* test was not significantly different between Time 1 and Time 2 at the group level ($p = .17$), yet 52% of athletes had meaningfully faster reaction times at Time 2 according to SWCs.

Cognitive variables on measures of inhibition (*Response Inhibition* test) and planning ability (*Tower of London – Freiburg Version*) were not significantly different between Time 1 and Time 2 (ps > .05).

Sensitivity analyses that excluded 12 athletes who sustained a concussion between Time 1 and Time 2 replicated the results from the whole sample (Table 5).

Table 3

Differences in Cognition Across the Two Time Points

Test Variable	*n*	Time 1 *M*	Time 1 *SD*	Time 2 *M*	Time 2 *SD*	Mean Difference [95% CI]	Test Statistic	*p*-value	Effect size
Executive functions									
N-Back Non-Verbal Test									
Number correct	57	9.21	2.73	9.91	2.54	0.58 [-0.14, 1.30]	$t(56) = 1.60$	0.11	$d = 0.21$
Mean RT	56	838.24	178.69	783.29	140.36	-57.62 [-104.64, -10.61]	$t(55) = -2.46$	0.02*	$d = -0.33$
Response Inhibition Test									
Number of commission errors	55	2.56	3.11	1.71	1.89	1.00 [-0.00004, 2.00][a]	$z = -1.67$	0.09	$r = -0.28$
Mean RT (standard stimuli)	58	353.90	49.44	354.03	50.89	0.14 [-7.64, 7.92]	$t(57) = 0.035$	0.97	$d = 0.01$
Mean RT (shift stimuli)	57	379.62	52.62	383.25	55.36	5.82 [-4.65, 16.30]	$t(56) = 1.11$	0.27	$d = 0.15$
Determination Test									
Number correct	57	266.56	28.96	284.52	28.83	17.75 [12.73, 22.78]	$t(56) = 7.08$	<.001***	$d = 0.94$
Median RT	57	697.37	60.70	677.24	54.48	30.00 [15.00, 35.00][a]	$z = -4.40$	<.001***	$r = -0.66$
Tower of London – Freiburg Version									
Planning ability	58	6.48	2.60	7.00	2.05	0.52 [-0.19, 1.22]	$t(57) = 1.47$	0.15	$d = 0.19$
Attention									
Movement Detection Test									
Median RT	58	520.84	42.60	540.11	50.91	19.27 [6.79, 31.75]	$t(57) = 3.09$	0.003**	$d = 0.41$
Signal Detection Test									
Number correct	57	71.33	5.78	72.76	6.25	1.68 [0.26, 3.11]	$t(56) = 2.37$	0.02*	$d = 0.31$
Median RT	58	817.10	119.03	801.03	104.89	-16.07 [-39.28, 7.15]	$t(57) = -1.39$	0.17	$d = -0.18$

Note. CI = confidence interval; RT = reaction time (ms).
[a] median difference [95% CI] for Wilcoxon Signed-Rank Tests
* $p < .05$. ** $p < .01$. *** $p < .001$

Table 4

Meaningful Changes in Cognition Across the Two Time Points

Test Variable	n	Mean Difference (SD)	SWC	*n* (%) athletes Δ < (-1) SWC (Negative Change)	Δ ≤ |SWC| (Trivial Change)	Δ > (+1) SWC (Positive Change)
Executive functions						
N-Back Non-Verbal Test						
Number correct	57	0.58 (2.73)	0.55	23 (40)	3 (5)	31 (54)
Mean RT	56	-57.62 (175.57)	35.74	30 (54)	9 (16)	17 (30)
Response Inhibition Test						
Number of commission errors	55	-0.62 (2.72)	0.62	21 (38)	20 (36)	14 (25)
Mean RT (standard stimuli)	58	0.14 (29.58)	9.89	23 (40)	14 (24)	21 (36)
Mean RT (shift stimuli)	57	5.82 (39.47)	10.52	15 (26)	16 (28)	26 (46)
Determination Test						
Number correct	57	17.75 (18.94)	5.79	6 (11)	5 (9)	46 (81)
Median RT	57	-20.53 (29.91)	12.14	30 (53)	19 (33)	8 (14)
Tower of London – Freiburg Version						
Planning ability	58	0.52 (2.68)	0.52	19 (33)	12 (21)	27 (47)
Attention						
Movement Detection Test						
Median RT	58	19.27 (47.46)	8.52	15 (26)	8 (14)	35 (60)
Signal Detection Test						
Number correct	57	1.68 (5.37)	1.16	15 (26)	14 (25)	28 (49)
Median RT	58	-16.07 (88.29)	23.81	30 (52)	11 (19)	17 (29)

Note. Mean differences represent the change from Time 2 to Time 1. Positive mean differences for accuracy measures represent a greater score at Time 2 (i.e., more correct or more errors). Negative mean differences for RT variables represent faster RT at Time 2. Each athlete's change (Δ) was compared to the threshold set by the SWC. If an athlete's change was below (-1) SWC, their score at Time 2 was smaller than Time 1 (i.e., less correct, less errors, or faster RT). If an athlete's change was above (+1) SWC, their score on Time 2 was larger than Time 1 (i.e., more correct, more errors, or slower RT). If an athlete's change falls within the absolute value of SWC, their change is deemed trivial. RT = reaction time (ms); SWC = smallest worthwhile change

Table 5

Sensitivity Analysis for the Differences in Cognition Across the Two Time Points

Test Variable	*n*	Time 1 *M*	Time 1 *SD*	Time 2 *M*	Time 2 *SD*	Mean difference [95% CI]	Test Statistic	*p*-value	Effect size
Executive functions									
N-Back Non-Verbal Test									
Number correct	45	9.28	2.86	9.82	2.52	0.38 [-0.48, 1.23]	$t(44) = 0.89$	0.38	$d = 0.13$
Mean RT	44	842.11	162.71	785.98	141.92	-59.70 [-113.84, -5.57]	$t(43) = -2.22$	0.03*	$d = -0.33$
Response Inhibition Test									
Number of commission errors	44	2.40	2.83	1.55	1.66	1.00 [-0.000002, 2.00][a]	$z = -1.48$	0.14	$r = -0.28$
Mean RT (standard stimuli)	46	692.44	56.25	676.30	55.31	-2.24 [-10.45, 5.97]	$t(45) = -0.55$	0.59	$d = -0.08$
Mean RT (shift stimuli)	45	381.98	52.46	386.29	54.61	7.04 [-5.65, 19.74]	$t(44) = 1.12$	0.27	$d = 0.17$
Determination Test									
Number correct	45	265.53	29.43	281.59	29.63	15.73 [9.86, 21.61]	$t(44) = 5.39$	<.001***	$d = 0.80$
Median RT	45	692.44	56.25	676.30	55.31	-16.67 [-25.38, -7.95]	$t(44) = -3.86$	<.001***	$r = -0.58$
Tower of London – Freiburg Version									
Planning ability	46	6.63	2.71	7.13	2.08	0.50 [-0.33, 1.33]	$t(45) = 1.21$	0.23	$d = 0.18$
Attention									
Movement Detection Test									
Median RT	46	520.20	39.75	537.63	49.02	17.43 [4.49, 30.38]	$t(45) = 2.71$	0.009**	$d = 0.40$
Signal Detection Test									
Number correct	45	71.82	6.03	73.33	6.31	1.84 [0.24, 3.45]	$t(44) = 2.31$	0.03*	$d = 0.34$
Median RT	46	813.26	115.85	797.48	103.54	-15.78 [-44.71, 13.15]	$t(45) = -1.10$	0.28	$d = -0.16$

Note. Analyses excluded 12 athletes who sustained a concussion between Time 1 and Time 2. CI = confidence interval; RT = reaction time (ms).
[a] median difference [95% CI] for Wilcoxon Signed-Rank Tests
* $p < .05$. ** $p < .01$. *** $p < .001$

Cognitive Stability Across the Three Time Points

A subset of athletes (n = 24) had an additional third time point (Time 3), 6-18 months following Time 2 (M = 10.63 months, SD = 3.46). Athletes were from four sports: artistic swimming, boxing, short-track speed skating, and trampoline. The average age of athletes at Time 1 was 20.20 years (SD = 2.92, range: 16.80-29.08). There was a relatively even proportion of male and female athletes in the sample (N_{female} = 14; % female = 58). Demographic characteristics of all participants stratified by sport are presented in Table 6.

Table 6

Baseline Demographic Characteristics for Study 1 (Three Time Points)

	All sports	Artistic swimming	Boxing	Short-track speed skating	Trampoline
n	24	2	4	16	2
Sex, *n* (%)					
Female	14 (58%)	2 (100%)	2 (50%)	9 (56%)	1 (50%)
Male	10 (42%)	0 (0%)	2 (50%)	7 (44%)	1 (50%)
Age, years					
Mean (*SD*)	20.20 (2.92)	18.32 (0.33)	23.91 (3.55)	19.53 (2.34)	20.05 (2.65)
Range	16.80-29.08	18.09-18.55	21.02-29.08	16.80-24.65	18.17-21.92

Repeated-measures ANOVAs and Friedman's tests evaluated whether cognitive performance was stable across time at the group level (Table 7), and when significant, pairwise comparisons were conducted (Table 8). Individual-level changes were investigated using SWCs between the three time points (Table 9).

The number of correct reactions on the *Determination Test* (cognitive flexibility) was significantly different across the three time points, $F(2,46) = 22.05$, $p < .001$, $\eta^2 = 0.10$, representing a medium effect. Post-hoc pairwise comparisons revealed significant differences between Time 1 and Time 2 ($p < .001$) and Time 1 and Time 3 ($p < .001$), whereby athletes had a higher number of correct reactions at Time 2 ($M = 288.17$; $SD = 28.18$) and Time 3 ($M = 292.21$; $SD = 30.44$) compared to Time 1 ($M = 269.83$; $SD = 30.34$). Notably, 88% of athletes showed a meaningful improvement on the *Determination Test* between Time 1 and Time 2. There was no significant difference at the group level between Time 2 and Time 3 ($p = 0.83$). Median reaction time on the *Determination Test* was also significantly different across the three time points, $F(2,46) = 18.69$, $p < .001$, $\eta^2 = 0.10$, representing a medium effect. Post-hoc pairwise comparisons revealed significant differences between Time 1 and Time 2 ($p < .001$) and Time 1 and Time 3 ($p < .001$), whereby athletes had faster reaction times at Time 2 ($M = 670.83$ ms; $SD = 59.26$) and Time 3 ($M = 666.25$ ms; $SD = 54.20$) compared to Time 1 ($M = 705.00$ ms; $SD = 57.71$). At the individual level, 67% of athletes showed faster median reaction times between Time 1 and Time 2. There was no significant difference at the group level between Time 2 and Time 3 ($p =1.0$).

The number of correct responses on the *N-Back Non-Verbal* test (working memory) was significantly different across the three time points, $\chi^2(2) = 9.26$, $p = .01$. The effect was small ($W = 0.19$). Post-hoc Wilcoxon signed-rank tests revealed a significant difference between Time 1 and Time 3 ($p = .01$), whereby athletes had a greater number of correct responses at Time 3 ($Mdn = 12.00$; IQR = 3.25) compared to Time 1 ($Mdn = 9.00$; IQR = 3.25). At the individual-level, 75% of athletes showed meaningful improvements from Time 1 to Time 3. There were significant differences at the group level between Time 1 and Time 2 ($p = 0.17$) and between

Time 2 and Time 3 (p = 0.56). Mean reaction time of correct responses on the *N-Back Non-Verbal* test was also significantly different across the three time points, $F(2,46) = 4.22$, $p = .02$, $\eta^2 = 0.07$, representing a medium effect. Post-hoc pairwise comparisons revealed a significant difference between Time 1 and Time 2 (p = 0.02), whereby athletes had a faster mean reaction time at Time 2 (M = 746.96 ms; SD = 130.32) compared to Time 1 (M = 851.25 ms; SD = 182.52). This was also supported when looking at individual-level changes among athletes, whereby 63% showed faster reaction times between Time 1 and Time 2. There were no significant differences at the group level between Time 1 and Time 3 (p = 0.65) or Time 2 and Time 3 (p = 0.39).

Planning ability on the *Tower of London – Freiburg Version* was significantly different across the three time points, $F(2,46) = 9.40$, $p < .001$. The effect was deemed large ($\eta^2 = 0.15$). Post-hoc pairwise comparisons revealed significant differences between Time 1 and Time 2 (p = .01) and between Time 1 and Time 3 (p = .006), whereby athletes solved a greater number of items in the minimum number of moves at Time 2 (M = 7.29; SD = 1.94) and Time 3 (M = 7.50; SD = 1.67) compared to Time 1 (M = 5.62; SD = 2.46). The trend for improvement over time was also apparent at the individual level, whereby 63% of athletes had better planning ability at Time 2 compared to Time 1. There was no significant difference between Time 2 and Time 3 (p = 1.0).

Performance and reaction time on measures of inhibition (*Response Inhibition* test), selective attention (*Movement Detection Test*), and sustained attention (*Signal Detection* test) were not significantly different across the three time points (ps > .05).

Table 7

Differences in Cognition Across the Three Time Points

Test Variables	*n*	Time 1		Time 2		Time 3		Test Statistic	*p*-value	Effect size
		M	*SD*	*M*	*SD*	*M*	*SD*			
Executive functions										
N-Back Non-Verbal Test										
Number correct	24	9.21	2.59	10.25	3.08	10.88	2.69	χ^2 (2) = 9.26	0.01*	*W* = 0.19
Mean RT	24	851.25	182.52	746.96	130.32	807.00	149.42	*F*(2,46) = 4.22	0.02*	η^2 = 0.07
Response Inhibition Test										
Number of commission errors	22	2.32	3.27	1.59	1.50	1.27	1.88	χ^2 (2) = 3.46	0.18	*W* = 0.16
Mean RT (standard stimuli)	24	350.42	51.88	361.58	56.10	352.08	60.60	*F*(2,46) = 1.60	0.21	η^2 = 0.008
Mean RT (shift stimuli)	24	381.46	60.73	387.25	72.61	391.46	71.69	*F*(2,46) = 0.69	0.51	η^2 = 0.004
Determination Test										
Number correct	24	269.83	30.34	288.17	28.18	292.21	30.44	*F*(2,46) = 22.05	<.001***	η^2 = 0.10
Median RT	24	705.00	57.71	670.83	59.26	666.25	54.20	*F*(2,46) = 18.69	<.001***	η^2 = 0.09
Tower of London – Freiburg Version										
Planning ability	24	5.62	2.46	7.29	1.94	7.50	1.67	*F*(2,46) = 9.40	<.001***	η^2 = 0.15
Attention										
Movement Detection Test										
Median RT	24	527.62	40.11	538.87	58.34	547.04	52.03	*F*(2,46) = 1.87	0.17	η^2 = 0.03
Signal Detection Test										
Number correct	24	70.25	6.20	71.67	6.68	72.04	7.67	*F*(2,46) = 1.38	0.26	η^2 = 0.01
Median RT	24	825.25	138.24	806.58	103.34	823.50	161.39	*F*(2,46) = 0.43	0.65	η^2 = 0.004

Note. RT = reaction time (ms).
* $p < .05$. ** $p < .01$. *** $p < .001$

Table 8

Pairwise Comparisons Across the Three Time Points

Test Variables	Comparison	Mean Difference [95% CI]	Test Statistic	*p*-adj
N-Back Non-Verbal Test				
Number correct	Time 1 vs. Time 2	-1.22 [-2.50, 0.00002][a]	$z = -1.90$	0.17
	Time 1 vs. Time 3	-2.00[-3.00, -1.00)][a]	$z = -2.88$	0.01*
	Time 2 vs. Time 3	-1.00[-2.00, 0.50][a]	$z = -1.32$	0.56
Mean RT	Time 1 vs. Time 2	104.29 [32.02, 176.56]	$t(23) = 2.99$	0.02*
	Time 1 vs. Time 3	45.25 [-27.62, 116.12]	$t(23) = 1.27$	0.65
	Time 2 vs. Time 3	-60.04 [-139.25, 19.17]	$t(23) = -1.57$	0.39
Determination Test				
Number correct	Time 1 vs. Time 2	-18.33 [-25.56, -11.10]	$t(23) = -5.24$	<.001***
	Time 1 vs. Time 3	-22.38 [-29.90, -14.85]	$t(23) = -6.15$	<.001***
	Time 2 vs. Time 3	-4.04 [-11.57, 3.48]	$t(23) = -1.11$	0.83
Median RT	Time 1 vs. Time 2	34.17 [22.29, 46.04]	$t(23) = 5.95$	<.001***
	Time 1 vs. Time 3	38.75 [22.36, 55.14]	$t(23) = 4.89$	<.001***
	Time 2 vs. Time 3	4.58 [-9.78, 18.94]	$t(23) = 0.66$	1.0
Tower of London – Freiburg Version				
Planning ability	Time 1 vs. Time 2	-1.67 [-2.73, -0.61]	$t(23) = -3.25$	0.01*
	Time 1 vs. Time 3	-1.88 [-2.98, -0.77]	$t(23) = -3.50$	0.006**
	Time 2 vs. Time 3	-0.21 [-0.93, 0.52]	$t(23) = -0.59$	1.0

Note. Positive mean differences for accuracy measures represent a greater score at the second comparison group (i.e., more correct or more errors). Negative mean differences for RT variables represent faster RT at the second comparison group. CI = confidence interval; P-adj = Bonferroni-corrected *p*-values; RT = reaction time (ms).
[a] median difference [95% CI] for Wilcoxon Signed-Rank Tests
* $p < .05$. ** $p < .01$. *** $p < .001$

Table 9

Meaningful Changes in Cognition Across the Three Time Points

					n (%) athletes		
Test Variables	Time Comparison	*n*	Mean Difference (SD)	SWC	Δ < (-1) SWC (Negative Change)	Δ ≤ |SWC| (Trivial Change)	Δ > (+1) SWC (Positive Change)
N-Back Non-Verbal Test							
Number correct	Time 1 vs. Time 2	24	1.04 (2.63)	0.52	8 (33%)	1 (4%)	15 (63%)
	Time 1 vs. Time 3	24	1.67 (2.14)	0.52	3 (13%)	3 (13%)	18 (75%)
	Time 2 vs. Time 3	24	0.62 (2.18)	0.62	9 (38%)	3 (13%)	12 (50%)
Mean RT	Time 1 vs. Time 2	24	-104.29 (171.15)	36.50	15 (63%)	5 (21%)	4 (17%)
	Time 1 vs. Time 3	24	-44.25 (170.25)	36.50	13 (54%)	2 (8%)	9 (38%)
	Time 2 vs. Time 3	24	60.04 (187.59)	26.06	9 (38%)	1 (4%)	14 (58%)
Response Inhibition Test							
Number of errors	Time 1 vs. Time 2	23	-0.78 (2.47)	0.65	7 (30%)	10 (43%)	6 (26%)
	Time 1 vs. Time 3	22	-1.05 (3.17)	0.65	11 (50%)	7 (32%)	4 (18%)
	Time 2 vs. Time 3	23	-0.39 (1.85)	0.29	12 (52%)	5 (22%)	6 (6%)
Mean RT (standard)	Time 1 vs. Time 2	24	11.17 (27.63)	10.38	4 (17%)	8 (33%)	12 (50%)
	Time 1 vs. Time 3	24	1.67 (35.78)	10.38	8 (33%)	7 (29%)	9 (38%)
	Time 2 vs. Time 3	24	-9.50 (34.97)	11.22	11 (46%)	9 (38%)	4 (17%)
Mean RT (shift)	Time 1 vs. Time 2	24	5.79 (44.46)	12.15	6 (25%)	8 (33%)	10 (42%)
	Time 1 vs. Time 3	24	10.00 (44.66)	12.15	8 (33%)	7 (29%)	9 (38%)
	Time 2 vs. Time 3	24	4.21 (36.38)	14.52	6 (25%)	12 (50%)	6 (25%)
Determination Test							
Number correct	Time 1 vs. Time 2	24	18.33 (17.13)	6.07	1 (4%)	2 (8%)	21 (88%)
	Time 1 vs. Time 3	24	22.38 (17.83)	6.07	1 (4%)	5 (21%)	18 (75%)
	Time 2 vs. Time 3	24	4.04 (17.82)	5.64	9 (38%)	4 (17%)	11 (46%)

Median RT	Time 1 vs. Time 2	24	-34.17 (28.12)	11.54	16 (67%)	8 (33%)	0 (0%)
	Time 1 vs. Time 3	24	-38.75 (38.82)	11.54	19 (79%)	3 (13%)	2 (8%)
	Time 2 vs. Time 3	24	-4.58 (34.01)	11.85	9 (38%)	9 (38%)	6 (25%)
Tower of London – Freiburg Version							
Planning ability	Time 1 vs. Time 2	24	1.67 (2.51)	0.49	5 (21%)	4 (17%)	15 (63%)
	Time 1 vs. Time 3	24	1.88 (2.63)	0.49	3 (13%)	7 (29%)	14 (58%)
	Time 2 vs. Time 3	24	0.21 (1.72)	0.39	7 (29%)	7 (29%)	10 (42%)
Movement Detection Test							
Median RT	Time 1 vs. Time 2	24	11.25 (53.75)	8.02	11 (46%)	0 (0%)	13 (54%)
	Time 1 vs. Time 3	24	19.42 (36.31)	8.02	4 (17%)	7 (29%)	13 (54%)
	Time 2 vs. Time 3	24	8.17 (55.64)	11.67	6 (25%)	8 (33%)	10 (42%)
Signal Detection Test							
Number correct	Time 1 vs. Time 2	24	1.42 (6.16)	1.24	8 (33%)	5 (21%)	11 (46%)
	Time 1 vs. Time 3	24	1.79 (4.90)	1.24	5 (21%)	6 (25%)	13 (54%)
	Time 2 vs. Time 3	24	0.38 (5.61)	1.34	9 (38%)	6 (25%)	9 (38%)
Median RT	Time 1 vs. Time 2	24	-18.67 (82.60)	27.65	11 (46%)	6 (25%)	7 (29%)
	Time 1 vs. Time 3	24	-1.75 (121.82)	27.65	11 (46%)	6 (25%)	7 (29%)
	Time 2 vs. Time 3	24	16.92 (116.96)	20.67	9 (38%)	7 (29%)	8 (33%)

Note. Positive mean differences for accuracy measures represent a greater score for the second comparison group (i.e., more correct or more errors). Negative mean differences for RT variables represent faster RT for the second comparison group. Each athlete's change (Δ) was compared to the threshold set by the SWC. If an athlete's change was below (-1) SWC, their score at Time 2 was smaller than Time 1 (i.e., less correct, less errors, or faster RT). If an athlete's change was above (+1) SWC, their score on Time 2 was larger than Time 1 (i.e., more correct, more errors, or slower RT). If an athlete's change falls within the absolute value of SWC, their change is deemed trivial. RT = reaction time (ms); SWC = smallest worthwhile change

Sensitivity analyses that excluded 8 athletes who sustained any concussion between the three time points replicated the full sample results from repeated-measures ANOVAs and Friedman's tests (Table 10), as well as post-hoc analyses (Table 11), with the exception of cognitive variables from the *N-Back Non-Verbal* test. The number of correct responses on the *N-Back Non-Verbal* test was no longer significantly different across the three time points (p = .15). Likewise, the mean reaction time of correct responses on the *N-Back Non-Verbal* test was not statistically different across the three time points (p = .06). Cognitive performance on the *Determination Test* and *Tower of London – Freiburg Version* remained significant across the three time points. Pairwise comparisons also showed the same findings, whereby there were significant improvements between Time 1 and Time 2, and between Time 1 and Time 3 (ps <.05), but not between Time 2 and Time 3 (ps > .05).

Table 10

Sensitivity Analysis for the Differences in Cognition Across the Three Time Points

		Time 1		Time 2		Time 3				
Test Variables	*n*	*M*	*SD*	*M*	*SD*	*M*	*SD*	Test Statistic	*p*-value	Effect size
Executive functions										
N-Back Non-Verbal Test										
Number correct	16	9.38	2.75	10.31	3.07	10.81	2.74	$\chi^2(2) = 3.76$	0.15	$W = 0.24$
Mean RT	16	850.31	159.03	744.81	134.72	819.94	163.50	$F(2,30) = 3.01$	0.06	$\eta^2 = 0.08$
Response Inhibition Test										
Number of commission errors	15	2.20	2.14	1.56	1.36	1.31	2.06	$\chi^2(2) = 2.78$	0.25	$W = 0.19$
Mean RT (standard stimuli)	16	342.81	43.41	348.50	47.04	346.19	54.47	$F(2,30) = 0.21$	0.81	$\eta^2 = 0.002$
Mean RT (shift stimuli)	16	377.81	64.62	386.13	78.92	391.38	73.50	$F(2,30) = 0.72$	0.50	$\eta^2 = 0.006$
Determination Test										
Number correct	16	266.38	30.68	284.63	29.15	289.56	32.36	$F(2,30) = 13.25$	<.001***	$\eta^2 = 0.10$
Median RT	16	696.88	53.01	664.38	63.56	666.25	58.98	$F(2,30) = 10.78$	<.001***	$\eta^2 = 0.06$
Tower of London – Freiburg Version										
Planning ability	16	5.69	2.60	7.56	1.79	7.50	1.63	$F(2,30) = 6.11$	.006**	$\eta^2 = 0.16$
Attention										
Movement Detection Test Median RT	16	525.69	33.24	523.56	59.86	544.63	48.75	$F(2,30) = 2.52$	0.10	0.04
Signal Detection Test										
Number correct	16	70.81	6.65	72.81	7.15	72.75	7.53	$\chi^2(2) = 2.23$	0.33	$W = 0.14$
Median RT	16	829.50	137.98	802.38	93.38	823.00	163.10	$F(2,30) = 0.48$	0.63	$\eta^2 = 0.008$

Note. Analyses excluded 8 athletes who sustained a concussion between any of the three time points. RT = reaction time (ms).
* $p < .05$. ** $p < .01$. *** $p < .001$

Table 11

Sensitivity Analysis for the Pairwise Comparisons Across the Three Time Points

Test Variables	Comparison	Mean Difference [95% CI]	Test Statistic	*p*-adj
Executive functions				
Determination Test				
Number correct	Time 1 vs. Time 2	-18.25 [-28.66, -7.84]	$t(15) = -3.74$	.006**
	Time 1 vs. Time 3	-23.19 [-32.30, -14.08]	$t(15) = -5.43$	<.001***
	Time 2 vs. Time 3	-4.94 [-15.69, 5.82]	$t(15) = -0.98$	1.0
Median RT	Time 1 vs. Time 2	32.50 [17.12, 47.88]	$t(15) = 4.50$	.001***
	Time 1 vs. Time 3	30.62 [13.17, 48.08]	$t(15) = 3.74$	.006**
	Time 2 vs. Time 3	-1.88 [-19.19, 15.44]	$t(15) = -0.23$	1.0
Tower of London – Freiburg Version				
Planning ability	Time 1 vs. Time 2	-1.88 [-3.26, -0.49]	$t(15) = -2.88$	0.03*
	Time 1 vs. Time 3	-1.81 [-3.25, -0.38]	$t(15) = -2.70$	0.05*
	Time 2 vs. Time 3	0.06 [-0.98, 1.10]	$t(15) = 0.13$	1.0

Note. Analyses excluded 8 athletes who sustained a concussion between any of the three time points. Positive mean differences for accuracy measures represent a greater score at the second comparison group (i.e., more correct). Negative mean differences for RT variables represent faster RT at the second comparison group. CI = confidence interval; P-adj = Bonferroni-corrected *p*-values; RT = reaction time (ms).

* $p < .05$. ** $p < .01$. *** $p < .001$

Discussion

Study 1 established the use of the VTS in our sample of elite athletes. Test-retest reliability of cognitive measures from the VTS was evaluated in a sample of 58 athletes who completed pre-season cognitive testing at two time points (9-21 months apart). ICCs ranged from 0.34 to 0.83 across cognitive measures, indicating poor-to-good test-retest reliability of the VTS. Group- and individual-level changes in cognitive performance were also investigated in this sample, as well as in a sub-sample of 24 athletes with an additional third testing session. Our findings provide strong evidence to suggest that cognitive flexibility significantly improves over time. We also found that working memory, selective attention, and sustained attention changed across the two and/or three time points.

Test-Retest Reliability

Our test-retest reliability of the VTS (0.34 to 0.83) was similar to or better than the long-term test-retest reliability of the SAC from the SCAT (0.34 to 0.52), ImPACT (0.21 to 0.76), and CogState (0.49 to 0.59; Bailey et al., 2022; Broglio et al., 2018; Bruce et al., 2014; Schatz, 2010; Tsushima et al., 2016). When comparing ICCs across cognitive tests on the VTS, the test-retest reliability of the *Determination Test*, a measure of cognitive flexibility, had the highest reliability in our sample of athletes (0.67; 0.82). The test-retest reliability on a measure of inhibition (*Response Inhibition* test) varied according to the cognitive variable, whereby reaction time measures had moderate-to-good test-retest reliability (0.72; 0.83), but the number of commission errors had poor reliability (0.36). In terms of other measures of executive functions, we found poor test-retest reliability for measures of planning ability (*Tower of London – Freiberg Version* ICC: 0.34) and working memory (*N-Back Non-Verbal* test ICCs: 0.37, 0.43). While ICCs cannot be directly compared between tests, reliability of the *N-Back Non-Verbal* test was slightly lower

than the working memory composite from CogState (0.59; Broglio et al., 2018). Across measures of attention on the VTS, the *Signal Detection* test (sustained attention) had moderate test-retest reliability (0.56; 0.69), and the *Movement Detection Test* (selective attention) had poor test-retest reliability (0.46). These ICCs are similar to the ICC reported for the attention composite score of CogState (0.56; Broglio et al., 2018).

Cognitive Stability

Group- and individual-level changes in cognitive performance on the VTS showed some variation across time. Cognitive stability of tests of executive functions (cognitive flexibility, working memory, planning ability, and inhibition) and attention (selective and sustained) are outlined below and interpreted in the context of test-retest results from Study 1.

Cognitive flexibility significantly improved between Time 1 and Time 2. The mean number of correct reactions on the *Determination Test* showed a large improvement across the two time points (d = 0.94), with 81% of athletes showing meaningful improvements at Time 2 compared to Time 1 according to SWCs. Since the reliability of the *Determination Test* was available, RCIs were also calculated. We found that 35% of athletes showed clinically significant improvements on the *Determination Test*. Athletes also had significantly faster reaction times on this task at Time 2 compared to Time 1, with 53% showing meaningful improvements according to SWCs (16% based on RCIs). In a sub-sample of athletes with a third time point, improvements in the number of correct reactions and reaction time remained significant. In pairwise comparisons, significant improvements occurred between Time 1 and Time 2, and between Time 1 and Time 3, but not between Time 2 and Time 3. In sensitivity analyses that excluded athletes who sustained a concussion between time points, all results remained significant. Given that we found moderate-to-good long-term test-retest reliability on the

Determination Test, we can be more confident that these changes in cognitive flexibility are meaningful and reliable rather than attributable to test measurement error. One reason athletes may be improving across time is that cognitive flexibility continues to develop with age (Cepeda et al., 2001; Dajani & Uddin, 2015). Another reason for improvements could be due to training effects from our sample's participation at INS Québec. For instance, among healthy adults, a 10-week intervention study of physical activity found significant improvements on computerized measures of cognitive flexibility (Masley et al., 2009). Other studies have detected superior cognitive performance on tasks of cognitive flexibility among elite athletes compared to low-performance athletes (Huijgen et al., 2015; Vestberg et al., 2012). Therefore, as athletes are training intensely over the study period, it could be that their cognition is approving along with their age, cerebrovascular fitness, or sport expertise.

When comparing cognitive performance on a test of working memory (*N-Back Non-Verbal* test) in the full sample of athletes with two time points, reaction time for correct responses was significantly faster at Time 2 compared to Time 1, but the effect was small (d = -0.31). While the number of correct responses was not significantly different between Time 1 and Time 2, 54% of athletes showed meaningful improvements on the *N-Back Non-Verbal* test according to SWCs. When exploring cognitive stability in the sub-sample of athletes with three time points, both reaction time and the number of correct responses significantly improved across time. That said, when athletes who sustained a concussion between the three time points were excluded in sensitivity analyses, these findings were no longer significant. Taken together, there is weak evidence to suggest that working memory improves over time. However, it is likely that the number of correct items on the *N-Back Non-Verbal* test is subject to ceiling effects where athletes are performing at or near the maximum score at baseline, thus limiting the opportunity

for improvements to be identified over time (Wang et al., 2008). Small improvements on the test also may be due to measurement error since the test-retest reliability for the *N-Back Non-Verbal* test was deemed poor (0.37-0.43).

Planning ability on the *Tower of London – Freiburg Version* was not significantly different between Time 1 and Time 2 in the full sample of athletes with pre-season cognitive testing at two time points. However, in the sub-sample of athletes with a third time point, planning ability significantly improved across the three time points and remained significant in sensitivity analyses. This improvement was considered a large effect ($\eta^2 = 0.15$). Pairwise comparisons showed that there was a significant improvement in planning ability between Time 1 and Time 2, and between Time 1 and 3, but not between Time 2 and Time 3. Given that we characterized the test-retest reliability of the *Tower of London – Freiburg Version* as poor and that there was no significant difference between Time 1 and Time 2 in the full sample, inconsistencies in the effect may be attributable to measurement error rather than a true improvement in planning ability over time. For instance, studies have found that planning ability on Tower of London tasks is subject to ceiling and practice effects, whereby participants perform better when they have been exposed to the test before (Lemay et al., 2004).

There were no significant changes on the *Response Inhibition* test across the two or three time points, suggesting that inhibition was stable across time. Considering that the test-retest reliability was in the moderate-to-good range for reaction time measures (0.72; 0.83), we can be confident that reaction time on inhibition is stable across time. However, even though there were no significant group-level change in the number of commission errors across time, the test-retest reliability was deemed poor (0.36), therefore, there may still be differences across time. This variation was evident when investigating individual-level changes based on SWCs. In the full

sample of athletes with two time points, 38% of athletes had less commission errors at Time 2 compared to Time 1, 25% had more commission errors, and 36% showed trivial changes.

Athletes had significantly slower median reaction times on a test of selective attention (*Movement Detection* test) at Time 2 compared to Time 1. While the effect size was deemed to be small (d = 0.41), 60% of athletes showed meaningfully slower reaction time at Time 2 based on SWCs (21% according to RCIs). This test required athletes to respond as quickly as possible when a circle at the centre of the screen moved towards one of four coloured corners. Therefore, slower reaction time would indicate poorer performance over time, which was unexpected based on literature on practice effects that suggests that improvements in cognition occur with increased exposure (Bartels et al., 2010; Calamia et al., 2012). Although significant findings were found between Time 1 and Time 2, a repeated measures ANOVA did not find a significant difference in the sub-sample of athletes with three time points. Given that we classified the long-term test-retest reliability of the *Movement Detection Test* as poor (0.46) and that the effect became non-significant when investigating change across the three time points, findings of slower reaction times between the two time points should be interpreted with caution.

There was a small group-level improvement in sustained attention, as measured by the *Signal Detection* test, at Time 2 compared to Time 1 (d = 0.31). At the individual level, 49% of athletes showed a meaningful improvement in the number of correct responses based on SWCs. However, a repeated measures ANOVA did not find any significant difference in the number of correct responses across the three time points. Moreover, the median reaction time for correct responses on the *Signal Detection* test was not significantly different across the two or three time points. Although the test-retest reliability of the *Signal Detection* test showed moderate

reliability, the small improvement in accuracy between Time 1 and Time 2 was not apparent across the three time points. Therefore, these findings should be interpreted with caution.

Taken together, findings demonstrate that cognitive performance may not be stable across pre-season cognitive testing sessions. With the exception of the *Response Inhibition* test, all other cognitive measures from the VTS changed across the two time points and/or the three time points. Athletes showed improvements in performance on measures of cognitive flexibility (*Determination Test)*, sustained attention (*Signal Detection* test), and planning ability (*Tower of London – Freiburg Version*) across time. Reaction time also became faster on tests of cognitive flexibility (*Determination Test*) and working memory (*N-Back Non-Verbal* test) across the two and three time points. In contrast, reaction time was slower on a test of selective attention (*Movement Detection Test*) at Time 2 compared to Time 1, although this was not significant across the three time points. In general, improvements on cognitive measures could be attributed to actual improvements in cognitive performance due to factors such as age and training effects. However, cognitive changes may also occur because of random fluctuations in cognitive performance due to test measurement error, such as ceiling and practice effects. Determining the long-term test-retest reliability of the cognitive measures of the VTS helped in interpreting the meaning behind changes in cognition across time for the specific cognitive measures.

Notably, when investigating the stability of cognitive measures across the three time points, pairwise comparisons found differences between Time 1 and Time 2 and/or between Time 1 and Time 3. No pairwise comparison found a significant difference between Time 2 and Time 3. It could be that training and practice effects eventually reach a plateau, whereby cognition does not continue to improve with time. One reason for this could be ceiling effects due to either

the design of the cognitive measure (i.e., maximum number of correct items) or because of biological capacity (i.e., fastest possible reaction time; Wang et al., 2008)

Study 1 aimed to determine the test-retest reliability and cognitive stability of the VTS. Findings from Study 1 will help inform the results from Study 2, which investigated the utility of the VTS as a measure of cognition for exploring the associations between cognition, concussion, and LEMSK injury.

Chapter 3.

Study 2

No study to date has utilized the VTS to explore the association between pre-season cognitive performance and the risk of subsequent LEMSK injury and concussion. The majority of research that has explored these associations have used the SCAT SAC, ImPACT, CogState, or other computerized measures. Given that Study 1 established the use of the VTS as an alternative neuropsychological test battery among elite athletes, Study 2 aimed to utilize the VTS to explore the associations between cognition, concussion, and LEMSK injury.

Studies have found that worse pre-season cognitive performance is associated with an increased risk of sustaining an LEMSK injury (Avedesian, Forbes, et al., 2022; Wilke & Groneberg, 2022). Based on this literature, authors have hypothesized that cognition would also predict the risk of concussion. However, studies have yet to find an association between pre-season cognitive performance and subsequent concussions (Caccese et al., 2020; Lopez-Flores et al., 2022; Putukian et al., 2021). It could be the case that the measures used in the literature have not been sensitive enough to detect subtle disparities in pre-season cognitive performance among elite athletes. Given other evidence that concussion history predicts subsequent LEMSK injury and concussions (Abrahams et al., 2014; Howell, Lynall, et al., 2018; McPherson et al., 2019; Ramirez et al., 2022; Reneker et al., 2019), this study also addresses the recognized need for research exploring the underlying mechanisms of this relationship. Studies posit that concussion history is associated with persistent effects that extend beyond clinical recovery (Baillargeon et al., 2012; Chmielewski et al., 2021; Gosselin et al., 2012; Howell, Lynall, et al., 2018; Ozen et al., 2013). It could be the case that concussion history is associated with lingering effects in cognition that exist after an athlete returns to sport (Howell, Osternig, Van Donkelaar, et al.,

2013; Lempke et al., 2020; Martini & Broglio, 2018; McGowan et al., 2019; Taylor et al., 2018; Thoma et al., 2015), which may increase their risk of subsequent LEMSK injuries and concussions.

Therefore, the objective of this study was to investigate the roles of concussion history and cognition as risk factors for subsequent LEMSK injury and concussion. The following associations were examined in regression analyses: (i) concussion history and cognition; (ii) concussion history and subsequent LEMSK injury; (iii) cognition and subsequent LEMSK injury; (iv) concussion history and subsequent concussion; and (v) cognition and subsequent concussion. In alignment with the literature, we hypothesized that (i) concussion history would predict cognition; (ii) concussion history would predict subsequent LEMSK injury; (iii) cognition would predict subsequent LEMSK injury; (iv) concussion history would predict subsequent concussion; and (v) cognition would predict subsequent concussion. Despite null findings in the literature on the association between cognition and subsequent concussion (Caccese et al., 2020; Lopez-Flores et al., 2022; Putukian et al., 2021), the relationship has not yet been investigated using the VTS, which may be more sensitive in detecting cognitive effects. The purpose of the study was also to investigate whether cognition mediated the relationship between (vi) concussion history and subsequent LEMSK injury; or (vii) concussion history and subsequent concussion. No study to date has investigated the potential mediating role of cognition in these associations, but based on findings on potential lingering effects of cognition following a concussion (Howell, Osternig, Van Donkelaar, et al., 2013; Lempke et al., 2020; McGowan et al., 2019), we hypothesized that cognition would mediate the relationship between (vi) concussion history and subsequent LEMSK injury; and (vii) concussion history and subsequent concussion.

Methods

Participants

The sample was elite/international-level athletes from INS Québec who competed in one of the following six sports: artistic swimming, boxing, diving, short-track speed skating, trampoline, or water polo. As part of INS Québec's concussion management program and post-injury protocols, all athletes in these sports were required to complete pre-season cognitive testing and to report all concussions and injuries to sport medicine personnel. Athletes were included in the study if they completed pre-season cognitive testing at INS Québec between 2018 and 2023 and had one year of prospective injury data following pre-season cognitive testing.

Measures

Cognition. The study used the same six cognitive tests from the VTS as outlined in Study 1: *N-Back Non-Verbal* test (a measure of working memory); *Response Inhibition* test (inhibition); *Determination Test* (cognitive flexibility); *Tower of London – Freiburg Version* (planning ability); *Movement Detection Test* (selective attention); and the *Signal Detection* test (sustained attention).

Concussions. The study used the definition of a sport-related concussion provided by the consensus statement on concussion in sport (Patricios et al., 2023). *Concussion history* was a dichotomous variable categorized by whether the athlete sustained at least one concussion prior to pre-season cognitive testing. *History of multiple concussion* was also a dichotomous variable which classified athletes according to whether they sustained two or more concussions prior to pre-season cognitive testing. *Subsequent concussion* was classified according to whether athletes sustained a concussion in the year following pre-season cognitive testing.

Musculoskeletal Injuries. Injuries were defined based on the International Olympic Committee's consensus statement on recording and reporting injury and illnesses in sport (Bahr et al., 2020). To classify injuries, the consensus statement by the Sports Medicine Diagnostic Coding System (SMDCS) and the Orchard Sports Injury and Illness Classification Systems (OSIICS) guidelines were used (Orchard et al., 2020). For each injury, body part, tissue type, and pathology type were documented. MSK injuries were classified as any injury to the bones, muscles, cartilage, tendons, ligaments, joints, or other connective tissues. MSK injuries did not include damage to the nervous system, superficial tissues/skin, vessels, or internal organs. Analyses only included MSK injuries to the lower extremities (i.e., LEMSK injuries), which included MSK injuries to the hip/groin, thigh, knee, lower leg, ankle, or foot. Only new injuries or injury recurrences (i.e., same injury to the same body part after a full recovery) were included in analyses. Injury exacerbations (i.e., same injury to the same body part when not fully recovered) were excluded. *Subsequent LEMSK injury* was classified as whether athletes sustained at least one LEMSK injury in the year following pre-season cognitive testing.

Procedure

Cognitive testing was conducted in a quiet room by a sport neuropsychologist and took approximately one hour to complete, with breaks included. Cognitive testing was scheduled during the sport's pre-season. For winter sports (short-track speed skating), pre-season was between March and April. For summer sports (artistic swimming, boxing, diving, trampoline, and water polo), pre-season was between September and October. The exact schedule of pre-season cognitive testing depended on whether it was an Olympic year and if testing occurred during the COVID-19 pandemic.

All concussions and injuries that occurred between 2018 and 2023 were documented prospectively by sports medicine personnel using standardized criteria via an injury surveillance program. Concussion history prior to 2018 was documented via self-report in a medical history interview with sports medicine personnel. Our secondary use of data was approved by the Human Participants Review Committee at the York University Office of Research Ethics.

Statistical Analyses

Descriptive statistical analyses were conducted before inferential statistical analyses. Demographic characteristics of the athletes were compared between groups using chi-square or two-sample *t*-tests.

Association between concussion history and cognition. Linear regression models examined whether concussion history predicted cognitive performance. Each cognitive variable of interest was tested as the outcome variable in individual linear regression models. A second set of linear regression models were conducted to determine whether history of *multiple* concussions predicted cognitive performance. All models included age and sex as covariates.

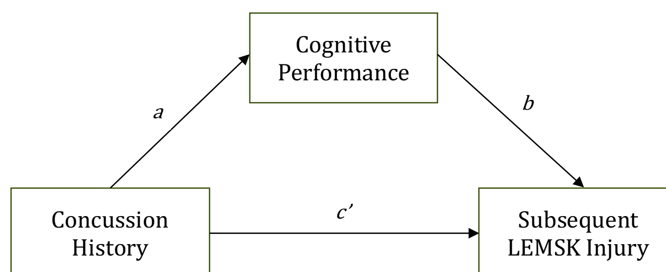
Associations between concussion history, cognition, and subsequent LEMSK injury. A logistic regression model was conducted to assess whether concussion history predicted the odds of sustaining an LEMSK injury in the year following pre-season cognitive testing. A second model was conducted to examine the association between history of *multiple* concussions and subsequent LEMSK injury. Both models included age and sex as covariates.

Logistic regression models examined whether cognitive performance predicted the odds of sustaining an LEMSK injury in the year following pre-season cognitive testing. Each cognitive variable of interest was tested as the predictor in the model. All models included age, sex, and concussion history as covariates.

Mediation analyses were conducted to examine whether the association between concussion history and subsequent LEMSK injury was mediated by cognitive performance. As shown in Figure 2, we tested unstandardized regression coefficients for path *a* (path from concussion history to cognitive performance); path *b* (path from cognitive performance to subsequent LEMSK injury); path *c'* (the direct effect of concussion history on LEMSK injury while controlling for cognitive performance); and path *ab* (the indirect effect of concussion history on subsequent LEMSK injury through cognitive performance). Each cognitive variable of interest was tested as the mediator in individual models. A second set of mediation models were conducted that used history of *multiple* concussions as the predictor, instead of concussion history. All mediation models included age and sex as covariates.

Figure 2

Conceptual Framework of the Mediation Models for Subsequent LEMSK Injury



Note. Each cognitive variable was tested individually in the mediation analyses. Concussion history and subsequent LEMSK injury were dichotomous, while cognitive variables were continuous. LEMSK = lower extremity musculoskeletal.

The mediation analyses were conducted using PROCESS in R (Hayes, 2014). Given that subsequent LEMSK injury was a dichotomous variable, maximum likelihood logistic regression

was used to estimate unstandardized coefficients, standard errors of the estimate, and *p*-values of the direct (*c'* path) and indirect (*ab* path) effects. Bias-corrected 95% confidence intervals of the unstandardized coefficient of the indirect effect were calculated using 10,000 bootstrap samples. The indirect effect was considered significant if zero was excluded in the 95% confidence interval. Since the outcome variable was dichotomous, the total effect was not calculated because logistic regression coefficients are not directly comparable to linear coefficients, and therefore, the approach of taking the product of indirect and direct coefficients may not be valid for nonlinear models (Hayes & Rockwood, 2017). Therefore, we conducted separate regression models as outlined above.

Associations between concussion history, cognition, and subsequent concussion. A logistic regression model was conducted to assess whether concussion history predicted the odds of sustaining a concussion in the year following pre-season cognitive testing. A second logistic regression model was conducted to examine the association between history of *multiple* concussions and subsequent concussion. Both models included age and sex as covariates.

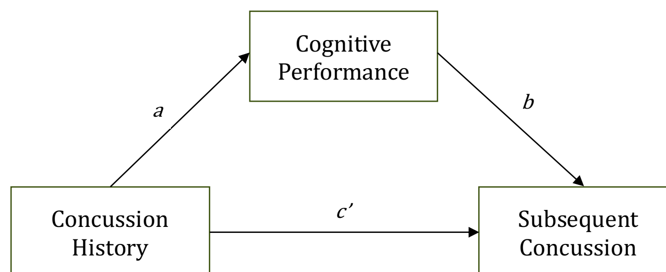
Logistic regression models examined whether cognitive performance predicted the odds of sustaining a concussion in the year following pre-season cognitive testing. Each cognitive variable of interest was tested as the predictor in separate logistic regression models. All models included age, sex, and concussion history as covariates.

Mediation analyses were conducted to examine whether the association between concussion history and subsequent concussion was mediated by cognitive performance (Figure 3). The mediation models were conducted in the same manner as described above, but instead of subsequent LEMSK injury as the outcome variable, subsequent concussion was the outcome variable. Each cognitive variable of interest was tested as the mediator in individual models. A

second set of mediation models were conducted that used history of *multiple* concussions as the predictor, instead of concussion history. All mediation models included age and sex as covariates.

Figure 3

Conceptual Framework of the Mediation Models for Subsequent Concussion



Note. Each cognitive variable was tested individually in the mediation analyses. Concussion history and subsequent concussion were dichotomous, while cognitive variables were continuous.

All analyses were conducted in R (version 4.3.1). For cognitive variables, outliers beyond 3 standard deviations of the mean were excluded. R^2 and McFadden's pseudo R^2 were used as measures of effect size for linear and logistic regression models, respectively. Reaction time was measured in milliseconds. Two-tailed alpha values of less than 0.5 were considered statistically significant.

Results

Demographic Characteristics

The sample included 145 athletes across six sports: artistic swimming, boxing, diving, short-track speed skating, trampoline, and water polo. The average age of athletes was 21.51 years (*SD* = 4.02, range: 14.42-35.58). There was a relatively even proportion of male and female athletes in the sample (N_{female} = 86; % female = 59). Demographic characteristics of athletes stratified by sport are presented in Table 12.

Table 12

Demographic Characteristics for Study 2

	All sports	Artistic swimming	Boxing	Diving	Short-track speed skating	Trampoline	Water Polo
n	145	31	22	5	49	4	34
Sex, *n* (%)							
Female	86 (59%)	31 (100%)	6 (27%)	2 (40%)	25 (51%)	3 (75%)	19 (56%)
Male	59 (41%)	0 (0%)	16 (73%)	3 (60%)	24 (49%)	1 (25%)	15 (44%)
Age, years							
Mean (*SD*)	21.50 (4.05)	19.02 (2.07)	24.47 (4.80)	21.29 (5.27)	20.26 (3.40)	20.69 (1.80)	23.76 (3.64)
Range	14.42-35.58	14.42-24.93	18.22-35.58	16.75-29.58	15.49-34.97	18.17-22.06	18.50-33.87

Sixty-three athletes (43%) had a history of concussion before pre-season cognitive testing. A Chi-square test revealed a significant relationship between concussion history and sex, $\chi^2(1) = 4.38$, $p = .04$, whereby a higher percentage of females were in the *Concussion History* group (70%) compared to the *No Concussion History* group (51%). The groups did not significantly differ by age, $t(143) = -1.07$, $p = .29$. Demographic characteristics of athletes stratified by history of concussion are presented in Table 13.

Table 13

Demographic Characteristics for Study 2 by Concussion History Group

	No Concussion History	Concussion History	Test Statistic	*p*-value
N	82	63		
Sex, *n* (%)			χ^2 (1) = 4.38	0.04*
Female	42 (51%)	44 (70%)		
Male	40 (49%)	19 (30%)		
Age, years			*t*(143) = -1.07	0.29
Mean (*SD*)	21.19 (4.05)	21.91 (4.05)		
Range	14.42-35.58	16.59-34.97		
Sport, *n* (%)				
Artistic swimming	21 (26%)	10 (16%)		
Boxing	18 (22%)	4 (6%)		
Diving	3 (4%)	2 (3%)		
Short-track speed skating	22 (27%)	27 (43%)		
Trampoline	0 (0%)	4 (6%)		
Water polo	18 (22%)	16 (25%)		

Twenty-seven athletes (18.62%) had a history of multiple concussions before pre-season cognitive testing. There were no significant differences between *History of Multiple Concussions* and *No History of Multiple Concussions* groups with respect to sex or age (*ps* > .05).

Associations Between Concussion History and Cognition

Linear regression models explored whether concussion history predicted cognitive performance (Table 14).

Concussion history significantly predicted inhibition at pre-season cognitive testing (*p* = .046), whereby athletes with a history of concussion had on average 1.13 more commission errors on the *Response Inhibition* test than athletes without a history of concussion. The model that included concussion history, age, and sex explained 10% of the variance in the number of

commission errors ($R^2 = 0.10$). The mean reaction time to standard stimuli, but not shift stimuli, was also significantly predicted by concussion history ($p = .005$, $R^2 = 0.11$). On average, athletes with a history of a concussion had faster reaction times to standard stimuli than athletes without a concussion (B = -23.04 ms). A speed-accuracy trade-off analysis was conducted to further investigate these results. There was a significant negative correlation between reaction time and the number of commission errors ($r = -0.43$, $p < .001$), indicating that faster reaction time for standard stimuli was associated with significantly more commission errors. This suggests that athletes prioritized speed over accuracy.

Concussion history also significantly predicted the median reaction time for correct responses on a measure of sustained attention ($p = .02$, $R^2 = 0.14$), whereby athletes with a history of concussion, on average, had faster reaction times on the *Signal Detection* test than athletes without a history of concussion (B = -44.33 ms). Concussion history did not significantly predict the number of correct responses on the *Signal Detection* test ($p = .67$). However, from a speed-accuracy trade-off analysis, there was a significant negative correlation between reaction time and number of correct responses on the *Signal Detection* test ($r = -0.48$, $p < .001$), where faster reaction times were associated with a greater number of correct responses. Therefore, there was no speed-accuracy trade-off, but rather, a general sign of efficiency for the *Signal Detection* test, whereby athletes who responded faster tended to also be more accurate in their responses.

Concussion history did not significantly predict pre-season cognitive performance on measures of working memory (*N-Back Non-Verbal* test), cognitive flexibility (*Determination Test*), planning ability *(Tower of London – Freiburg Version),* or selective attention (*Movement Detection Test;* *p*s > .05).

Table 14

Linear Regression Models of Concussion History Predicting Pre-Season Cognitive Performance

Outcome (Cognitive Variable)	B [95% CI]	SE	*z*	*p*
Executive functions				
N-Back Non-Verbal Test				
Model 1: Number correct	0.87 [-0.09, 1.84]	0.49	1.79	0.08
Model 2: Mean RT	20.28 [-39.07, 79.63]	30.01	0.68	0.50
Response Inhibition Test				
Model 3: Number of commission errors	1.13 [0.02, 2.24]	0.56	2.02	0.046*
Model 4: Mean RT (standard stimuli)	-23.04 [-39.02, -7.06]	8.08	-2.85	0.005**
Model 5: Mean RT (shift stimuli)	-4.10 [-21.18, 12.97]	8.64	-0.48	0.64
Determination Test				
Model 6: Number correct	8.60 [-1.16, 18.36]	4.94	1.74	0.08
Model 7: Median RT	-9.99 [-29.24, 9.26]	9.74	-1.03	0.31
Tower of London – Freiburg Version				
Model 8: Planning ability	0.39 [-0.39, 1.18]	0.40	1.00	0.32
Attention				
Movement Detection Test				
Model 9: Median RT	-14.10 [-30.31, 2.11]	8.20	-1.72	0.09
Signal Detection Test				
Model 10: Number correct	0.44 [-1.63, 2.52]	1.05	0.42	0.67
Model 11: Median RT	-44.33 [-82.90, -5.77]	19.51	-2.27	0.02*

Note. Each linear regression model included age and sex as covariates. B = unstandardized coefficients; CI = confidence interval; SE = standard error of the estimate.
* $p < .05$. ** $p < .01$.

History of multiple concussion was also examined as a predictor of cognitive performance (Table 15). History of multiple concussions significantly predicted the median reaction time on a test of selective attention ($p = .003$). On average, athletes with a history of multiple concussions had faster reaction times on the *Movement Detection Test* compared to athletes without a history of multiple concussions (B = -30.40 ms). The model that included history of multiple concussions, age, and sex explained 11% of the variance in the mean reaction time on the *Movement Detection Test* ($R^2 = 0.11$). History of multiple concussions did not

significantly predict cognitive performance on measures of working memory (*N-Back Non-Verbal* test), inhibition (*Response Inhibition* test), cognitive flexibility (*Determination Test*), planning ability (*Tower of London – Freiburg Version)*, or sustained attention (*Signal Detection* test; *p*s > .05).

Table 15

Linear Regression Models of History of Multiple Concussions Predicting Pre-Season Cognitive Performance

Outcome (Cognitive Variable)	B [95% CI]	SE	z	*p*
Executive functions				
N-Back Non-Verbal Test				
Model 1: Number correct	0.09 [-1.14, 1.32]	0.62	0.14	0.89
Model 2: Mean RT	21.62 [-52.83, 96.08]	37.65	0.57	0.57
Response Inhibition Test				
Model 3: Number of commission errors	0.90 [-0.50, 2.30]	0.71	1.27	0.21
Model 4: Mean RT (standard stimuli)	-13.75 [-34.07, 6.57]	10.28	-1.34	0.18
Model 5: Mean RT (shift stimuli)	-7.22 [-28.50, 14.06]	10.76	-0.67	0.50
Determination Test				
Model 6: Number correct	2.90 [-9.52, 15.31]	6.28	0.46	0.65
Model 7: Median RT	-14.83 [-39.08, 9.41]	12.26	-1.21	0.23
Tower of London – Freiburg Version				
Model 8: Planning ability	0.81 [-0.17, 1.79]	0.49	1.64	0.10
Attention				
Movement Detection Test				
Model 9: Median RT	-30.40 [-50.16, -10.65]	0.99	-3.04	0.003**
Signal Detection Test				
Model 10: Number correct	0.46 [-2.14, 3.06]	1.32	0.35	0.73
Model 11: Median RT	-30.89 [-79.67, 17.90]	24.67	-1.25	0.21

Note. Each linear regression model included age and sex as covariates. B = unstandardized coefficients; CI = confidence interval; SE = standard error of the estimate.
* $p < .05$. ** $p < .01$.

Associations Between Concussion History, Cognition, and Subsequent LEMSK Injury

A logistic regression model showed that concussion history significantly predicted subsequent LEMSK injury (p = 0.03; Table 16). Athletes with a history of concussion were 2.28 times more likely to sustain a subsequent LEMSK injury than athletes without a history of concussion (OR = 2.28, 95% CI [1.12, 4.81]). The model that included concussion history, age, and sex as predictors explained 3.5% of the variance in subsequent LEMSK injury (McFadden's R^2 = 0.035).

Table 16

Logistic Regression Model of Concussion History Predicting Subsequent LEMSK Injury

Variable	B	SE	*z*	*p*	OR [95% CI]
Constant	1.29	0.96	1.35	0.18	
Concussion History	0.83	0.37	2.22	0.03*	2.28 [1.12, 4.81]
Sex	0.12	0.36	0.34	0.74	1.13 [0.55, 2.30]
Age	-0.05	0.04	-1.26	0.21	0.95 [0.87, 1.03]

Note. Reference groups for categorical variables were *No Concussion History* and *Male*. B = unstandardized coefficients; CI = confidence interval; LEMSK = lower extremity musculoskeletal; SE = standard error of the estimate; OR = odds ratio.
* $p < .05$.

A separate logistic regression model also showed that history of multiple concussions significantly predicted subsequent LEMSK injury (p = .03; Table 17). Athletes with a history of multiple concussions were 3.27 times more likely to sustain an LEMSK injury than athletes who either sustained a single concussion or had no concussion history (OR = 3.27, 95% CI [1.22, 10.45]). The model that included history of multiple concussions, age, and sex as predictors explained 3.8% of the variance in subsequent LEMSK injury (McFadden's R^2 = 0.038).

Table 17

Logistic Regression Model of History of Multiple Concussions Predicting Subsequent LEMSK Injury

Variable	B	SE	*z*	*p*	OR [95% CI]
Constant	1.44	0.96	1.50	0.13	
History of Multiple Concussions	1.18	0.54	2.20	0.03*	3.27 [1.22, 10.45]
Sex	0.19	0.36	0.53	0.60	1.21 [0.59, 2.44]
Age	-0.06	0.04	-1.30	0.20	0.94 [0.87, 1.03]

Note. Reference groups for categorical variables were *No History of Multiple Concussions* (i.e., athletes have sustained one concussion or have never sustained a concussion) and *Male*. B = unstandardized coefficients; CI = confidence interval; SE = standard error of the estimate; OR = odds ratio.
* $p < .05$.

The association between cognitive performance and subsequent LEMSK injury was evaluated by separate logistic regression models (Table 18). The mean reaction time of correct responses on a working memory test (*N-Back Non-Verbal* test) significantly predicted the odds of sustaining a subsequent LEMSK injury ($p = 0.03$), whereby for every 100 ms increase in mean reaction time, the odds of sustaining an LEMSK injury increased by 24% (OR: 1.0024, 95% CI: [1.0002, 1.005]). The logistic regression model with age, sex, and concussion history as covariates accounted for 6.4% of the variance in subsequent LEMSK injury risk (McFadden's R^2 = 0.064). The number of correct responses on the *N-Back Non-Verbal* test did not significantly predict subsequent LEMSK injury ($p = .50$). Cognitive variables from the *Response Inhibition* test, *Determination Test, Tower of London – Freiburg Version*, *Movement Detection Test*, and the *Signal Detection* test did not significantly predict subsequent LEMSK injury (*p*s > .05).

Table 18

Logistic Regression Models of Cognitive Variables Predicting Subsequent LEMSK Injury

Predictor (Cognitive Variable)	B	SE	*z*	*p*	OR [95% CI]
Executive functions					
N-Back Non-Verbal Test					
Model 1: Number correct	-0.04	0.07	-0.67	0.50	0.96 [0.84, 1.09]
Model 2: Mean RT	0.002	0.001	2.11	0.03*	1.0024 [1.0002, 1.005]
Response Inhibition Test					
Model 3: Number of commission errors	-0.006	0.06	-0.10	0.92	0.99 [0.89, 1.12]
Model 4: Mean RT (standard stimuli)	-0.002	0.004	-0.57	0.57	0.998 [0.99, 1.01]
Model 5: Mean RT (shift stimuli)	0.0004	0.004	0.10	0.92	1.0004 [0.99, 1.01]
Determination Test					
Model 6: Number correct	-0.003	0.01	-0.46	0.65	0.997 [0.98, 1.01]
Model 7: Median RT	-0.003	0.003	-0.90	0.37	0.997 [0.99, 1.003]
Tower of London – Freiburg Version					
Model 8: Planning ability	0.03	0.08	0.42	0.67	1.03 [0.89, 1.20]
Attention					
Movement Detection Test					
Model 9: Median RT	0.002	0.004	0.60	0.55	1.002 [0.99, 1.01]
Signal Detection Test					
Model 10: Number correct	0.006	0.03	0.22	0.83	1.01 [0.95, 1.07]
Model 11: Median RT	-0.002	0.002	-1.20	0.23	0.998 [0.99, 1.001]

Note. Each logistic regression model included age, sex, and concussion history as covariates. B = unstandardized coefficients; CI = confidence interval; SE = standard error of the estimate; OR = odds ratio.
* $p < .05$.

No cognitive variables mediated the relationship between concussion history and subsequent LEMSK injury (Table 19). All bootstrap 95% confidence intervals of the indirect effect's unstandardized estimates contained zero, indicating that the mediating effect was non-significant. The direct effect of concussion history on subsequent LEMSK injury was significant in all models ($ps < .05$), with the exception of median reaction time on the *Signal Detection* test ($p = 0.06$).

Similarly, no cognitive variables mediated the relationship between history of multiple concussions and subsequent LEMSK injury (Table 20). All bootstrap 95% confidence intervals of the indirect effect's unstandardized estimate contained zero, indicating that the mediating effect was non-significant. The direct effect of history of multiple concussions on subsequent LEMSK injury was significant in all models ($ps < .05$).

Table 19

Results of Cognitive Variables Mediating the Relationship Between Concussion History and Subsequent LEMSK Injury

Cognitive Domain	Mediator (Cognitive Variable)	Unstandardized estimates (SE) of the direct effects			Bootstrapped unstandardized estimates (SE) of the indirect effect	
		a	*b*	*c'*	*ab*	95% CI
Executive Function	*N-Back Non-Verbal* Test					
	Model 1: Number correct	0.87 (0.49)	-0.04 (0.07)	0.94 (0.39)*	-0.04 (0.08)	[-0.23, 0.09]
	Model 2: Mean RT	20.28 (30.01)	0.002 (0.001)*	0.85 (0.39)*	0.05 (0.09)	[-0.10, 0.26]
	Response Inhibition Test					
	Model 3: Number of commission errors	1.13 (0.56)*	-0.006 (0.06)	0.80 (0.38)*	-0.01 (0.07)	[-0.15, 0.16]
	Model 4: Mean RT (standard stimuli)	-23.04 (8.08)**	-0.002 (0.004)	0.84 (0.39)*	0.05 (0.10)	[-0.13, 0.29]
	Model 5: Mean RT (shift stimuli)	-4.11 (8.64)	0.0004 (0.004)	0.76 (0.38)*	-0.002 (0.04)	[-0.11, 0.06]
	Determination Test					
	Model 6: Number correct	8.60 (4.94)	-0.003 (0.006)	0.99 (0.39)*	-0.03 (0.07)	[-0.16, 0.12]
	Model 7: Median RT	-9.99 (9.73)	-0.003 (0.003)	0.88 (0.38)*	0.03 (0.06)	[-0.04, 0.20]
	Tower of London – Freiburg Version					
	Model 8: Planning ability	0.39 (0.40)	0.03 (0.08)	0.08 (0.37)*	0.01 (0.05)	[-0.06, 0.13]
Attention	*Movement Detection Test*					
	Model 9: Median RT	-14.10 (8.20)	0.002 (0.004)	0.89 (0.38)*	-0.03 (0.07)	[-0.19, 0.09]
	Signal Detection Test					
	Model 10: Number correct	0.44 (1.05)	0.006 (0.03)	0.77 (0.37)*	0.003 (0.04)	[-0.07, 0.09]
	Model 11: Median RT	-44.33 (19.51)*	-0.002 (0.002)	0.71 (0.38)	0.09 (0.09)	[-0.05, 0.32]

Note. All mediation models included age and sex as covariates. a = path from concussion history to the cognitive variable; ab = indirect path from concussion history to subsequent LEMSK injury, through the cognitive variable; b = path from the cognitive variable to subsequent LEMSK injury; c' = direct path from concussion history to subsequent LEMSK injury; CI = confidence interval; SE = standard error of the estimate.
* $p < .05$.

Table 20

Results of Cognitive Variables Mediating the Relationship Between History of Multiple Concussion and Subsequent LEMSK Injury

Cognitive Domain	Mediator (Cognitive Variable)	Unstandardized estimates (SE) of the direct effects			Bootstrapped unstandardized estimates (SE) of the indirect effect	
		a	*b*	*c'*	*ab*	95% CI
Executive Function	*N-Back Non-Verbal* Test					
	Model 1: Number correct	0.09 (0.62)	-0.02 (0.07)	1.13 (0.55)*	-0.002 (0.06)	[-0.13, 0.12]
	Model 2: Mean RT	21.62 (37.65)	0.003 (0.001)*	1.11 (0.56)*	0.05 (0.12)	[-0.16, 0.33]
	Response Inhibition Test					
	Model 3: Number of commission errors	0.90 (0.71)	0.002 (0.06)	1.15 (0.54)*	0.002 (0.07)	[-0.15, 0.17]
	Model 4: Mean RT (standard stimuli)	-13.75 (10.27)	-0.003 (0.004)	1.12 (0.54)*	0.05 (0.07)	[-0.07, 0.22]
	Model 5: Mean RT (shift stimuli)	-7.22 (10.76)	0.0005 (0.004)	1.13 (0.54)*	-0.004 (0.04)	[-0.10, 0.07]
	Determination Test					
	Model 6: Number correct	2.90 (6.28)	-0.0009 (0.006)	1.12 (0.54)*	-0.003 (0.05)	[-0.10, 0.10]
	Model 7: Median RT	-14.83 (12.26)	-0.003 (0.003)	1.10 (0.54)*	0.04 (0.08)	[-0.07, 0.25]
	Tower of London – Freiburg Version					
	Model 8: Planning ability	0.81 (0.50)	0.02 (0.08)	1.14 (0.54)*	0.02 (0.07)	[-0.12, 0.19]
Attention	*Movement Detection Test*					
	Model 9: Median RT	-30.40 (9.99)**	0.003 (0.004)	1.29 (0.55)*	-0.10 (0.14)	[-0.41, 0.13]
	Signal Detection Test					
	Model 10: Number correct	0.46 (1.32)	0.007 (0.03)	1.14 (0.54)*	0.003 (0.04)	[-0.09, 0.10]
	Model 11: Median RT	-30.89 (24.67)	-0.002 (0.002)	1.13 (0.54)*	0.07 (0.08)	[-0.06, 0.27]

Note. All mediation models included age and sex as covariates. a = path from history of multiple concussions to the cognitive variable; ab = indirect path from history of multiple concussions to subsequent LEMSK injury, through cognitive variable; b = path from cognitive variable to subsequent LEMSK injury; c' = direct path from history of multiple concussions to subsequent LEMSK injury; CI = confidence interval; SE = standard error of the estimate.
* $p < .05$.

Associations Between Concussion History, Cognition, and Subsequent Concussion

A logistic regression model indicated that concussion history did not significantly predict subsequent concussion (p = .87; Table 21). Similarly, history of multiple concussions did not significantly predict subsequent concussion (p = .13; Table 22). No cognitive variables predicted subsequent concussion (ps > .05; Table 23). In mediation analyses, direct and indirect paths were not significant (ps > .05) for concussion history to subsequent concussion (Table 24) or for history of multiple concussions to subsequent concussion (Table 25).

Table 21

Logistic Regression Model of Concussion History Predicting Subsequent Concussion

Variable	B	SE	*z*	*p*	OR [95% CI]
Constant	0.11	1.42	0.08	0.94	
Concussion History	0.08	0.47	0.16	0.87	1.08 [0.42, 2.70]
Sex	0.88	0.51	1.70	0.09	2.40 [0.92, 7.11]
Age	-0.11	0.07	-1.66	0.10	0.89 [0.77, 1.01]

Note. Reference groups for categorical variables were *No Concussion History* and *Male*. B = unstandardized coefficients; CI = confidence interval; SE = standard error of the estimate; OR = odds ratio.

Table 22

Logistic Regression Model of History of Multiple Concussions Predicting Subsequent Concussion

Variable	B	SE	*z*	*p*	OR [95% CI]
Constant	0.25	1.44	0.17	0.86	
History of Multiple Concussions	0.81	0.53	1.51	0.13	2.24 [0.75, 6.28]
Sex	0.85	0.51	1.65	0.10	2.33 [0.89, 6.89]
Age	-0.12	0.07	-1.81	0.07	0.88 [0.76, 1.00]

Note. Reference groups for categorical variables were *No History of Multiple Concussions* (i.e., athletes have sustained one concussion or have never sustained a concussion) and *Male*. B = unstandardized coefficients; CI = confidence interval; SE = standard error of the estimate; OR = odds ratio.

Table 23

Logistic Regression Models of Different Cognitive Variables Predicting Subsequent Concussion

Predictor (Cognitive Variable)	B	SE	*z*	*p*	OR [95% CI]
Executive functions					
N-Back Non-Verbal Test					
Model 1: Number correct	-0.02	0.08	-0.23	0.82	0.98 [0.84, 1.16]
Model 2: Mean RT	0.0002	0.001	0.15	0.89	1.0002 [0.997, 1.003]
Response Inhibition Test					
Model 3: Number of commission errors	0.06	0.06	1.01	0.32	1.07 [0.94, 1.21]
Model 4: Mean RT (standard stimuli)	-0.006	0.005	-1.20	0.23	0.99 [0.98, 1.004]
Model 5: Mean RT (shift stimuli)	-0.009	0.005	-1.77	0.08	0.99 [0.98, 1.0007]
Determination Test					
Model 6: Number correct	0.005	0.009	0.55	0.58	1.005 [0.99, 1.02]
Model 7: Median RT	0.005	0.004	1.08	0.28	1.005 [0.996, 1.01]
Tower of London – Freiburg Version					
Model 8: Planning ability	-0.02	0.10	-0.20	0.84	0.98 [0.80, 1.20]
Attention					
Movement Detection Test					
Model 9: Median RT	-0.003	0.005	-0.60	0.55	0.997 [0.99, 1.01]
Signal Detection Test					
Model 10: Number correct	-0.004	0.04	-0.11	0.91	0.996 [0.92, 1.08]
Model 11: Median RT	-0.001	0.002	-0.56	0.58	0.999 [0.99, 1.003]

Note. Each logistic regression model included age, sex, and concussion history as covariates. B = unstandardized coefficients; CI = confidence interval; SE = standard error of the estimate; OR = odds ratio.

Table 24

Results of Cognitive Variables Mediating the Relationship Between Concussion History and Subsequent Concussion

Cognitive Domain	Mediator (Cognitive Variable)	Unstandardized estimates (SE) of the direct effects			Bootstrapped unstandardized estimates (SE) of the indirect effect	
		a	*b*	*c'*	*ab*	95% CI
Executive Function	*N-Back Non-Verbal* Test					
	Model 1: Number correct	0.87 (0.49)	-0.02 (0.08)	0.09 (0.48)	-0.02 (0.10)	[-0.21, 0.20]
	Model 2: Mean RT	20.29 (30.01)	0.0002 (0.001)	0.06 (0.48)	0.004 (0.07)	[-0.17, 0.11]
	Response Inhibition Test					
	Model 3: Number of commission errors	1.13 (0.56)*	0.06 (0.06)	-0.10 (0.48)	0.07 (0.11)	[-0.12, 0.34]
	Model 4: Mean RT (standard stimuli)	-23.04 (8.08)**	-0.006 (0.005)	-0.07 (0.48)	0.14 (0.17)	[-0.08, 0.56]
	Model 5: Mean RT (shift stimuli)	-4.11 (8.64)	-0.009 (0.005)	-0.04 (0.48)	0.04 (0.10)	[-0.17, 0.24]
	Determination Test					
	Model 6: Number correct	8.60 (4.94)	0.005 (0.009)	0.06 (0.48)	0.04 (0.10)	[-0.10, 0.29]
	Model 7: Median RT	-9.99 (9.74)	0.005 (0.004)	0.15 (0.47)	-0.05 (0.07)	[-0.23, 0.08]
	Tower of London – Freiburg Version					
	Model 8: Planning ability	0.39 (0.40)	-0.02 (0.10)	0.06 (0.47)	-0.008 (0.07)	[-0.15, 0.14]
Attention	*Movement Detection Test*					
	Model 9: Median RT	-14.10 (8.20)	-0.003 (0.005)	-0.09 (0.48)	0.04 (0.09)	[-0.12, 0.27]
	Signal Detection Test					
	Model 10: Number correct	0.44 (1.05)	-0.004 (0.04)	0.05 (0.47)	-0.002 (0.05)	[-0.09, 0.11]
	Model 11: Median RT	-44.33 (19.51)*	-0.001 (0.02)	0.009 (0.48)	0.05 (0.12)	[-0.14, 0.34]

Note. All mediation models included age and sex as covariates. a = path from concussion history to the cognitive variable; ab = indirect path from concussion history to subsequent concussion, through the cognitive variable; b = path from the cognitive variable to subsequent concussion; c' = direct path from concussion history to subsequent concussion; CI = confidence interval; SE = standard error of the estimate.
* $p < .05$.

Table 25

Results of Cognitive Variables Mediating the Relationship Between History of Multiple Concussion and Subsequent Concussion

Cognitive Domain	Mediator (Cognitive Variable)	Unstandardized estimates (SE) of the direct effects		Bootstrapped unstandardized estimates (SE) of the indirect effect		
		a	*b*	*c'*	*ab*	95% CI
Executive Function	*N-Back Non-Verbal* Test					
	Model 1: Number correct	0.09 (0.62)	-0.02 (0.08)	0.82 (0.54)	-0.002 (0.07)	[-0.15, 0.16]
	Model 2: Mean RT	21.62 (37.65)	0.0001 (0.001)	0.81 (0.54)	0.001 (0.09)	[-0.22, 0.15]
	Response Inhibition Test					
	Model 3: Number of commission errors	0.90 (0.71)	0.05 (0.06)	0.70 (0.54)	0.05 (0.11)	[-0.13, 0.30]
	Model 4: Mean RT (standard stimuli)	-13.75 (10.28)	-0.006 (0.005)	0.71 (0.54)	0.08 (0.12)	[-0.06, 0.39]
	Model 5: Mean RT (shift stimuli)	-7.22 (10.76)	-0.009 (0.005)	0.75 (0.54)	0.07 (0.10)	[-0.08, 0.33]
	Determination Test					
	Model 6: Number correct	2.90 (6.28)	0.004 (0.009)	0.83 (0.54)	0.01 (0.07)	[-0.12, 0.19]
	Model 7: Median RT	14.83 (12.26)	0.006 (0.004)	0.98 (0.55)	-0.08 (0.11)	[-0.36, 0.08]
	Tower of London – Freiburg Version					
	Model 8: Planning ability	0.81 (0.49)	-0.05 (0.11)	0.83 (0.54)	-0.04 (0.12)	[-0.29, 0.21]
Attention	*Movement Detection Test*					
	Model 9: Median RT	-30.40 (9.99)**	-0.0009 (0.005)	0.72 (0.57)	0.03 (0.18)	[-0.33, 0.40]
	Signal Detection Test					
	Model 10: Number correct	0.46 (1.32)	-0.006 (0.04)	0.79 (0.53)	-0.003 (0.06)	[-0.08, 0.15]
	Model 11: Median RT	-30.89 (24.67)	-0.0009 (0.002)	0.74 (0.54)	0.03 (0.10)	[-0.14, 0.28]

Note. All mediation models included age and sex as covariates. a = path from history of multiple concussions to the cognitive variable; ab = indirect path from history of multiple concussions to subsequent concussion, through the cognitive variable; b = path from the cognitive variable to subsequent concussion; c' = direct path from history of multiple concussions to subsequent concussion; CI = confidence interval; SE = standard error of the estimate.

Discussion

This study aimed to explore the associations between cognition, concussion, and LEMSK injury. Results showed that associations exist between concussion history and cognition, as well as cognition and subsequent LEMSK injury. The study also provided further evidence that there is an increased odds of sustaining an LEMSK injury among athletes with a concussion history compared to athletes with no concussion history. We also replicated this finding among athletes with a lifetime history of multiple concussions (defined as two or more concussions prior to pre-season cognitive testing). In contrast to the literature, this study did not find an increased odds of sustaining a concussion among athletes with a history of concussion or a history of multiple concussions. This study also aimed to investigate cognition as a potential mechanism underlying the association between concussion history and subsequent LEMSK injury and between concussion history and subsequent concussion. Results showed that cognition did not mediate the relationships between concussion history (or history of multiple concussions) and subsequent LEMSK injury or subsequent concussion.

Long-Term Cognitive Effects of Concussion

Our study found that concussion history was associated with more commission errors and faster reaction time on a test of inhibition. On the *Response Inhibition* test, we found a significant speed-accuracy trade-off where athletes prioritized speed over accuracy. Our finding may suggest two things: (i) those who prioritized speed may be more susceptible to injury; or (ii) there are potential lingering deficits in inhibition following a concussion, which aligns well with the literature (Caffey & Dalecki, 2021, 2021; McGowan et al., 2019; Stafford et al., 2020). However, our study design cannot make these direct conclusions because we did not have measures of baseline cognitive functioning prior to an athlete's first concussion or post-

concussion cognitive testing data that could help understand whether acute inhibition deficits persisted over time. A study by McGowan and colleagues (2019) investigated the longitudinal trajectory of inhibitory control deficits following a concussion. The study found that athletes with a concussion showed acute inhibition deficits following the concussion compared to controls, and that these deficits persisted one month after the athletes returned to sport (McGowan et al., 2019). In terms of lifetime history of concussion, which may be more analogous to our study design, a large study of 19,261 participants reported that individuals who self-reported a history of concussion in their lifetime performed significantly worse on an inhibition task compared to individuals who have never sustained a concussion (Stafford et al., 2020). The finding of greater errors on an inhibition task among individuals with concussion history was also replicated in a smaller sample of young adults who self-reported sustaining a concussion in their adolescence (Caffey & Dalecki, 2021). Therefore, our result for a deficit in inhibition among those with a history of concussion aligns well with the literature.

Our study also found that athletes with concussion history had faster reaction time on a test of sustained attention compared to athletes with no history of concussion. However, the number of correct responses on this task was not significantly predicted by concussion history. Athletes with a history of two or more concussions also had on average, faster reaction times on a measure of selective attention than athletes with either one or no previous concussions. These findings of faster reaction times among athletes with a history of concussion is difficult to interpret as it is unknown how this group of athletes would have performed prior to their first concussion. Generally, this effect of faster performance on attention tasks does not align with findings from a study conducted by Stafford et al. (2020) that did not find any significant

differences on tests of attention or reaction time between adults with and without a lifetime history of concussion.

Across other cognitive measures, neither concussion history nor history of multiple concussions predicted cognitive performance on tests of working memory, cognitive flexibility, or planning ability. These null findings align with studies that have found no significant differences on measures of visual working memory, cognitive flexibility and multitasking, and spatial planning between individuals with or without a lifetime history of concussion (Fox et al., 2022, 2024; Stafford et al., 2020).

Association Between Concussion History, Cognition, and Subsequent LEMSK Injury

Concussion history and history of multiple concussions (defined as two or more) both significantly predicted subsequent LEMSK injury. In our sample, the odds of sustaining a subsequent LEMSK injury was 2.28 times greater in athletes with a history of concussion compared to those without a concussion. This finding aligns with prior studies that have found an increased risk of subsequent LEMSK injury among athletes with a concussion history (Gilbert et al., 2016; Jildeh et al., 2022; Ramirez et al., 2022). Our odds ratio of sustaining a subsequent LEMSK injury among athletes with a history of multiple concussion was slightly higher (3.27) which is also consistent with the literature (Harada et al., 2019).

We next examined whether cognitive performance may underlie these associations. Our study found that reaction time for correct responses on a test of working memory predicted subsequent LEMSK injury. Specifically, slower reaction time on the *N-Back Non-Verbal* test was associated with an increased odds of sustaining an LEMSK injury. It is notable that the primary outcome measure of interest for the *N-Back Non-Verbal* was the number of correct responses, as opposed to reaction time on these trials, but there was no significant association between the

number of correct items and subsequent LEMSK injury. As such, it is difficult to ascertain the meaning of slower reaction time on the working memory test (i.e., whether it indicates uncertainty or hesitancy in making a correct response). While no other reaction time measures from the VTS were significant, our finding of slower reaction time on the *N-Back Non-Verbal* test aligns with findings in the literature that suggest that slower reaction time is associated with LEMSK injury risk (McDonald et al., 2019; Swanik et al., 2007; Wilkerson, 2012). Papers have also found that working memory deficits were associated with biomechanical landing properties that place athletes at risk for injury (Avedesian et al., 2021; Giesche et al., 2020).

Subsequent LEMSK injury was not significantly associated with measures of selective attention, sustained attention, cognitive flexibility, inhibition, or planning ability. Our null findings of the association between attention and subsequent LEMSK injury are in contrast to one study of visuospatial selective attention that found that slower reaction time was associated with an increased risk of LEMSK injury (Avedesian, McPherson, et al., 2022). Since executive functions were not measured by ImPACT, studies investigating the risk of executive functioning on LEMSK injury are limited in the present literature. In fact, a recent systematic review by Wilke and Groneberg (2022) stated that no studies have explored the association between executive functions and subsequent LEMSK injury. Our findings suggest that there is no association between cognitive flexibility, inhibition, or planning ability and the risk of subsequent LEMSK injury.

No cognitive measures mediated the association between concussion history (or history of multiple concussion) and subsequent LEMSK injury as the indirect path of concussion history to subsequent LEMSK injury through cognition was not significant for any of the cognitive measures. The direct path between concussion history and subsequent LEMSK injury remained

significant for all but one mediation model (median reaction time on the *Signal Detection* test). These findings suggest that the association between concussion history and LEMSK injury are not due to lingering cognitive deficits following a concussion. As explored in the literature, it could instead be the case that persistent deficits in neuromuscular control following a concussion may place an athlete at risk for a subsequent LEMSK injury (Chmielewski et al., 2021; Howell, Lynall, et al., 2018). Even after clinical recovery of concussion, deficits in gait (Catena et al., 2009; Martini et al., 2011; Parker et al., 2006), dual-task gait performance (Berkner et al., 2017; Howell, Osternig, & Chou, 2013; Howell, Osternig, et al., 2018), and dynamic or static postural control (Buckley et al., 2016, 2021; Johnston et al., 2020; Reilly et al., 2020) have been reported. Alternatively, there may be risk-taking behaviours or sport characteristics that increase an athlete's risk of both concussions and LEMSK injuries independently from each other, rather than concussion directly influencing the risk of LEMSK injury (Beidler et al., 2017; Burman et al., 2016; Clay et al., 2013; Hootman et al., 2007; Nordström et al., 2014; Pfister et al., 2016; Pierpoint & Collins, 2021).

Association Between Concussion History, Cognition, and Subsequent Concussions

In our sample of athletes, we did not find an association between concussion history (or history of multiple concussions) and the odds of sustaining a subsequent concussion. This is in contrast to many reports of an increased risk of subsequent concussion among athletes with a history of concussion (Abrahams et al., 2014; Reneker et al., 2019; Van Ierssel et al., 2021). One reason for our null findings could be the relatively small number of athletes (n = 24; 17% of total sample) who sustained a concussion in the year following pre-season cognitive testing.

Our study did not find any associations between cognitive performance and subsequent concussion. This is consistent with other studies in the literature that report null findings

(Caccese et al., 2020; Lopez-Flores et al., 2022; Putukian et al., 2021). Given the non-significant associations above, unsurprisingly, cognition did not mediate the relationship between concussion history (or history of multiple concussions) and subsequent concussion. Indirect and direct paths between concussion history and subsequent concussion were not significant. Although the association between concussion history and subsequent concussion was not significant in our study, the mechanism underlying this relationship remains unknown.

Chapter 4.

General Discussion

The overall objective of this thesis was to better understand the relationship between cognition, concussion, and LEMSK injury among elite athletes. Specifically, this research aimed to better understand the potential roles of concussion history and cognition as risk factors for LEMSK injuries and concussions. This was accomplished across two studies. Study 1 established the use of the VTS in our sample of athletes, while Study 2 used the VTS as the measure of cognitive performance when investigating associations between cognition, concussion, and LEMSK injury.

Study 1 showed that the VTS has utility in measuring cognitive functioning among elite athletes. Cognitive measures had similar to or better long-term test-retest reliability compared to studies investigating the SCAT SAC, ImPACT, and CogState (Bailey et al., 2022; Broglio et al., 2018; Bruce et al., 2014; Schatz, 2010; Tsushima et al., 2016). Given that these widely used cognitive measures do not extensively measure executive functions or attention, the VTS may provide value in the assessment and management of concussion. Test-retest reliabilities of the VTS also help to inform the cognitive stability findings from Study 1, as well as the role of VTS as a measure of pre-season cognitive performance in the associations between cognition, concussion, and LEMSK injury in Study 2.

On a test of working memory, the *N-Back Non-Verbal* test, the test-retest reliabilities for the accuracy and reaction time measures were deemed poor. On analyses of cognitive stability, athletes improved in the number of correct responses and reaction time for correct responses across the three time points. However, these effects were small, and changes did not survive sensitivity analyses that excluded athletes who sustained a concussion between the three time

points. Taken together, it may be more likely that changes on the *N-Back Non-Verbal* test were due to test measurement error, such as ceiling or practice effects (Bartels et al., 2010; Calamia et al., 2012; Wang et al., 2008). In Study 2, slower reaction time on the *N-Back Non-Verbal* test was also associated with an increased risk of subsequent LEMSK injury. While this finding aligns with the literature suggesting that slower reaction times and working memory deficits are associated with an increased risk of injury (Avedesian et al., 2021; Avedesian, Forbes, et al., 2022; Giesche et al., 2020; McDonald et al., 2019; Swanik et al., 2007; Wilkerson, 2012), the poor test-retest reliability of the *N-Back Non-Verbal* test may confound the interpretability of these findings.

The measure of cognitive flexibility, the *Determination Test*, had the strongest test-retest reliability on the VTS. Therefore, when improvements on the number of correct reactions and reaction time on the *Determination Test* were observed across two time points (9-15 months apart) and three time points (6-18 months after the second time point), this may signal a true improvement in cognitive flexibility among athletes rather than attributable to test measurement error. At the individual level, 81% of athletes showing meaningful improvements across the two time points according to SWCs (35% according to RCIs). Considering that cognitive flexibility is associated with age (Cepeda et al., 2001; Dajani & Uddin, 2015), aerobic fitness (Masley et al., 2009), and level of sport expertise (Huijgen et al., 2015; Vestberg et al., 2012), it could be that as athletes are training at INS Québec between time points, their cognitive flexibility is improving. Since improvements were observed across time (i.e., scores were not stable), this could have impacted the lack of association in Study 2 between the *Determination Test* and the risk of subsequent LEMSK injury or concussion. Study 2 also did not find an association between lifetime history of concussion and cognitive flexibility.

There was also an improvement in planning ability, as measured by the *Tower of London – Freiburg Version*, across the sub-sample of athletes with three time points. However, this was not significant between Time 1 and Time 2 in the full sample of athletes. This inconsistency in findings may be due to measurement error as suggested by the poor test-retest reliability. For instance, the task was subject to ceiling effects which may limit the range of improvement among athletes who scored high on the test at baseline. In Study 2, planning ability was not associated with concussion history or the risk of subsequent LEMSK injury or concussion.

The *Response Inhibition* test was deemed stable across time. No significant changes were detected across the two or three time points. Test-retest reliability varied according to the cognitive variable, whereby the number of commission errors had poor reliability, but reaction time measures had moderate-to-good reliability. In Study 2, while cognitive performance on the *Response Inhibition* test did not predict the risk of subsequent LEMSK injury or concussion, it was associated with concussion history. Athletes with a lifetime history of concussion showed poorer performance on the *Response Inhibition* test, whereby they demonstrated a speed-accuracy trade-off (i.e., significantly faster, but made more errors). Our findings are similar to studies that have found inhibition deficits in participants with a lifetime history of a concussion (Caffey & Dalecki, 2021; Stafford et al., 2020). Our findings also align with a study that found that acute inhibitory deficits following a concussion were still apparent the month following return to sport (McGowan et al., 2019).

In terms of attention measures, the *Signal Detection* test, a measure of sustained attention had moderate test-retest reliability. Improvements in the number of correct responses was only significant between Time 1 and Time 2 in the full sample of athletes (i.e., changes were not significant across the three time points). No significant changes were detected for the reaction

time of correct responses. The test of selective attention, the *Movement Detection Test*, also showed significant changes between Time 1 and Time 2 in the full sample of athletes, but did not remain significant across the three time points. The test-retest reliability was deemed poor for the *Movement Detection Test*. Moreover, the direction of change was in the opposite direction as what would be expected, whereby athletes were slower on the task at Time 2 compared to Time 1. Considering that this decline in reaction time was no longer significant across the three time points in the sub-sample of athletes with available data and that the test-retest reliability was poor, these findings of a potential slowing of reaction time should not be overinterpreted. Neither performance nor reaction time measures on either test of attention significantly predicted the risk of subsequent LEMSK injury or concussion. However, concussion history was associated with faster reaction times on both attention measures. Given the design of our study, we did not have measures of baseline cognitive functioning prior to an athlete's first concussion. Since cognition has been found to differ by sport (J. Jacobson & Matthaeus, 2014; Yongtawee et al., 2022) and sport expertise (Kalén et al., 2021; Scharfen & Memmert, 2019), it is unknown whether these effects existed prior to an athlete's first concussion.

Study 2 also provided additional support for the association between concussion history and LEMSK injury risk. We found that both concussion history and history of multiple concussions increased the likelihood that athletes would sustain a LEMSK injury in the one-year observation period. This aligns well with the literature supporting the association between concussion history and the risk of LEMSK injury (Gilbert et al., 2016; Jildeh et al., 2022; McPherson et al., 2019; Ramirez et al., 2022). When examining whether cognition may explain this association, mediation effects of cognitive performance were non-significant. Therefore, the mechanism underlying the association between concussion history and subsequent LEMSK

injury remains unknown. It could be the case that lingering effects of neuromuscular control following a concussion exist beyond the clinical resolution of symptoms (Chmielewski et al., 2021; Howell, Lynall, et al., 2018). This may include subtle deficits in gait (Berkner et al., 2017; Catena et al., 2009; Howell, Osternig, & Chou, 2013; Martini et al., 2011; Parker et al., 2006) and postural control (Buckley et al., 2016, 2021; Johnston et al., 2020; Reilly et al., 2020). Considering that neuromuscular control and biomechanics are associated with the risk of injury (Hewett et al., 2005; Read et al., 2016; Weiss & Whatman, 2015), these lingering effects may exist when an athlete returns to sport and place them at an increased risk for injury. Alternatively, there could be factors that independently increase an athlete's risk of both concussions and LEMSK injuries separately from one another (Burman et al., 2016; Nordström et al., 2014), such as risk-taking behaviour (Beidler et al., 2017) or sport characteristics (Clay et al., 2013; Hootman et al., 2007; Pfister et al., 2016; Pierpoint & Collins, 2021).

Study 2 found that cognition and concussion history were not associated with subsequent concussion. Our finding of a null effect for the association between pre-season cognitive performance and subsequent concussion aligns well with the literature that has explored this relationships thus far (Caccese et al., 2020; Lopez-Flores et al., 2022; Putukian et al., 2021). In contrast, concussion history and the odds of sustaining a subsequent concussion has been well established in the literature (Abrahams et al., 2014; Reneker et al., 2019; Van Ierssel et al., 2021). One reason why we did not replicate this finding in our sample may be because we had a relatively small number of athletes who sustained a subsequent concussion in our one-year observation window (n = 24, 17% of athletes). Therefore, it could be the case that this association would have been observable in a larger sample.

Limitations

While the current study addressed many gaps in the literature, there are several limitations to be considered. First, our sample included athletes competing at the highest level in artistic swimming, boxing, diving, short-track speed skating, trampoline, and water polo. While this sample differs from previous studies, some of our findings did align with the literature. Moreover, given that our sample was small for certain sports (e.g., diving, trampoline), we did not examine associations between cognition, concussion, and LEMSK injury while controlling for sport. This may miss important information given that cognitive performance may vary according to the sport. Our sample of athletes who sustained a subsequent concussion was also small (n = 24, 17% of athletes). Therefore, we may not have had the power to detect associations between concussion history and subsequent concussion or cognitive performance and subsequent concussion. Lastly, given our select sample of athletes, findings of the current study may not generalize to athletes in other sports or competition levels.

We also used the first ever pre-season cognitive assessment on the VTS that was available for the athletes. Therefore, we did not have a measure of baseline cognitive functioning prior to an athlete's first concussion for athletes who sustained a concussion prior to pre-season cognitive testing. We attempted to conduct analyses in a sub-sample of athletes with no history of concussion at pre-season cognitive testing who sustained their first concussion in the study period. However, the sample size was too small.

Another limitation to consider is that history of concussion prior to 2018 was collected via a medical history interview with sports medicine personnel. Therefore, there is a chance that if an athlete did not receive a formal diagnosis with a concussion, they may be unsure if they sustained a concussion in the past during the interview. This may impact the reliability of

concussion history as a measure. That said, all concussions that occurred while the athlete was training at INS Québec were documented prospectively using standardized criteria.

Additionally, while injuries were prospectively documented, it is still possible that injuries were missed. Moreover, specific missing information (e.g., injury location) was occasionally obtained from electronic medical records. Nevertheless, there were no systematic missing pieces of prospective LEMSK injury data.

Clinical Implications

The VTS may be used as an alternative computerized neuropsychological test battery for measuring cognition in elite athletes. It extensively measures executive functioning and attention compared to other computerized cognitive measures such as ImPACT or CogState. Given its strong test-retest reliability, the *Determination Test*, a measure of cognitive flexibility, may especially be useful in understanding cognitive performance among elite athletes and how it may change over time with age and training.

The findings from this thesis also support the use of annual pre-season cognitive assessments since cognitive performance did change across seasons. When post-concussion cognitive testing is compared to pre-season cognitive performance, annual testing can provide a more accurate measure of how a concussion impacted an athlete's cognitive performance.

The proposed research also provides additional support of concussion history and cognition as potential risk factors for subsequent LEMSK injuries. The current research did not provide evidence that worse cognitive performance is associated with an increased risk of subsequent concussion. Therefore, preventing concussion history and improving cognitive performance may be targets of primary prevention strategies for LEMSK injuries. Preventing concussions and injuries should be prioritized in sports medicine research and health policies

since they are associated with future injuries (Abrahams et al., 2014; Fulton et al., 2014) and potential long-term consequences, such as depression or cognitive decline (Hallock et al., 2023; Kujala et al., 2003; McCrory et al., 2017). Even in the short-term, recently injured athletes have also been found to have lower quality of life compared to non-injured athletes (Houston et al., 2016). This underscores the importance of research exploring risk factors for concussion and LEMSK injuries.

Future Directions

Future research should explore the utility of the VTS in post-concussion cognitive testing. Given that it shows comparable test-retest reliability to other common computerized cognitive test batteries and includes measures of executive functioning and attention, the VTS may also have utility in the diagnosis and management of sport-related concussions.

Research should continue to explore mechanisms that underly the association between concussion history and subsequent LEMSK injury. While our study did not find a mediating effect of cognition on the relationship between concussion history and subsequent LEMSK injury, or concussion history and subsequent concussion, studies should continue to investigate this potential mediating effect in different athlete samples. Other mechanisms that can be explored include lingering effects of neuromuscular control (e.g., gait and postural control disparities) following a concussion. Lastly, studies should also control for factors that influence the risk of concussion and LEMSK injury independently from one another. This may include risk-taking behaviours or participation in sports or positions that put an athlete at a greater risk of both concussion and LEMSK injury. Future research should also continue exploring the associations between cognition, concussion, and LEMSK injury in under-represented sports.

Conclusion

Overall, this thesis provides evidence for the utility of the Vienna Test System in measuring cognitive performance among elite athletes. We also demonstrate that cognitive performance changes across sport seasons, with the most evidence in support of improvements in cognitive flexibility. We also determined that there were differences in cognitive performance according to history of concussion. Athletes with a history of concussion showed poorer performance on a test of inhibition and faster reaction time on measures of attention. This research also provided some evidence that cognitive performance is associated with an increased risk of subsequent LEMSK injury. There was an increased likelihood of sustaining an LESMK injury among athletes with slower reaction time on a working memory test. In contrast, no cognitive measures predicted subsequent concussion. Both of these findings aligned well with the literature as studies have reported that slower reaction time and working memory deficits were associated with an increased risk of injury, but no study has found an association between cognitive performance and subsequent concussion risk. We also replicated findings in the literature that concussion history is associated with an increased risk of subsequent LEMSK injury. However, we did not replicate the well-established association between concussion history and subsequent concussion, perhaps due to limitations in sample size. In mediation analyses, no cognitive measures mediated the relationships between concussion history and subsequent LEMSK injury or concussion history and subsequent concussion. Therefore, future research should continue exploring the mechanisms that underly the associations between concussion history and the risk of LEMSK injury and concussion.

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