Does concussion history affect softball pitch recognition, swing timing, and swing decision making in collegiate softball players?

Kim Uyeno, BASc in Kinesiology

Applied Health Sciences, Kinesiology

Submitted in partial fulfillment of the requirements for the degree of
Master of Science in Applied Health Sciences
(Kinesiology)

Faculty of Applied Health Sciences, Brock University
St. Catharines, Ontario

Abstract

Concussions can affect an athlete's cognitive and physical performance. The negative effects of concussion can linger beyond symptom resolution and can result in reduced sport performance and increased risk of injury upon return to play. The effect of concussion history, including time since concussion and number of concussions, on sport performance is not well understood. The purposes of this study were to examine the effects of concussion history on softball batting measures, such as pitch recognition, swing timing, and swing decision making, and to compare a computerized reaction time (RT) test to a sport-specific RT test. A cross-sectional study design was used to evaluate softball batting measures among collegiate softball players. Eighteen collegiate softball players from across Ontario were recruited to participate. Participants were divided into two groups: those with previous concussion (n = 7; mean age, 20.7 years; mean time since last concussion, 3.9 years) and those without (n = 11; mean age, 20.4 years). Pitch recognition, swing timing, and swing decision making were based on participants responses to pre-recorded pitching videos. Pitch recognition, swing timing, and swing decision making were similar between groups. There was not a significant correlation between the computerized RT and swing RT. These results suggest that collegiate softball players with less than three concussions perform similarly to those without concussion for softball cognition and swing timing when tested an average of 3.9 years post-concussion.

Acknowledgements

I want to first express my genuine gratitude to my supervisors, Dr. Gail Frost and Dr. Jae Patterson. I am very grateful for all of your guidance and support throughout my master's journey. This thesis would not have been possible without your dedication and encouragement. I am thankful to have had the opportunity to work with and learn from both of you.

Secondly, I want to thank my committee members, Dr. Michael Holmes and Dr. Nicole Chimera. Thank you, Mike, for allowing me to use your lab space and equipment to complete my data collection. I appreciate you taking the time to explain the necessary equipment and troubleshoot when needed. Thank you, Nicole, for stepping in and agreeing to be on my committee. I am grateful for your insight, as well as your patience and willingness to help.

Lastly, I want to thank my family and friends that have supported me along the way. A special thank you to my mom, dad, and sister for encouraging me to pursue my passions and for always supporting me in everything that I do.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

Concussion is a serious brain injury that affects millions of athletes each year (McCrory et al., 2017). Concussions cause a cascade of changes within the brain resulting in a variety of physical and cognitive symptoms (Churchill et al., 2019; Giza & Hovda, 2014; McCrory et al., 2017). While each concussion is unique, most symptoms resolve within 14 days of the injury in collegiate athletes (Asken et al., 2018; McCrory et al., 2017; Schranz et al., 2017). The recovery from concussion is usually tracked using a symptom evaluation as well as balance and cognitive assessments (McCrory et al., 2017). While this multidimensional approach is effective in the short-term, these tests may not be effective for identifying subtle neurological deficits beyond symptom resolution and return to play (RTP) (Chin et al., 2016; Echemendia et al., 2017; McCrory et al., 2017). This is evident as studies have found impairments in neurophysiological processes, reductions in postural control and neurocognition, and autonomic nervous system dysfunction beyond RTP through more complex tests (Broglio et al., 2007; Buttner et al., 2020; Howell et al., 2018; Senthinathan et al., 2017). This indicates that current tests may not be designed to identify impairments beyond the first few weeks of recovery, and that underlying impairments may affect sport performance when athletes RTP.

One integral skill that contributes to elite performance in most sports and is affected by concussion is reaction time (RT). The recovery of clinically assessed RT in athletes usually occurs within one month of the concussion (Caccese et al., 2020; Del Rossi, 2017; Eckner et al., 2011), however, it is possible that recovery of more complex RT, that is required for sport, may persist beyond that time frame. Current RT tests used to monitor concussion recovery are limited by their testing methods and application to sport (Lempke et al., 2020), meaning that they may not accurately determine when an athlete is safe and ready to RTP. This suggests the need for sport-specific RT tests to ensure that athletes are ready to RTP in order to protect them from another injury, but also to maximize sport performance.

Game performance has been studied in professional athletes following concussion, and one sport that is affected is baseball (Chow et al., 2019; Peterson et al., 2020; Ramkumar et al., 2018; Wasserman et al., 2015). Studies assessing game performance following concussion in professional baseball players found reduced batting statistics 15-30 days after RTP which continued in some players for the remainder of their career (Chow et al., 2019; Peterson et al., 2020; Ramkumar et al., 2018; Wasserman et al., 2015). Baseball and softball batting are sensitive to minor alterations in vision, RT, decision making, attention, coordination, and balance, all of which can be affected by a concussion (Buckley et al., 2019; Wasserman et al., 2015; Yamashiro et al., 2013). This increases the likelihood that baseball and softball players' batting performance will be affected following concussion and possibly beyond RTP. While studies have analyzed professional baseball statistics following concussion, there is a need to determine if softball batting is affected, what aspects of batting are affected, and how long they are affected. Since RT is an important aspect of batting and may be affected following concussion, batting provides an opportunity to measure sport-specific RT and compare results to current clinical tests.

The purposes of this study were to determine if softball batting was affected by a previous concussion, the relationship between time since concussion and softball batting, and to compare results from a clinical RT test to a sport-specific RT test.

2.0 Background

Concussion

Concussion is a form of traumatic brain injury affecting millions of athletes each year (McCrory et al., 2017; Mullally, 2017; Zuckerman et al., 2015). Concussion is caused by a blow to the head, neck, or body resulting in the acceleration-deceleration of the brain inside the skull (McCrory et al., 2017). The rapid forces applied to the brain cause stretching and tearing of the axons within the brain, resulting in inflammation, reduced cerebral blood flow, and altered axon function, energy metabolism, and neurotransmission (Churchill et al., 2019; Giza & Hovda, 2014; Mullally, 2017; Schranz et al., 2017). These neurophysiological changes within the brain result in the onset of signs and symptoms including headache, nausea, drowsiness, fatigue, lack of balance, sensitivity to noise, sensitivity to light, loss of consciousness, and impaired cognition (Giza & Hovda, 2014; McCrory et al., 2017; Mullally, 2017). Concussion symptoms usually have the greatest adverse effects within 24-72 hours and resolve within 2 weeks of the injury in collegiate athletes (Asken et al., 2018; McCrory et al., 2017; Schranz et al., 2017). Each concussion is unique, meaning that the symptoms experienced, severity of symptoms, and recovery trajectory may vary between concussions (McCrory et al., 2017). Symptom resolution and brain recovery are important prior to RTP as athletes who return prematurely are at a greater risk of prolonged symptoms, more severe symptoms, sustaining another concussion, and in severe cases, permanent damage or death (Asken et al., 2018; Guskiewicz et al., 2003; McCrea et al., 2020; McCrory et al., 2017).

Current Concussion Tests & Limitations

Concussions cannot be identified using standard clinical imaging techniques such as magnetic resonance imaging (MRI) or computed tomography (CT), meaning that currently the most effective concussion evaluation involves symptom inventories, as well as balance and cognitive assessments (McCrory et al., 2017). The Sport Concussion Assessment Tool version 5 (SCAT5) is the recommended concussion assessment tool and can be used both as a sideline evaluation and to track concussion recovery (McCrory et al., 2017). The SCAT5 includes the Maddocks questions and Standardized Assessment of Concussion to assess cognitive function, the Modified Balance Error Scoring System test (mBESS) and tandem gait to assess postural control, and a symptom evaluation (McCrory et al., 2017). Similar tests and symptom inventories are used to track the recovery from concussion and determine when an athlete is safe to RTP (McCrory et al., 2017).

While these tests provide the most accurate assessment of concussion when used in combination, each has its own limitations. Symptom inventories are limited by an athlete's willingness to honestly report their symptoms and the discrepancy between clinical and physiological recovery. Symptom tracking is a subjective measure that relies on athletes being truthful about their symptoms and can be confounded by baseline symptoms (Asken et al., 2017). Athletes may also overlook or downplay symptoms in order to RTP sooner, complicating the recovery tracking process and reducing the accuracy of the symptom evaluation for determining recovery. In addition, decisions around recovery are complicated by the fact that there is a mismatch between clinical and physiological recovery, in which brain healing outlasts symptom resolution (Churchill et al., 2018; Churchill et al., 2019; Kamins et al., 2017; Schranz et al., 2017). Despite athletes no longer experiencing symptoms, some neurophysiological processes remain impaired weeks to months beyond the point of clinical recovery (Churchill et al., 2018; Churchill et al., 2019; Kamins et al., 2017; Schranz et al., 2017). While concussion is not recognizable using standard MRI, newer techniques, such as diffusion tensor imaging (DTI) have identified changes to the microstructures and physiological processes within the brain following concussion (Churchill et al., 2018; Churchill et al., 2019; Meier et al., 2016; Wu et al., 2020). These neurophysiological changes have been identified in athletes acutely following concussion and beyond the resolution of symptoms (Churchill et al., 2018; Churchill et al., 2019; Meier et al., 2016; Schranz et al., 2017; Wu et al., 2020). In addition, there is growing evidence showing that some of these neurological deficits can persist for up to one year following concussion, and in the absence of positive findings on current clinical concussion tests (Churchill et al., 2018; Churchill et al., 2019; Meier et al., 2016; Schranz et al., 2017; Wu et al., 2020). While the implications of these impaired neurological processes are not well understood, these results highlight the fact that the resolution of symptoms may not equate to full brain recovery and athletes may still be affected by concussion beyond symptom resolution and RTP.

While current clinical concussion assessments (balance and cognitive assessments) are effective for identifying concussion in athletes acutely following the injury, their diagnostic utility decreases 3-5 days post-injury and with the resolution of symptoms (Chin et al., 2016; Echemendia et al., 2017; McCrory et al., 2017). In conjunction with the idea that symptoms usually resolve within 14 days of the injury, there is no clinical test to identify neurological deficits beyond symptom resolution.

While the neurophysiological deficits associated with concussion may not translate to functional deficits beyond symptom resolution, current tests may not be equipped to identify lingering effects of concussion.

Current clinical concussion assessments may lack the sensitivity necessary to identify these neurological impairments because of the test designs, the environment in which they are delivered, and the impairments themselves. Collegiate athletes are highly trained in balance, muscular strength, and coordination, and therefore clinical concussion tests may not be challenging enough physically to identify deficits in this population (Hanninen et al., 2021; Martini & Broglio, 2018). Current postural assessments are single-task tests meaning that the athletes are instructed to focus on a single motor task, such as balancing or walking. However, dual-task tests where athletes are instructed to complete a motor task and cognitive task simultaneously may more effectively identify deficits beyond symptom resolution (Buttner et al., 2020; Howell et al., 2018; Parker et al., 2006). These cognitive-motor dual-task tests not only identify performance decrements in concussed individuals up to two months following concussion, but they also better reflect the demands of sport (Buttner et al., 2020; Howell et al., 2018; Martini & Broglio, 2018). Sport utilizes both cognition and motor performance simultaneously, and therefore dual-task tests may determine if an athlete is recovered and ready to return to their sport more accurately than single-task tests (Buttner et al., 2020; Howell et al., 2018). In addition, the environment in which the cognitive assessments are completed is not representative of the sport environment. The cognitive assessments are usually completed in a quiet room, free of distractions, and at a self-selected pace. However, the sport environment includes loud crowds, pressure from coaches and teammates, an unpredictable opponent, and is fast paced. Various factors including physical exertion prior to testing, time of season, motivation level, and instructions provided can influence the results on the cognitive tests and also differ between testing and sporting environments (Alsalaheen et al., 2016). The disparity between testing and sporting environments limits the ability to determine if the athlete will be able to handle the cognitive load of their sport and may not accurately determine if an athlete is ready to RTP (Alsalaheen et al., 2016; Buttner et al., 2020; Parker et al., 2006). It is also possible that the cognitive tests are not challenging enough to identify cognitive impairments in this population or have become too familiar to these athletes (Hanninen et al., 2021; Ozen & Fernandes, 2012). With repeated exposures through yearly baseline testing and following concussion, athletes may become experienced and a ceiling effect may decrease the effectiveness of these tests (Hanninen et al., 2021). This is evident when more complex and novel cognitive tasks are able to identify cognitive deficits following concussion that were not found through standard concussion cognitive assessments (Ozen & Fernandes, 2012). In addition, collegiate athletes have been reported to purposefully score lower on baseline cognitive assessments in order to RTP faster following a concussion (Alsalaheen et al., 2016; McCrea et al., 2020). This makes it difficult for clinicians to identify impairments following concussion using an athlete's baseline data. Lastly, these neurological impairments are minor, complex, and resolve at different rates (Churchill et al., 2019; Henry et al., 2016; Meier et al., 2016), making it difficult to design tests that accurately assess various brain functions and identify small deficits following concussion. To complicate testing further, there are high levels of variability for balance and cognition between and within healthy collegiate athletes from one day to the next (Hanninen et al., 2016; Henry et al., 2016; McCrea et al., 2020). This highlights the complexity of concussion and concussion testing, and the need for more research in this field.

Prolonged Effects of Concussion

While the implications of the neurophysiological deficits following concussion are unclear, studies have provided evidence of the effects of concussion extending beyond the resolution of symptoms and RTP (Abaji et al., 2016; Broglio et al., 2007; Buttner et al., 2020; Fino, 2016; Howell et al., 2018; Iverson et al., 2006; Martini et al., 2011; Parker et al., 2006; Powers et al., 2013; Senthinathan et al., 2017). Studies evaluating gait and postural control, more specifically dual-task gait performance, provide evidence of athletes walking slower, having greater medial-lateral displacement, double support time, and a more conservative gait pattern up to 2 months following concussion (Buttner et al., 2020; Fino, 2016; Howell et al., 2018; Martini et al., 2011; Parker et al., 2006; Powers et al., 2013). In addition, these deficits in postural control may persist for up to 6 years post-concussion in university students with a history of 2 or more concussions (Martini et al., 2011). Athletes also have an increased risk of sustaining a lower extremity musculoskeletal (MSK) injury up to 1 year following concussion, which may be explained by the reduced postural control (Lynall et al., 2015). There is also evidence to support a prolonged recovery of neurocognition (Henry et al., 2016), as 37-38% of high school and collegiate athletes continued to have at least one neurocognitive impairment beyond the resolution of symptoms (Broglio et al., 2007; Iverson et al., 2006). The areas of delayed recovery included verbal memory, visual memory, visual-motor speed, and reaction time (RT), with RT being the most frequent impairment

(Broglio et al., 2007; Henry et al., 2016; Iverson et al., 2006). Another area that is affected by concussion beyond RTP is the autonomic nervous system (ANS) (Abaji et al., 2016; Senthinathan et al., 2017). Studies have identified ANS disruption both 1 week following RTP and 3 months post-injury in athletes with concussion through altered heart rate variability (Abaji et al., 2016; Senthinathan et al., 2017). These studies indicate that concussion can have prolonged effects lasting beyond symptom resolution and RTP, meaning that concussion deficits may go unnoticed on currently used concussion tests. More research is needed to determine how these deficits may affect sport performance.

Concussion & Reaction Time

One area of cognitive function that is affected following concussion is RT (Broglio et al., 2007; Caccese et al., 2020; Churchill et al., 2020; Del Rossi, 2017; Eckner et al., 2014; Eckner et al., 2011; Henry et al., 2016; Howell et al., 2018; Iverson et al., 2006; McCrory et al., 2017; Vartiainen et al., 2016). RT represents the time between a stimulus and response to that stimulus and is commonly measured using computerized neurocognitive tests following concussion (Alsalaheen et al., 2016; McCrory et al., 2017). These neurocognitive tests involve sitting at a computer, in a quiet room, responding to words, colours, and shapes appearing on the screen, while the computer measures response speed and accuracy. The results from the neurocognitive tests are usually compared to baseline values measured prior to the season, to monitor recovery and assist in RTP decision making (Alsalaheen et al., 2016; McCrory et al., 2017). Studies using computerized neurocognitive tests suggest that athletes experience slowed RT from 36 hours to 6 days following concussion, with RT being 215 ms slower than baseline values 72 hours post-concussion (Broglio et al., 2007; Churchill et al., 2020;

Eckner et al., 2011; Henry et al., 2016; Howell et al., 2018; Vartiainen et al., 2016). RT appears to be the slowest around 48-72 hours post-concussion, and then continues to improve in the weeks following (Broglio et al., 2007; Eckner et al., 2011; Henry et al., 2016; Iverson et al., 2006). However, studies measuring RT following a mild traumatic brain injury (mTBI), have provided evidence of impaired RT at 1 year and 3.5 years after the injury compared to controls (Danna-Dos-Santos et al., 2018; Dean & Sterr, 2013). In addition, one study demonstrated that concussion history may influence RT, as rugby players with three or more concussions displayed reduced visual motor speed and processing speed compared to rugby players of the same age without previous concussion (Gardner et al., 2010). Based on the results from the computerized tests, RT appears to recover with the resolution of symptoms, however, there may be individual cases of extended recovery following concussion and with an increased number of previous concussions.

In contrast, studies have also measured RT following concussion using a clinical RT test, which involves catching a falling rod. This RT test is usually completed in a seated position where the participant reacts to the drop of a weighted rod by catching it with one hand as fast as possible. The distance between the hand and the bottom of the rod is then used to calculate RT. These studies have found RT to be 18 ms, 15 ms, 26 ms, 17.9 ms, and 8.5 ms slower than baseline values at 6 hours, 24-48 hours, 3 days, 7 days, and 10 days post-concussion, respectively (Caccese et al., 2020; Del Rossi, 2017; Eckner et al., 2014; Eckner et al., 2011). These studies also found RT to be recovered to baseline values at 14 days post-concussion and with the resolution of symptoms (Caccese et al., 2020; Del Rossi, 2017). These studies show slowed RT as early as 6 hours post-concussion, slowest RT at 3 days post-concussion and recovery around 14 days or with the resolution of symptoms.

While the results between the two types of RT tests are similar, the differences in results may be due to a variety of reasons including the test difficulty, motivation/feedback, and score type. The computerized tests may result in a longer recovery of RT following concussion because they involve simple, choice, and Stroop RT tests, making the tests more difficult than the clinical RT test, which is only a simple RT test. The computerized tests involve making decisions around whether or not to respond and then making the correct response, whereas the clinical test only involves one response, catching the rod. The increased difficulty with the computerized tests may better identify subtle impairments later in the recovery process because the tests are more difficult meaning that they require more cognitive resources (Ozen & Fernandes, 2012). In addition, the clinical test for RT provides athletes with feedback on their performance and may inherently increase motivation to improve with each attempt (Caccese et al., 2020; Del Rossi, 2017). This may result in improved performance with an increasing number of attempts, whereas the computerized tests do not provide feedback and may be less susceptible to improvements because of increased motivation rather than recovery. The scores provided from each of these tests also differ, as the clinical test provides a raw score, while the computerized tests provide a composite score that combines the results from multiple tests (Del Rossi, 2017). This may also explain some of the differences in RT scores between testing methods because the computerized results are a combination of scores from tasks of varying difficulty, rather than just the simple RT test. This highlights some of the differences between current clinical and computerized RT tests despite both being valid and sensitive measures for RT acutely following concussion.

In addition to the differences between the tests mentioned above, both tests are limited in their application to sport performance. Current tests may not accurately determine if an athlete is ready to return to their sport because of various factors including the testing environment, motivation level, limb involvement, movement pattern, single-task nature, and visual field (Arpante et al., 2014; Lempke et al., 2020; Lempke et al., 2021; Vartiainen et al., 2016). Both clinical and computerized RT tests are completed individually, in a quiet room, and free of distractions. This differs dramatically from the sport environment as many sports involve collaborating with teammates and coaches, loud noises, and distractions, such as fans (Lempke et al., 2020). In addition, athletes may lack motivation and psychological excitement that is involved in sport, when completing RT tasks in a laboratory or clinic. Team sports also involve responding to an unpredictable opponent and sometimes unpredictable playing conditions, whereas the RT tests have pre-determined responses (i.e., catch the falling rod). In addition, the movements and limbs involved in the RT tests are minimal compared to what is required in sport (Lempke et al., 2020; Vartiainen et al., 2016). Sport involves whole-body movements in response to stimuli, while the RT tests only require movement of one upper limb for the clinical test and one hand for the computerized test (Lempke et al., 2020; Vartiainen et al., 2016). Studies have found that computerized and clinical RT tests are either minimally or not correlated with functional RT tests, such as jump landing and unanticipated cutting (Johnson et al., 2019; Lempke et al., 2020; Vartiainen et al., 2016). This means that current tests may not accurately assess functional abilities necessary for sport performance, and impairments in whole-body RT may be missed upon RTP. Current RT tests also differ from sport in their ability to test cognitive-motor dual-task performance that is necessary for sport (Lempke et al., 2020; Lempke et al., 2021). Current RT tests involve either a cognitive task or motor task, whereas sports involve both cognition and motor function simultaneously. The use of dual-task RT tests has been supported as dual-task tests better identify subtle deficits in RT following concussion (Lempke et al., 2020; Lempke et al., 2021; Vartiainen et al., 2016). The last difference between sport and RT tests is the visual field (Arpante et al., 2014). The visual field for the RT tests is small compared to the visual field seen in sports, which can also limit the application of these tests to sport performance (Arpante et al., 2014). The study by Arpante et al. (2014) showed that larger visual fields that require more visuomotor function may better differentiate between athletes with and without previous concussion. All of these limitations indicate that current RT tests may not assess the functional abilities necessary for sport and therefore, may not accurately determine whether an athlete is ready to return to their sport. It is possible that the recovery of sport-specific RT may be prolonged, which may contribute to the increased risk of MSK injury for one year following concussion and may reduce sport performance. This highlights the need for more sport-specific RT tests that will challenge athletes both physically and cognitively, simultaneously.

Sport Performance Post-Concussion

Concussion has the greatest effect on motor and cognitive function during the symptomatic period, however, it is possible that concussions can continue to impact athletes beyond the resolution of symptoms and RTP clearance (Asken et al., 2018;

Howell et al., 2018; Iverson et al., 2006; Martini et al., 2011; McCrory et al., 2017; Parker et al., 2006; Schranz et al., 2017). Sport performance following concussion has been studied in professional soccer, hockey, basketball, baseball, and football players, and the results vary depending on the sport (Buckley et al., 2019; Chow et al., 2019; Hardy et al., 2017; Kuhn et al., 2016; Kumar et al., 2014; Peterson et al., 2020; Ramkumar et al., 2018; Wasserman et al., 2015; Yengo-Kahn et al., 2016). There were no differences in game performance measures following concussion in professional hockey, basketball, or football players, however performance decrements were noted in professional soccer and baseball players (Buckley et al., 2019; Chow et al., 2019; Hardy et al., 2017; Kuhn et al., 2016; Kumar et al., 2014; Peterson et al., 2020; Ramkumar et al., 2018; Wasserman et al., 2015; Yengo-Kahn et al., 2016). All of these studies included professional athletes, however the differences in results may be explained by the performance measures chosen and the susceptibility of each sport to the subtle effects of concussion. Some studies included performance measures that are more indicative of individual performance, while other studies included measures that are strongly influenced by the performance of teammates and opponents (Buckley et al., 2019; Chow et al., 2019; Hardy et al., 2017; Kuhn et al., 2016; Kumar et al., 2014; Peterson et al., 2020; Ramkumar et al., 2018; Wasserman et al., 2015; Yengo-Kahn et al., 2016). Using measures that are influenced by external variables, such as teammates, can increase the likelihood of concussion deficits being masked and sub-optimal performances going unnoticed (Buckley et al., 2019). In addition, each sport requires unique cognitive demands and motor qualities, meaning that certain sports may challenge postural control and cognitive resources more than others. Performance in certain sports may be less sensitive to changes in neurocognitive function and may allow athletes to compensate for their deficits without affecting overall sport performance.

In contrast, baseball batting is highly individual with performance being very sensitive to changes in vision, RT, decision making, attention, balance, and coordination (Buckley et al., 2019; Yamashiro et al., 2013). Studies assessing major league baseball (MLB) players' batting performance following concussion found decreased batting averages, on-base percentages, slugging percentages, and stolen bases (Chow et al., 2019; Peterson et al., 2020; Ramkumar et al., 2018; Wasserman et al., 2015). In addition, swing rate increased, plate discipline declined, and the probability of remaining in the league at 1, 3, and 5 years was lower in MLB players following concussion (Chow et al., 2019; Ramkumar et al., 2018). The duration of these reduced batting statistics varies across studies. Most studies noted the decreased statistics at 15-30 days following RTP, however some studies found these performance decrements lasting up to one year, and even for the rest of their career (Chow et al., 2019; Peterson et al., 2020; Ramkumar et al., 2018; Wasserman et al., 2015). These studies indicate that batting performance is affected following concussion, suggesting that batting may be sensitive to changes associated with concussion and deficits may persist beyond RTP clearance. However, there is limited research assessing the cause of the reduced batting statistics following concussion and whether softball batting performance is affected beyond RTP.

Softball & Concussion

Softball is considered to be a limited-contact sport, however, the sport does involve balls travelling at high velocities, bats, and collisions with teammates, opponents, and playing boundaries (Cusimano & Zhu, 2017). Injuries to the head and neck account for about 11% of all injuries in collegiate and professional softball players (Patel et al., 2021; Wasserman et al., 2019), with up to 40% of those head and neck injuries being concussion and closed head injuries (Strickland et al., 2019; Wasserman et al., 2019). Based on the injury occurrence from softball from 2013 to 2017 in the US, it is estimated that there are 46,056 concussions and closed head injuries annually, with the majority being in collegiate softball players (Strickland et al., 2019). Although the rates of concussion from softball are relatively low compared to other contact sports, there are still concussions that arise from participation in collegiate softball. The most common mechanism of concussion among softball players is being struck by the ball, either up to bat or in the field, followed by colliding with other players and colliding with the ground or other fixed objects (Cusimano & Zhu, 2017; Strickland et al., 2019).

Softball Batting

Hitting a softball or baseball has been described as being one of the most difficult tasks in sport because of the limited amount of time to respond, precision necessary to hit the ball, and challenge of battling against nine opponents to get a hit (Washington & Oliver, 2018). In softball, the pitching rubber from which pitchers start their wind-up is 43 ft or 13.1 m from home plate. The pitching mound is flat, and pitchers use a backwards windmill arm rotation to deliver the ball. Pitchers stride forward towards home plate while completing the arm circle to deliver the pitch. Collegiate pitchers stride an average distance of 5 ft before releasing the pitch at speeds of 58 to 70 mph, depending on the pitch type (Werner et al., 2006). This results in collegiate batters having about 400 milliseconds to respond to the incoming pitch. In this time, batters must identify the location and type of the pitch, determine if they should swing, and then execute the swing at the correct time and location to make contact with the ball. In addition, pitchers use a combination of different pitch types and speeds to confuse the batter, making hitting even more difficult. This highlights the difficulty of hitting a softball and emphasizes the need for optimal vision, RT, attention, anticipation, and coordination.

Pitch Recognition

One important aspect of successful batting is being able to recognize the incoming pitch. This includes identifying the pitch type (e.g., fastball, change-up, curve, screw, drop, or riseball), speed, and location out of the pitcher's hand, and anticipating whether the pitch will be a ball or strike early enough to have time to swing. Pitch identification is important for batting performance because it dictates the decision to swing and is necessary for making adjustments to the timing and location of the swing (Morris-Binelli et al., 2018). Pitch prediction accuracy rate among professional baseball hitters is around 50%, 55%, 60%, and 70% with occlusion at pitch release, 80 ms after pitch release, 200 ms after pitch release, and with no occlusion, respectively (Morris-Binelli et al., 2018). In contrast, high school baseball players have a pitch prediction accuracy rate around 45% for identifying pitch type and 63% for identifying strike/ball when the pitch is occluded 150 ms after release (Gray, 2017). This shows that pitch recognition (PR) can vary depending on the competition level and age, and that even without a concussion, identifying pitches can be a difficult task.

The relationship between PR and batting statistics has been identified in professional batters, such that there were positive correlations between pitch prediction accuracy and slugging percentage, on-base percentage, and walk-to-strikeout ratio, and a negative correlation between pitch prediction accuracy and strikeouts (Morris-Binelli et al., 2018). This indicates that those who had greater PR accuracy, got more bases with each hit, were on base more, and had more walks and less strikeouts than their counterparts. It is possible that concussions can negatively affect a batter's ability to recognize pitches which may result in reduced batting performance. PR has not been studied in softball players following concussion and will be used in this study as a method for assessing sport-specific cognitive function following concussion.

2.1 Study Purposes

The purposes of this study were to examine the effects of concussion history on softball batting measures, such as pitch recognition, swing timing, and swing decision making, and to compare results from a computerized RT test to a sport-specific RT test.

2.2 Hypotheses

It was hypothesized that softball players with a previous concussion would have less accurate pitch recognition, impaired swing decision making, and slower swing timing than the softball players without a previous concussion. It was also hypothesized that concussion history would have a negative relationship with pitch recognition and a positive relationship with swing timing measures. Computerized RT tests would not correlate with sport-specific RT tests.

3.0 Methods

3.1 Study Design

This study used a cross-sectional design to evaluate softball batting measures among university and college softball players with and without a history of concussion and compared results from a sport-specific RT test to a computerized RT test.

3.2 Ethical Considerations

This study was reviewed and received ethics clearance through the Research Ethics Board at Brock University (21-061).

3.3 Participants

Participants included current university and college softball players 18 years or older from across Ontario. Participants were excluded if they had a restriction or injury that affected batting or were recovering from a concussion at the time of the study. Participants were divided into two groups based on their self-reported concussion history: those with a previous concussion (CONC) and those without concussion (NC). Participants self-reported if they had been diagnosed with a concussion by a physician, as well as the number of diagnosed concussions, and length of recovery and date of latest concussion in those with previous concussion. Potential participants were required to provide written informed consent prior to participating in the study.

Based on data from the literature and assuming a medium effect size (0.50), power = 0.95, and $\alpha = 0.05$, this study would require 105 participants per group, for a total sample size of 210 participants for the independent t-test analyses. In contrast, assuming a coefficient of determination (r^2) = 0.56, power = 0.95, and $\alpha = 0.05$, this study would require a total sample size of 16 for the Pearson's Correlation analyses.

3.4 Recruitment

Potential participants were recruited through email, social media, and word of mouth. A recruitment email (Appendix C) was sent to university and college softball coaches in the area (using email addresses available on the internet) asking them to forward it on to their players. Posts were made on the PI's Facebook and Instagram accounts (Appendix D) and word of mouth included talking to any players that were interested in the study.

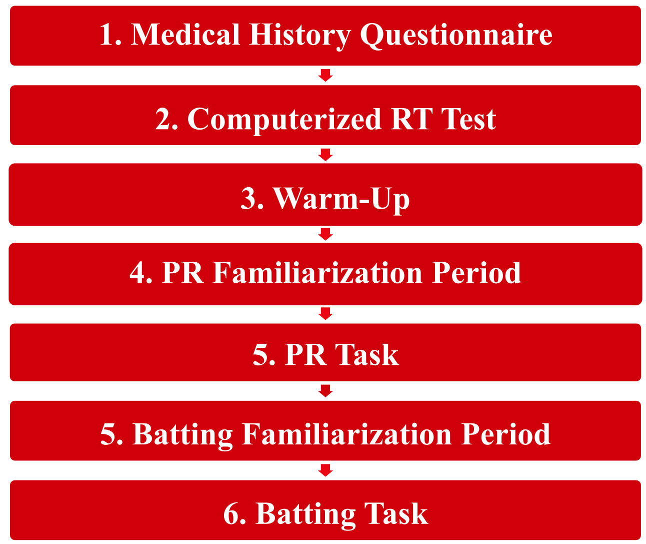
3.5 Study Procedure

Participants completed the Medical History Questionnaire (Appendix B) prior to their study visit. The Medical History Questionnaire included questions about participants' softball experience, concussion history, and medical history. The data collected from the questionnaire was used to characterize the participants, separate the participants into the two groups, and assist in identifying any relationships between concussion history and batting measures.

Participants completed the following testing in a laboratory in the order shown in Figure 1. Participants completed the computerized RT test, their own warmup, underwent the first familiarization period, pitch recognition task, second familiarization period, and finished with the batting task.

Figure 1

Study Procedure Order



Computerized Reaction Time Test

The computerized RT test was delivered using a computer program and included simple, choice, and go/no-go RT tests. The tests consisted of visual stimuli delivered through a computer screen, to which participants responded by pressing a button on a keyboard. For the simple RT test, participants pressed the '0' key as quickly as possible when the 'X' appeared on the screen. For the choice RT test, participants pressed the '1' key when an 'X' appeared and pressed the '2' key when a 'Y' appeared on the screen. For the go/no-go RT test, participants pressed the '1' key when an 'X' appeared and did not press a key when 'Y' appeared. For both the choice and go/no-go RT tests, participants were instructed to respond as quickly and accurately as possible. Each RT test consisted of 40 trials with a variable fore period between the fixation and the stimulus. Participants completed the computerized RT test independently, in a quiet room, and free of distractions.

Warm-Up

Participants were given as much time as they needed to feel sufficiently warmed up prior to the familiarization period and were instructed to complete a warm-up of their choice.

First Familiarization Period (Pitch Recognition)

The PR task was in response to pre-recorded videos of a collegiate pitcher throwing a variety of pitches. The familiarization period allowed participants to become comfortable with the videos (i.e., angle, viewpoint, and speed of the pitches) and practice identifying the type, location, and outcome of each pitch. The PR familiarization period consisted of three rounds of 10 pitches each, with all pitches coming from a single pitcher. The first round of videos showed the full pitch, while the videos in the second round were occluded around 220 ms after pitch release, and the videos in the third round were occluded around 150 ms after pitch release. The pitching videos used during the familiarization period were the same level of difficulty as the videos used for testing but came from a different pitcher. During the familiarization period, participants received feedback about the accuracy of their responses and pitches were shown in an order that was random to the participants.

Pitch Recognition Task

Participants stood in their batting stance at a distance of 4.35 m from the screen to receive each pitch and identified the type, location, and outcome of each pitch. Participants verbally provided the researcher with their responses for each pitch and were instructed to identify each pitch as quickly and accurately as possible. The testing order was identical to the familiarization period, in that the first round of pitching videos showed the full pitch (Round 1), second round of pitches were occluded at 220 ms after release (Round 2), and third round of pitches were occluded at 150 ms after release (Round 3). Each round consisted of 10 pitches each, for a total of 30 with one pitcher, and was expected to become more difficult with each round. The three rounds were then repeated in the same order with an additional pitcher, for a total of 60 pitches. Both pitchers included in this task were collegiate level pitchers and pitches were shown in a sequence that was random to the participants.

Second Familiarization Period (Batting Task)

The second familiarization period gave participants the opportunity to practice the batting task and become comfortable with swinging in response to the pitching videos. This period consisted of one round of 10 pitches, with 5 pitches each from 2 pitchers that participants were not familiar with yet (i.e., had not seen in the pitch recognition task), but were included in the batting task.

Batting Task

The batting task involved participants watching pitching videos and responding accordingly, by swinging at strikes and not swinging at balls (pitches outside the strike zone). Participants saw 40 full pitches (10 per pitcher) in a random order, including fastballs, change-ups, drop, rise, curve, and screw balls. The pitching videos used were from collegiate level pitchers and included three right-handed pitchers and one left-handed pitcher. Participants were instructed to time their swing to hit the ball as they normally would in a game and to only swing when they thought the pitch was within the strike zone. Participants were instructed to treat the simulation as a game and were given time to reset between pitches. Pitches for this section were shown in an order that was random to participants. Participants completed the batting section using their own bat, stood on the same side of the plate as they would in a game, and stood at a distance of 4.35 m from the screen.

3.6 Study Equipment/Technology

The computerized RT test was completed using the E-prime 2.0 software (Sharpsburg, PA) and computer keyboard.

The pitching videos were delivered through the GameSense Sports software (Denver, CO). This software includes videos of collegiate pitchers throwing live pitches and are recorded from both the left and right batter's viewpoints. The videos are recorded with a focus on the pitcher and ball flight into the catcher's glove, with no other fielders in view. The videos are then occluded (black video frame is applied) at designated time points after release based on important windows in which hitters must decide to swing or adjust their swing. The software has varying levels of difficulty based on ball flight time after release, with less time being more difficult. The videos are recorded at 30 frames per second and displayed at a resolution of 720 pixels. The videos were projected onto a screen (2.95 m x 1.72 m) in a laboratory to create a game-like experience.

Two Vicon Vue (Denver, CO) cameras were used to record video of the batting task with a sampling rate of 120 frames per second. One camera was positioned behind the batter with the pitcher in view to record the release of the pitch. The second camera was positioned facing the batter from the view of the opposing batter's box to capture the swing. The cameras were synchronized to record at the same time. Vicon Video Viewer was used to analyze and gather the outcome variables from each swing.

3.7 Measures

3.7.1 Participant Characteristics

Participants' age, height, hours slept the night prior, concussion history, and other medical history pertaining to the brain were recorded. Concussion history included questions about whether the participant had been diagnosed with a concussion by a medical professional, how many concussions they had been diagnosed with, date of the most recent concussion, and length of recovery from the latest concussion.

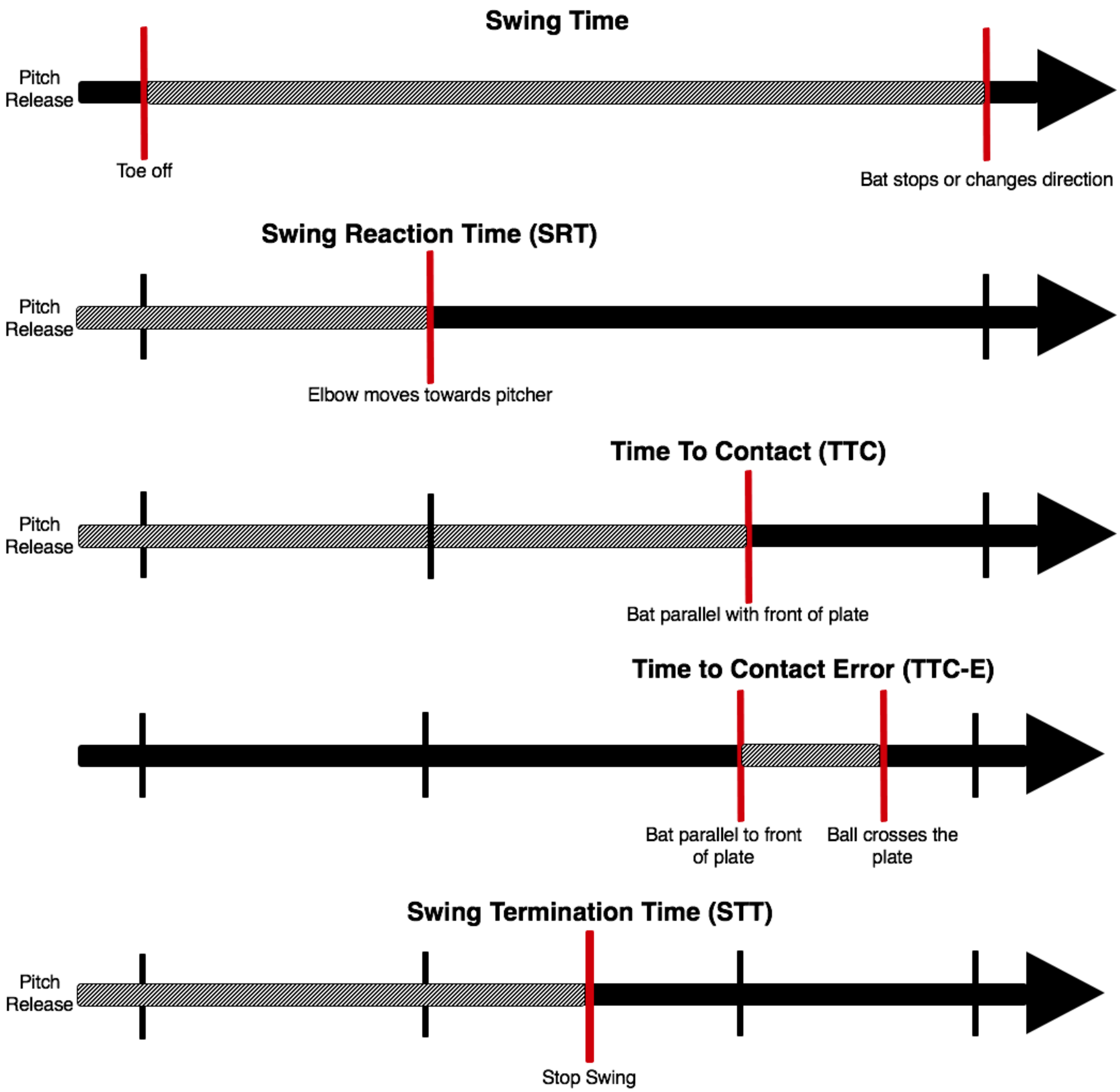
3.7.2 Outcomes

The computerized RT test assessed simple, choice, and go/no-go RT by measuring the time between the presence of the visual stimulus (on the computer screen) and the participant's response (button pressed). To reduce the effects of delayed button pressing due to not realizing the test had started or outside distractions, all outliers outside three standard deviations from the mean of the remaining points for each subject were removed. A total of 30 trials (1.4% of total trials) were removed. The remaining correct trials were used to calculate the average RT score for each test (i.e., simple, choice, go/no-go), in addition, the accuracy of responses (only choice and go/no-go RT test) was recorded for each participant.

Batting measures included swing time (SWT), swing RT (SRT), time to contact (TTC), time to contact error (TTC-E), swing termination time (STT), swing choice accuracy, and PR accuracy. SWT, SRT, TTC, and TTC-E were calculated using the videos from the participants' full swings and the mean of the swings was used for analysis (Figure 2). SWT represented the time to complete each swing and was measured from the start of the swing (lifting of the front foot) (Gray, 2009) to the completion of each swing (bat either stopped or changed direction). SRT was the difference in time between the release of the ball from the pitcher's hand to the downward and forward movement of the participant's front elbow towards the incoming pitch. TTC was the time from the release of the pitch from the pitcher's hand to the point when the bat was in line with the front of the plate. TTC-E assessed the amount of error (in milliseconds) in the participant's swing timing by determining the difference in time between when the pitch and bat crossed the plate. TTC-E was the difference in time between when the participant's bat was in line with the front of the plate and when the pitch crossed the front of the plate. The time that the pitch crossed the front of the plate was determined from visual inspection of the pitching videos for each pitch. This was determined to be the first frame in which the pitch was hovering over the front of the plate. The absolute TTC-E values were used to calculate the mean.

Figure 2

Swing Timing Measures



The videos recorded during the batting task were also used to measure STT. STT was the duration of time for participants to stop their swing, when they chose not to swing. STT was calculated as the time between the release of the pitch and the moment the participant stopped their swing (i.e., the moment that their bat or front elbow stopped progressing forward).

Swing choice accuracy assessed the batter's ability to accurately make the decision to swing or not based on each pitch. Swing choice correct was calculated as the total number of times the batter correctly swung at a strike and correctly refrained from swinging at a ball. Swing choice correct was out of a possible 40. Swing choice correct was also separated into swing correct (total correct swings at strikes), and no-swing correct (total correct no-swings at balls). Swing choice error was calculated as the total number of times the batter incorrectly swung at a pitch that was not a strike.

PR accuracy assessed the ability to recognize the pitch type, pitch location, and outcome of each pitch. The possible pitch types included fastball, screwball, curveball, drop ball, rise ball, and change-up. Pitch location was broken down into 4 zones, shown in a chart (Figure 3) displayed below the screen. The chart contained a 2 x 2 grid with a number (1-4) in each square, as follows for a right-handed batter: (1) inside high, (2) outside high, (3) inside low, (4) outside low. Pitch outcomes included either ball or strike. The strike zone was based on Softball Canada's designated strike zone, which included any pitch that crossed the plate between the height of the batter's knees and sternum. One point was given for each correct identification of pitch type, location, and outcome for a total of 3 points per pitch. The total number of correct responses for pitch type, location, and outcome were calculated separately out of a possible score of 60 for each. PR scores were also calculated for each round (i.e., Round 1, Round 2, and Round 3) out of a possible score of 60. PR accuracy was calculated as the total number of correct responses from 60 pitches out of a total possible score of 180.

Figure 3

Pitch Location Chart

1	**2**
3	**4**

3.8 Data Collection

Participant information was collected using a Medical History Questionnaire. Data from the computerized RT test was collected using the E-prime software (Sharpsburg, PA), while data from the batting task was collected from the video recordings of each swing. The time-related variables were determined from the videos, while swing choice accuracy was determined manually by recording the swing response (swing or no swing) and the outcome of each pitch (ball or strike). Data from the pitch recognition task was recorded manually for each pitch.

3.9 Data Management

Informed consent documents were kept in a locked cabinet in the FS's office (WC 283), separate from all of the data collected from the study. Data from the computerized RT tests were downloaded in an Excel file format and stored on the PI's password-protected computer. The videos recorded as part of this study were saved on password-protected computers. The data collected from the videos and PR task was saved on the FS and PI's password-protected computer. The videos and data will be kept on the FS's computer for up to five years after publication in a scholarly journal.

3.10 Statistical Analyses

Independent t-tests were used to determine if there was a difference between the CONC group and NC group for RT, PR, and batting measures. Pearson's Correlation was used to determine if there were any significant relationships between time since concussion, and recovery time, and RT, PR, and batting measures. The relationship between number of concussions and RT, PR, and batting measures was assessed through 95% confidence intervals (CI). Pearson's Correlation was calculated to determine the relationship between the computerized RT and SRT results. Pearson's Correlation was also used to determine if there was a relationship between hours slept and each of the RT tests. An alpha level of 0.05 was used as the cut-off for statistical significance and analyses were completed using IBM SPSS Statistics version 26.

COVID-19 Considerations

The conduction of this study was affected by the COVID-19 global pandemic and the associated provincial and federal restrictions. Due to COVID-19 restrictions, data collection was delayed and had to be paused once due to increased restrictions. The presence of COVID-19 also made participant recruitment difficult, as some potential participants were not comfortable visiting the laboratory, potential participants were not on-campus due to online learning, and some teams experienced COVID-19 outbreaks.

4.0 Results

4.1 Participant Characteristics

Eighteen collegiate softball players participated in this study, 7 with at least one self-reported physician-diagnosed concussion, and 11 self-reported never being diagnosed with concussion. The participants' characteristics are listed in Table 1. None of the participants reported being diagnosed with post-concussion syndrome. Both groups were similar for age (p = .73), height (p = .50), years played (p = .22), and hours slept (p = .92).

Table 1

Participant Characteristics

Characteristic	No Concussion (*n* = 11)	Concussion History (*n* = 7)
Age (years)	20.4 ± 1.7	20.7 ± 1.2
Height (cm)	168.6 ± 7.6	166.2 ± 6.2
Glasses/Contacts, *n*	6 Yes; 5 No	3 Yes; 4 No
Years Played	11.4 ± 4.3	13.7 ± 3.0
Hours Slept	7.4 ± 1.7	7.3 ± 1.5
Medical History, *n*	1- Epilepsy, seizures, neurological disorder 1-Attention deficit/ hyperactivity disorder	1- Attention deficit/ hyperactivity disorder
Number of concussions, *n* (%)	0	One- 5 (71.4%) Two- 2 (28.6%)
Time since concussion (months)	N/A	46.6 ± 16.3
Recovery time for last concussion (weeks)	N/A	12.1 ± 13.1
Loss of Consciousness, n	N/A	3 Yes; 4 No

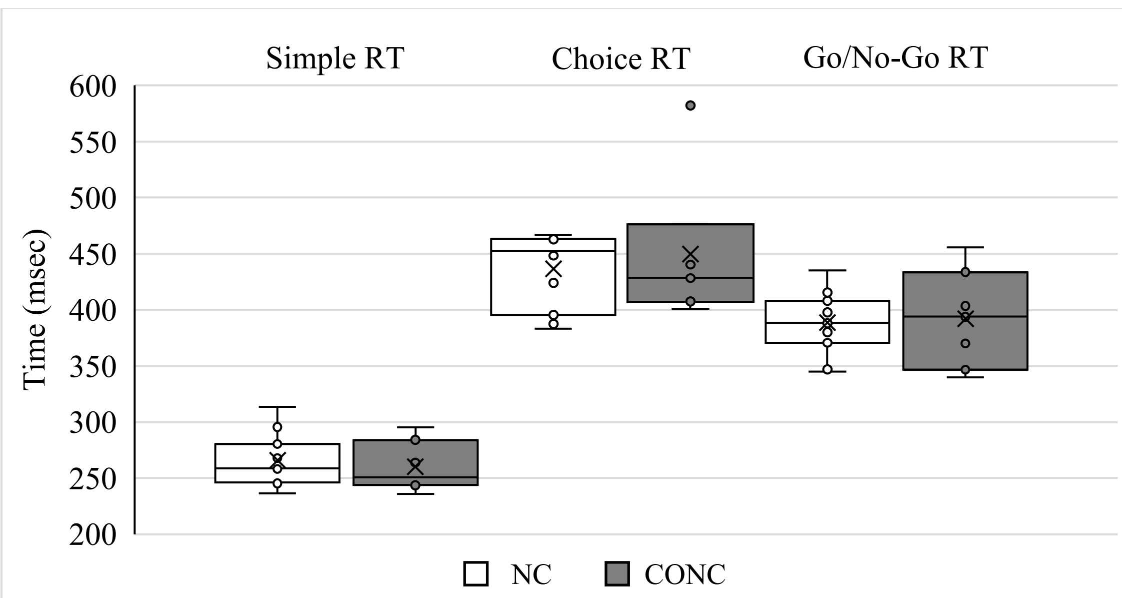
Note. Data are expressed as mean ± standard deviation unless otherwise stated. N/A, Not applicable.

4.2 Computerized Reaction Time

The results from the computerized RT tests were similar between groups for the simple, $t(16) = 0.50$, $p = .62$, d = 0.24, β = .92, choice, $t(16) = -0.59$, $p = .56$, $d = 0.28$, $\beta = .91$, and go/no-go, $t(16) = -0.20$, $p = .84$, $d = 0.10$, $\beta = .95$, tests (Figure 4). The mean RTs for the NC group were 265.8 ± 23.2 ms, 436.6 ± 33.0 ms, and 388.5 ± 27.4 ms, for the simple, choice, and go/no-go RT tests, respectively. The mean RTs for the CONC group were 260.2 ± 21.9 ms, 449.9 ± 63.6 ms, and 391.8 ± 43.1 ms for the simple, choice, and go/no-go RT tests, respectively. The mean number of errors on the RT tests were 1.9 ± 1.1 for the NC group and 2.6 ± 1.5 for the CONC group, which was not significantly different between groups, $t(16) = 0.30$, $p = .30$. The relationship between hours slept and simple, $r(16) = 0.11$, $p = .66$, choice, $r(16) = 0.183$, $p = .47$, and go/no-go, $r(16) = -0.04$, $p = .89$, RT tests was not statistically significant.

Figure 4

Computerized Reaction Time Test Results



Note. Boxplot displaying the results from the simple, choice, and go/no-go computerized reaction time tests. Individual participant's mean reaction times are plotted as dots. The horizontal line inside the box represents the median value, the 'X' represents the group mean, box widths represent first (25%) and third (75%) quartiles, and whiskers represent the maximum and minimum.

4.3 Pitch Recognition

The PR scores and accuracy for the NC and CONC groups are shown in Table 2 and Figure 5. There were no significant differences for pitch type, $t(16) = -0.56$, $p = .58$, $d = 0.27$, $\beta = .92$, outcome, $t(16) = -0.47$, $p = .65$, $d = 0.23$, $\beta = .93$, location, $t(16) = 0.24$, $p = .81$, $d = 0.12$, $\beta = .94$,or total correct, $t(16) = -0.43$, $p = .67$, $d = 0.21$, $\beta = .93$, between groups. The PR scores for the NC group were 32.7 ± 5.3, 33.3 ± 5.1, and 25.9 ± 2.9 for Rounds 1, 2, and 3, respectively. The PR scores for the CONC group were 33.4 ± 3.8, 31.9 ± 5.2, and 27.0 ± 5.5 for Rounds 1, 2, and 3, respectively (Figure 6). There were no significant differences between groups for Round 1, $t(16) = -0.30$, $p = .77$, $d = 0.15$, $\beta = .94$, Round 2, $t(16) = 0.57$, $p = .57$, $d = 0.27$, $\beta = .92$, or Round 3, $t(16) = -0.55$, $p = .59$, $d = 0.25$, $\beta = .92$.

Table 2

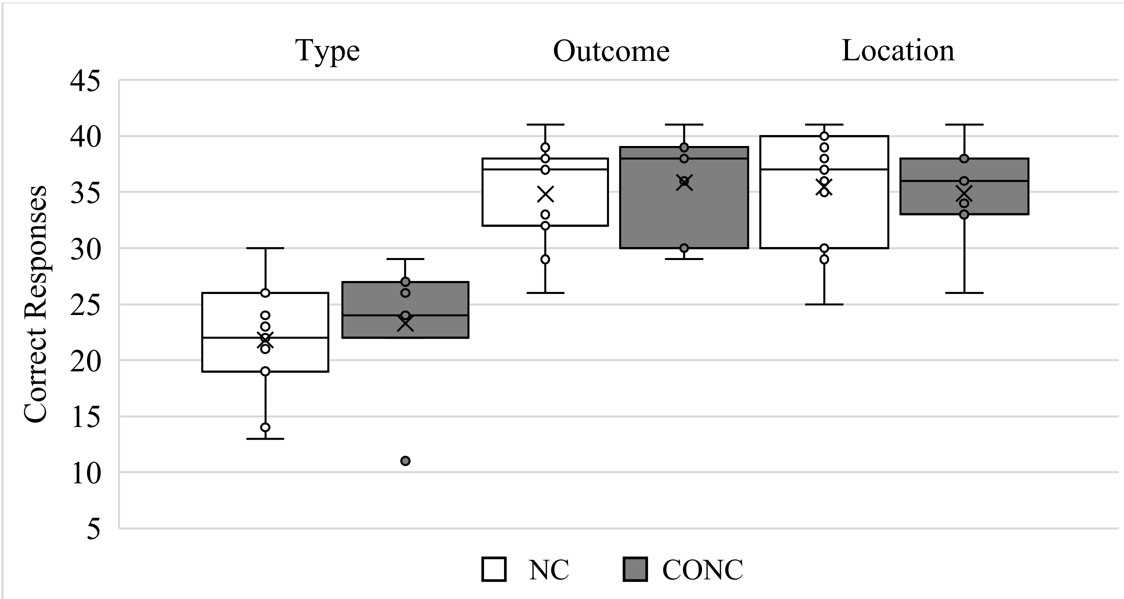
Pitch Recognition Scores

Group	Type	Outcome	Location	Total
No Concussion	21.8 ± 5.1	34.8 ± 4.6	35.4 ± 5.2	92.1 ± 9.4
Concussion History	23.3 ± 5.9	35.9 ± 4.6	34.9 ± 4.7	94.0 ± 8.8

Note. Data are expressed as mean ± standard deviation.

Figure 5

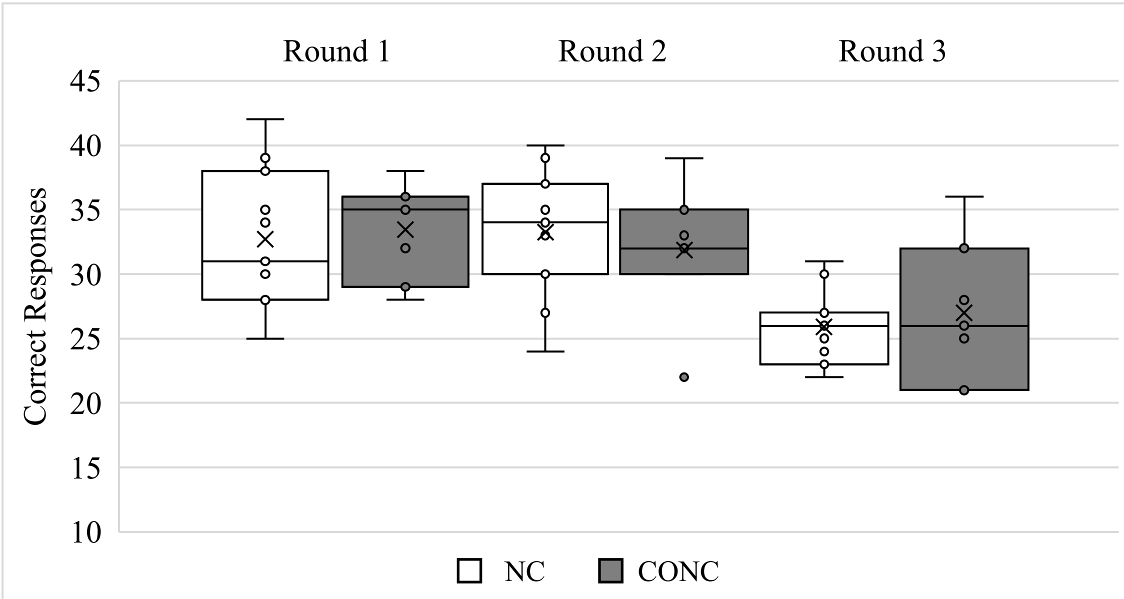
Pitch Recognition Accuracy by Category



Note. Boxplot displaying the pitch recognition results for pitch type, outcome, and location. Individual participant's mean number of correct responses are plotted as dots. The horizontal line inside the box represents the median value, the 'X' represents the group mean, box widths represent first (25%) and third (75%) quartiles, and whiskers represent the maximum and minimum.

Figure 6

Pitch Recognition Accuracy by Round



Note. Boxplot displaying the pitch recognition results for Rounds 1, 2, and 3. Individual participant's mean number of correct responses are plotted as dots. The horizontal line inside the box represents the median value, the 'X' represents the group mean, box widths represent first (25%) and third (75%) quartiles, and whiskers represent the maximum and minimum.

4.4 Swing Measures

Swing Choice Accuracy

The means for swing choice correct and swing choice error for both groups are shown in Table 3. There were no significant differences between groups for swing choice correct, $t(16) = -0.02$, $p = .98$, $d = 0.01$, $\beta = .95$, or swing choice error, $t(16) = 0.59$, $p = .56$, $d = 0.28$, $\beta = .91$. Swing choice accuracy is shown as a percentage in Figure 7.

Table 3

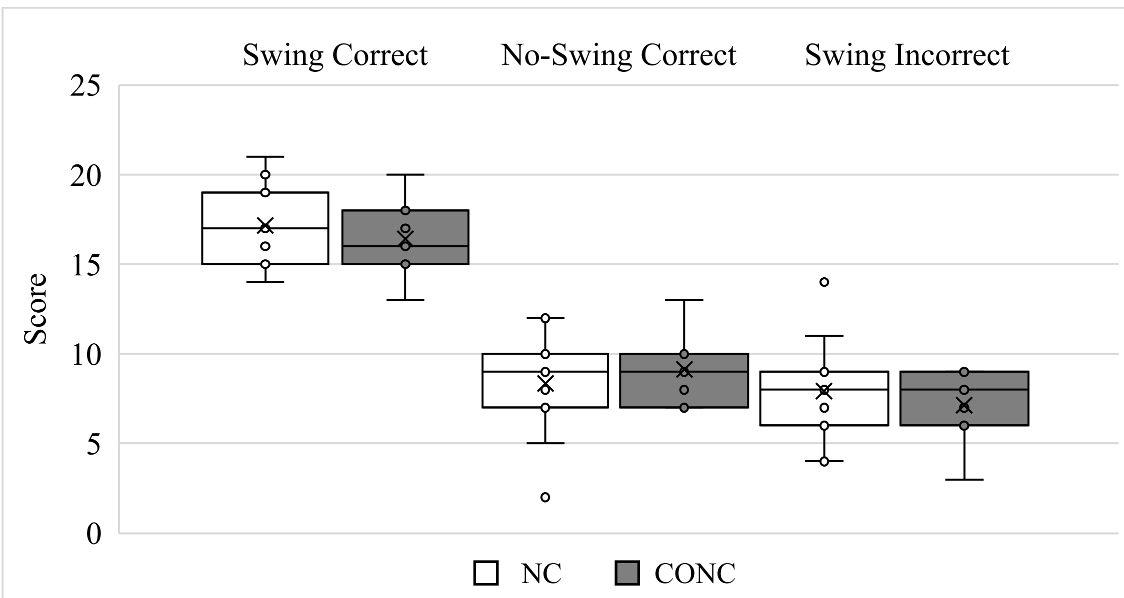
Swing Choice Accuracy Scores

Group	Swing Correct	No-Swing Correct	Total Correct	Swing Choice Error
No Concussion	17.2 ± 2.3	8.4 ± 3.0	25.5 ± 2.7	7.9 ± 3.0
Concussion History	16.4 ± 2.2	9.1 ± 2.1	25.6 ± 2.8	7.1 ± 2.1

Note. Data are expressed as mean ± standard deviation. Total Correct represents swing choice correct.

Figure 7

Swing Choice Accuracy Results



Note. Boxplot displaying the swing choice accuracy results, including swing correct, no-swing correct, and swing incorrect. Individual participant's mean scores are plotted as dots. The horizontal line inside the box represents the median value, the 'X' represents the group mean, box widths represent first (25%) and third (75%) quartiles, and whiskers represent the maximum and minimum.

Swing Timing

Swing timing measures are shown in Table 4. There were no significant differences between groups for SWT, $t(16) = 1.62$, $p = .12$, $d = 0.78$, $\beta = .67$, SRT, $t(16) = -0.29$, $p = .78$, $d = 0.14$, $\beta = .94$, TTC, $t(16) = 0.70$, $p = .49$, $d = 0.33$, $\beta = .90$, TTC-E, $t(16) = 0.97$, $p = .34$, $d = 0.47$, $\beta = .85$, or STT, $t(16) = 0.79$, $p = .44$, $d = 0.39$, $\beta = .88$. SRT, TTC, TTC-E, and STT are shown in Figure 8.

Table 4

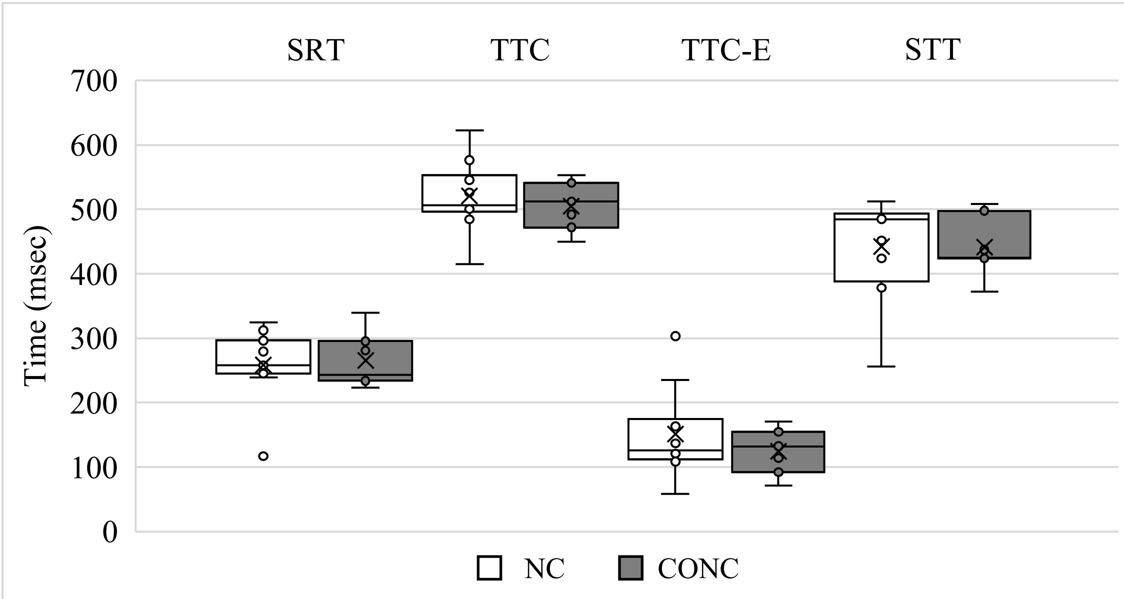
Swing Timing Results

Group	SWT (sec)	SRT (msec)	TTC (msec)	TTC-E (msec)	STT (msec)
No Concussion	1.1 ± 0.2	258.5 ± 54.5	521.0 ± 54.0	151.2 ± 67.4	442.1 ± 76.6
Concussion History	1.0 ± 0.2	265.5 ± 41.6	504.7 ± 36.8	124.2 ± 34.6	441.3 ± 47.0

Note. Data are expressed as mean ± standard deviation. SWT, swing time; SRT, swing reaction time; TTC, time to contact; TTC-E, time to contact error; STT, swing termination time.

Figure 8

Swing Timing Results



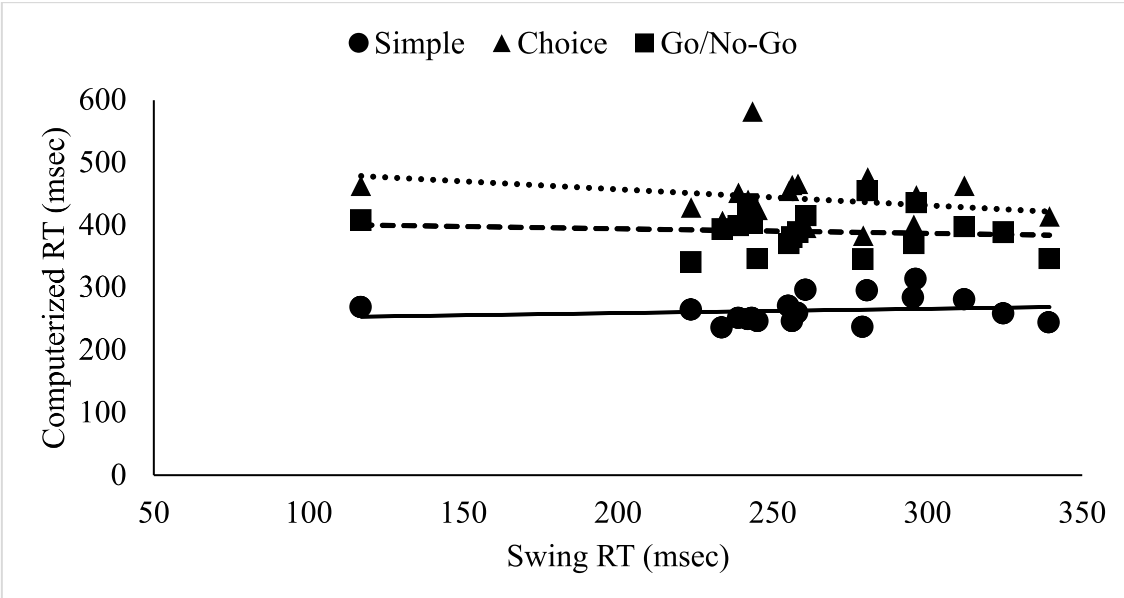
Note. Boxplot displaying the swing timing results from the batting task. Individual participant's mean times are plotted as dots. The horizontal line inside the box represents the median value, the 'X' represents the group mean, box widths represent first (25%) and third (75%) quartiles, and whiskers represent the maximum and minimum. SRT, swing reaction time; TTC, time to contact; TTC-E, time to contact error; STT, swing termination time.

4.5 Relationship Between Computerized RT and SRT

The mean simple RT, choice RT, go/no-go RT, and SRT for the groups combined were as follows: 263.6 ± 22.3, 441.8 ± 46.0, 389.8 ± 33.1, and 261.2 ± 48.7 (Figure 9). The relationships between batting RT and simple, $r(16) = .15$, $p = .55$, choice, $r(16) = -.27$, $p = .28$, and go/no-go, $r(16) = -.11$, $p = .67$ RT were not significant.

Figure 9

Computerized RT and SRT



Note. Scatterplot showing the correlations between swing reaction time and computerized reaction time (simple, choice, and go/no-go). The solid black line represents the line of best fit between the simple and swing reaction time data points. The dotted line represents the line of best fit between choice and swing reaction time data points. The dashed line represents the line of best fit between go/no-go and swing reaction time data points.

4.6 Relationships Between Variables

Concussion

There were no significant correlations between time since concussion and any of the RT, PR, or batting measures. There was one significant correlation between recovery time and swing incorrect, $r(5) = -.79$, $p = .03$. The 95% CI for number of concussions and RT, PR, and batting are shown in Table 5.

Table 5

Results for One and Two Concussions

	One Concussion (n = 5) 95% CI	Two Concussions (n = 2) 95% CI
Simple RT	(228.4, 286.4)	(55.6, 479.1)
Choice RT	(399.5, 467.0)	(-660.6, 1643.6)
Go/No-Go RT	(330.3, 457.6)	(174.8, 598.6)
Incorrect Responses RT	(1.0, 3.8)	(-22.4, 28.4)
Correct Pitch Type	(14.5, 32.3)	(10.3, 35.7)
Correct Pitch Outcome	(31.6, 42.0)	(-23.7, 90.7)
Correct Pitch Location	(32.4, 40.4)	(-32.5, 94.5)
PR Total Correct	(87.8, 105.5)	(-20.5, 195.5)
Swing Correct	(15.3, 19.5)	(1.3, 26.7)
No-Swing Correct	(6.3, 12.5)	(2.2, 14.9)
Swing Incorrect	(3.8, 10.2)	(1.2, 13.9)
Swing Time	(0.7, 1.2)	(0.6, 1.4)
Swing RT	(0.2, 0.3)	(-0.1, 0.6)
TTC	(0.5, 0.6)	(0.2, 0.8)
TTC-E	(0.1, 0.2)	(-0.2, 0.4)
STT	(0.4, 0.5)	(0.0, 0.9)

Note. This table shows the 95% confidence intervals for the participants with one previous concussion and two previous concussions.

Overall

There were the following statistically significant correlations when the groups were collapsed: choice RT and correct pitch location, $r(16) = -0.72$, $p = .001$, choice RT and PR total correct, $r(16) = -.58$, $p = .01$, go/no-go RT and correct pitch type, $r(16) = .48$, $p = .04$, SRT and TTC, $r(16) = .65$, $p = .003$, and SRT and TTC-E, $r(16) = .60$, $p = .008$.

5.0 Discussion

The purposes of this study were to identify the effects of concussion history on RT and specific softball batting measures in collegiate softball players, and to compare a sport-specific RT test to a clinical RT test. Overall, computerized RT, softball cognition, and softball swing timing were similar between those with concussion history and those without, when tested an average of 3.9 years post-concussion. This suggests that PR, swing timing, swing decision making, and RT are not affected by a previous concussion in collegiate softball players with a history of less than three concussions, and when tested approximately 3.9 years post-concussion. In addition, the computerized RT measures were not significantly correlated with SRT, which was a sport-specific, whole-body RT measure. This indicates that current clinical RT tests may not assess sport-specific RT and therefore, may not assess an athlete's readiness to return to their sport.

Reaction Time (RT)

The results of this study showed no statistical difference for any of the computerized RT measures between collegiate softball players with and without a history of concussion. This study used computerized RT tests similar to those used clinically for concussion detection and tracking (McCrory et al., 2017), and included collegiate softball players who self-reported a maximum of two concussions. Results from the present experiment support previous studies involving athletes from various sports, non-athletes, and those with four or more concussions that suggested no differences in clinical RT between those with a history of concussion and those without (Broglio et al., 2006; Caffey & Dalecki, 2021; Collie et al., 2006; Hume et al., 2017; Martini et al., 2017). Additionally, these studies found no difference in clinical RT performance between those reporting zero, one, two, three, or four or more previous concussions, indicating that number of previous concussions may not affect clinical RT (Broglio et al., 2006; Caffey & Dalecki, 2021; Collie et al., 2006; Hume et al., 2017). The findings from this study are consistent with the literature as there was no correlation between the computerized RT measures and time since concussion (Caffey & Dalecki, 2021). Caffey and Dalecki (2021) found no correlation between Stroop performance and time since first concussion or time since last concussion. The results from this study also extend previous findings to recovery time from last concussion, as there was also no correlation between computerized RT measures and recovery time.

The similarity between those with a history of concussion and those without for RT measures is not surprising as studies have found that clinical RT usually returns to baseline within one month of the injury in athletes (Cacese et al., 2020; Del Rossi, 2017; Henry et al., 2016). While recovery of clinical RT and symptom resolution usually occur acutely following concussion (Cacese et al., 2020; Del Rossi, 2017; Henry et al., 2016), studies including the use of advanced imaging techniques, such as functional magnetic resonance imaging (fMRI), have shown that physiological recovery outlasts clinical recovery (Churchill et al., 2018; Meier et al., 2016; Schranz et al., 2017; Wu et al., 2020). More specifically, studies have found alterations in brain metabolism, activation patterns, blood flow, and white matter following concussion that remains beyond the time of RTP, with some lasting up to one year after RTP (Churchill et al., 2018; Churchill et al., 2019; Dettwiler et al., 2014; Meier et al., 2016; Schranz et al., 2017; Wu et al., 2020). In addition, studies using advanced imaging methods, found no correlation between the imaging testing and cognitive tests, such as Sport Concussion Assessment Tool version 3

(SCAT3), Standard Assessment of Concussion, and Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) (Schranz et al., 2017; Wu et al., 2020). These findings suggest that clinical RT tests are likely not identifying minor neurological alterations associated with concussion beyond the symptomatic phase. The most recent concussion reported in this study was 2.4 years ago, meaning that the lack of differences between groups on the computerized RT tests in this study are likely due to the participants being recovered.

Consistent with other studies comparing clinical RT to functional RT, there was not a significant correlation between the computerized RT measures and SRT (Arpante et al., 2014; Johnson et al., 2019; Vartiainen et al., 2016). Results from the present study support previous studies suggesting that clinical RT tests may not accurately assess if an athlete is ready to RTP (Arpante et al., 2014; Johnson et al., 2019; Lempke et al., 2020; Vartianen et al., 2016). The present study expanded on previous studies as a clinical RT test was compared to a sport-specific RT test, which was dual-task in nature and mimicked sport demands. Participants had to decide whether or not to swing, then generate the motor program required to swing at the correct time. In addition, SRT involved a whole-body, coordinated response rather than just the press of a button. These features are important when testing RT in athletes following concussion, as studies have found that tests that are dual task in nature and involve larger visual fields and whole-body movements may better identify those with concussion compared to clinical tests (Arpante et al., 2014; Howell et al., 2018; Johnson et al., 2019; Lempke et al., 2020; Vartianinen et al., 2016). In addition, tests that involve these components better reflect sport performance, which may better assess athlete readiness than clinical RT tests

(Arpante et al., 2014; Johnson et al., 2019; Lempke et al., 2020; Vartianinen et al., 2016). The results from the present study suggest that clinical RT tests may not accurately assess an athlete's ability to safely and effectively perform in their sport upon RTP. Clinicians should consider including sport-specific tests that will assess an athlete's ability to safely perform in their sport in their RTP testing.

Pitch Recognition (PR)

To our knowledge, this is the first study to assess PR in softball players with and without a history of concussion. PR is the ability to identify incoming pitches based on cues from the pitcher as well as the rotation or movement of the ball and is necessary when making decisions about whether or not to swing. PR measured sport-specific cognition by indirectly testing concentration, attention, memory, and vision concurrently using a softball task. There were no differences in correct pitch type, pitch location, pitch outcome, or total correct between groups, suggesting that softball batting cognition was not affected by a previous concussion. This could mean that following concussion, softball players are able to return to the level of those without concussion sometime within approximately 3.9 years of the injury, or that they rely on their experience to achieve similar levels of PR as those without concussion. The reason for the similarity in PR between groups in this study is likely due to the participants in the CONC group being recovered, as the PR task was a fairly novel task to these players and showed no difference across varying levels of difficulty between groups. While recognizing pitch speed, type, and location is crucial to having success at the plate, PR is not a skill that is traditionally practiced in isolation and is done with automaticity when batting. Asking participants to state the pitch type, location, and outcome of each pitch was not something they were familiar with doing and it was with pitchers they had never seen before. Both increased the likelihood of finding possible differences between groups, due to the novelty of the PR task (Hanninen et al., 2021). In addition, the three rounds of PR increased in difficulty, increasing the likelihood of identifying any differences between groups. Studies have noted that tasks that require more cognitive resources better identify differences between those with a history of concussion and those without (Ozen & Fernandes, 2012; Vartiainen et al., 2016). The rounds were progressively more difficult as the videos were occluded earlier, however, there were no differences between groups for any of the rounds. This suggests that while both groups were challenged cognitively, the participants with concussion history were able to perform to the level of those without concussion. Although accurate pitch identification is required for skilled performance, the PR task presented as a novel and difficult task that likely would have identified differences in the softball players with a history of concussion if any were present.

In comparison to studies measuring PR accuracy in NCAA Division I softball players, the participants in this study performed worse for pitch type, but similarly for pitch outcome and location (DeCouto et al., 2019; Roberts, 2020). Decouto et al. (2019) reported an accuracy rate of 58% for pitch type and 59% for pitch location and outcome combined. Roberts (2020) reported an accuracy rate of 55% for pitch type and 58% for pitch outcome. When collapsed across groups, the PR accuracy rates for this study were 37.3%, 58.7%, and 58.7%, for pitch type, outcome, and location, respectively. The results from the present study extend the results from previous studies (DeCouto et al., 2019; Roberts, 2020) to those without concussion history and those with less than three concussions. The PR accuracy rate for pitch type in this study may have been lower than previously reported because both studies included Division I pitchers and hitters (DeCouto et al., 2019; Roberts, 2020), meaning that the hitters were familiar with the caliber of pitching and cues associated with certain pitch types. In contrast, many participants in this study had never seen certain pitch types before and therefore were not familiar with the trajectory or patterns of those pitches. The PR accuracy rates from this study were similar to elite softball players from other studies for pitch outcome and location (DeCouto et al., 2019; Roberts, 2020), indicating that those with concussion history also performed similarly to healthy elite softball players outside of this study.

Swing Measures

Swing choice accuracy evaluated sport-specific cognition by assessing each participant's ability to correctly swing at a strike and refrain from swinging at a ball. After gathering and analyzing information from the pitcher, batters need to decide very quickly whether or not to swing. The time constraint put on softball players to make that decision, makes it susceptible to declines following concussion. The accuracy of that decision can strongly influence the outcome of an at bat and success over a season, highlighting the reason for studying it in softball players with a previous concussion. Both groups in the present study showed similar results for correct swings, correct no-swings, and incorrect swings. These results are similar to a study that found increased overall swing rate (swinging at balls and strikes) 15-30 days after returning from concussion, but not for the remainder of the season, compared to pre-injury levels (Chow et al., 2019). These results are also consistent with studies that found similar values for walk percentages, strikeout percentages, and strikeouts in MLB players with concussion, compared to those who took a non-medical leave (Ramkumar et al., 2018; Wasserman et al., 2015). Wasserman et al. (2015) found no differences at 2 weeks or 4-6 weeks after returning to the lineup, while Ramkumar et al. (2018) found no differences between the season prior to and after the concussion. These studies including MLB players suggest that swing decision making is no longer affected beyond 30 days following concussion (Chow et al., 2019; Ramkumar et al., 2018; Wasserman et al., 2015). The results from the present study add to the literature, as no studies have directly assessed swing decision-making in softball players with and without concussion history. The results from the present study suggest that elite softball players with a previous concussion perform similarly to players without concussion for swing decision making at approximately 3.9 years post-concussion. The swing choice accuracy results are in line with the PR results from this study, as both suggest that collegiate softball players with a previous concussion perform similarly to those without concussion for softball cognition when assessed an average of 3.9 years post-concussion.

Within the concussion history group, there was a significant negative correlation between recovery time from last concussion and number of incorrect swings. This indicates that the longer the recovery was from the last concussion, the fewer times participants incorrectly swung at a pitch outside the strike zone. This is a novel finding as previous studies have not assessed the relationship between recovery time and swing decision making and suggests that softball players who took more time to recover from their last concussion were less likely to swing at a ball. This may indicate that players who take additional time to ensure full recovery prior to returning to game play following concussion, have better swing decision making than those who rush the RTP process.

This could translate into better pitch selection when up to bat in a game, and potentially better batting performance through more walks and better contact.

Following the decision to swing, batters must determine the speed of the pitch, timing necessary to make contact, and then swing accordingly to meet the ball. Any timing errors made throughout the swing process will likely result in a poor outcome, such as weak contact, no contact, a foul ball, or an out. Concussions may disrupt swing timing, due to slower processing speeds, delayed RT, poor concentration, or lack of coordination (McCrory et al., 2017). The results of the present study showed similar results between groups for SWT, SRT, TTC, TTC-E, and STT suggesting that concussion history did not affect swing timing. SRT, TTC, TTC-E, and STT addressed some of the limitations associated with current concussion tests, such as physical demands, limb involvement, motivation level, and application to sport. It is not surprising that SWT was not affected by a previous concussion as swing duration should be consistent and automatic. SWT does not involve any decisions, making it less susceptible to any effects of concussion. In contrast, SRT, TTC, TTC-E, and STT were measures that were susceptible to the residual effects of a previous concussion because they involved cognitive and motor skills that have been shown to be affected by concussion (McCrory et al., 2017). SRT was the time between the release of the pitch and when the front elbow started moving forward and downwards towards the pitcher. The start of the swing phase or when the elbow starts to come forward, is a critical part of the swing because it dictates the timing for the rest of the swing. Gray (2009) found that in male competitive baseball players, the bat started to move forward around 250 ms after pitch release. The results from this study extend that finding to collegiate softball players, as SRT was 258.5

ms in the NC group and 265.5 ms in the CONC group. SRT was measured through the batting task, which was more challenging than clinical RT tests because the participants were presented with more than one stimulus and the response involved a whole-body movement. Despite SRT being a more challenging test, there were no differences between groups, meaning that concussion history did not affect when the batters initiated the swing phase. This suggests that the participants with previous concussion perceived cues from the pitcher, made the decision to swing, and initiated the swing at a similar time to those without concussion.

TTC measured the duration between pitch release to the estimated point of contact. There were no differences between those with a history of concussion and those without for TTC, suggesting that those with previous concussion reached their contact point in a similar amount of time following pitch release as those without. While there were no differences between groups for TTC, the results from this study show longer TTCs than previous studies. Studies by Nasu et al. (2020) and Takamido et al. (2022) found TTC to be 444.9 ms and 480 ms, respectively. In contrast, the TTC in this study was 521.0 ms for the NC group and 504.7 ms in the CONC group. Additionally, Reilly-Boccia et al. (2015) found the time from swing onset to contact point in NCAA division I softball players to be 210 ms. When using Reilly-Boccia et al.'s (2015) definition, the time would be 262.5 ms for the NC group and 239.2 ms for the CONC group. The differences in results between the present study and previous findings could be due to the difference in environments and lack of feedback. In the present experiment, participants were asked to swing in response to pitching videos where they did not receive any tactile feedback in regards to ball contact. In contrast, in previous studies, participants batted in response to live pitching, which inherently provided the participants with feedback about the timing of their swing, allowing adjustments from pitch to pitch (Nasu et al., 2020; Reilly-Boccia et al., 2015; Takamido et al., 2022). While using a virtual batting task may have been more difficult than live batting, it allowed for the testing of temporal accuracy, through TTC-E. TTC-E measured the amount of error in seconds between the time the ball crossed the plate and when the bat crossed the plate. In the sport of softball, correct timing is crucial to a batter's success at the plate, meaning that TTC-E may have the potential to indicate a batter's in-game success. There were no differences between groups for TTC-E, suggesting that a previous concussion did not impact the temporal accuracy of the swing, when tested an average of 3.9 years post-concussion. This indicates that those with a previous concussion perceived the distance and speed of the incoming pitch and timed their swing to a similar accuracy level as those without a previous concussion. It should also be noted that both groups had an average TTC-E over 100 ms, which may have been due to the unfamiliarity of the virtual batting task and lack of tactile feedback.

STT evaluated the ability to inhibit a response and measured the duration of time between pitch release to response termination. Participants initiated a swing for every pitch, meaning that when they decided not to swing, they had to inhibit the swing response and terminate the swing (optimally before their bat crossed the plate). STT may be susceptible to the effects of concussion because it is measuring the time required to inhibit the swing and combines both cognition and motor control. However, there were no differences found between groups for STT, suggesting that the decision and movement involved to stop a swing was not impaired by a previous concussion when tested an average of 3.9 years post-concussion. This suggests that those with a previous concussion were able to make the decision and activate the necessary muscles to stop the swing at a similar time as those without concussion. The swing termination or inhibition response has been studied in baseball players with competitive playing experience (Gray, 2009). The results for STT from this study are faster than the results from the study by Gray (2009), who measured the time between onset of the swing phase to when the bat began moving backward as 212.3 ms (Gray, 2009). While STT in this study was 442.1 ms for the NC group and 441.3 for the CONC group, STT based on Gray's (2009) definition would be 183.6 for the NC group and 175.8 ms for the CONC group. The difference in results between studies is likely due to the fact that Gray's study (2009) divided the swings into four categories based on how far the swing progressed before the athlete decided not to swing. The result for STT from that study was based on swings that went beyond just starting their swing (bat began moving forward and downward) meaning that Gray's (2009) STT may have been made up of more complete swings than our study. Despite, no differences found between groups for STT, response termination or inhibition is an area that could be included in future concussion testing to assist with safe RTP.

Limitations

While the results from this study suggest that RT and batting measures are similar between those with a history of concussion and those without, this study used a cross-sectional study design, meaning that baseline values from before the participant's initial concussion were not recorded. Comparisons between pre- and post-concussion values cannot be made in the CONC group limiting our ability to know if the participants are actually recovered to pre-injury levels or just to the level of those without concussion. It is possible that the participants with concussion history may have had higher values than the NC group prior to sustaining a concussion and have not fully recovered, or the performance in the NC group may be below average for collegiate softball players, masking any impairments in the CONC group. However, results in the NC group were similar to those from other studies including elite softball and baseball players, meaning that the similarities found between groups were likely not due to lower scores in the NC group. In addition, all concussions reported were at least two years ago and the average number concussions in the CONC group was 1.3 concussions. The results of this study cannot be applied to those with more than two concussions or those who sustained a concussion more acutely. While there were no differences between groups for any of the variables measured, it is possible that some of the participants in the CONC group were still affected by a previous concussion in other areas, such as emotionally or cognitively, that were not measured in this study. This study was also limited by the fact that concussion history was based on self-reporting of concussions. Self-reporting may be subject to recall bias and may not accurately quantify the number of concussions that participants sustained. This may be due to athletes downplaying and underreporting concussion symptoms, preventing a concussion diagnosis, or the discrepancy between self-reported and physician-diagnosed concussions (Cunningham et al., 2021).

The quality of the pitching videos and the use of pitching videos instead of live pitching may have also affected the results. The pitching videos were recorded at 30 fps and were projected onto a screen potentially decreasing the clarity of the videos and possibly affecting the results. The pitching videos did not provide tactile feedback and participants may have had trouble gauging the depth of the pitch because of the nature of video rather than live pitching. This limited participants' ability to make adjustments to their swing based on the previous pitch and may have affected participant's swing timing. The results from this study are also limited in statistical power because of the limited number of participants and small effect size (Appendix H). The reported statistical power for all outcome variables between groups was low indicating a high probability of a type II error for all outcome variables compared between groups. This means that there may have been significant differences between those with a previous concussion and those without for RT, PR, swing decision-making or swing timing that went undetected due to the small sample size.

Future Directions

This study assessed softball cognition and swing timing in collegiate softball players, therefore, spatial accuracy of the swings was not assessed. More research is needed to determine if spatial accuracy in softball players is affected following concussion, as it is an important contributor to swing success. The participants in this study self-reported less than three concussions with the latest concussion being an average of 3.9 years ago. More research is needed to determine if any softball batting measures are affected in those with more than two concussions and those with a more recent concussion. Future studies should assess softball PR, swing timing, and swing decision-making more acutely following concussion to determine what measures are affected and how long it takes for them to recover. TTC-E may also be an important measure that is affected following concussion and allows for the tracking of recovery. TTC-E has the potential to identify effects of concussion because of the cognitive load and motor control required to accurately time a swing to hit the ball. TTC-E has not been studied previously as most studies have had batters swing in response to live pitching. However, if TTC-E is a measure that is sensitive to the effects of concussion more acutely, it may be a safe screening method for determining when an athlete is ready to RTP. Future research should assess TTC-E in a larger sample of softball players following concussion (Appendix H) and over time to determine its validity. In addition, more research is needed to expand these measures to other sports. Each sport has unique physical and cognitive demands, and athletes need to be tested in both those disciplines to ensure that they can handle the demands of their sport prior to returning to play. More studies are needed to determine what sport-specific skills are sensitive to the effects of concussion, as this will help with the RTP process as well as shaping future rehabilitation plans.

Conclusion

Collectively, the results from this study suggest that concussion history does not affect softball cognition or swing timing in collegiate softball players with less than three concussions, and when tested an average of 3.9 years post-concussion. The findings from the present study expand the literature for PR and swing timing results to collegiate softball players with a history of concussion, while adding results for swing decision making. SRT, a sport-specific measure of RT was not correlated to the computerized RT test results. This suggests that computerized RT tests may not accurately assess sport-specific RT involved in sport, limiting their ability to determine if an athlete is safe to RTP. Adding a sport-specific measure of RT may better inform RTP decisions and keep athletes safe. More research is needed to determine if softball batting is affected more acutely following concussion in collegiate softball players.

References

Abaji, J. P., Curnier, D., Moore, R. D., & Ellemberg, D. (2016). Persisting effects of concussion on heart rate variability during physical exertion. *Journal of Neurotrauma, 33*(9), 811-817.

Alsalaheen, B., Stockdale, K., Pechumer, D., & Broglio, S. P. (2016). Validity of the Immediate Post Concussion Assessment and Cognitive Testing (ImPACT). *Sports Medicine, 46*(10), 1487-1501.

Arpante, A. K., Smoliga, J. M., Giusto, C., Anh-Dung, N., & Ford, K. R. (2014). Impaired reaction time on large, not small, visual fields in athletes with history of concussion. *Medicine and Science in Sports and Exercise, 46*(5).

Asken, B. M., Bauer, R. M., Guskiewicz, K. M., McCrea, M. A., Schmidt, J. D., Giza, C. C., Snyder, A. R., Houck, Z. M., Kontos, A. P., McAllister, T. W., Broglio, S. P., & Clugston, J. R. (2018). Immediate removal from activity after sport-related concussion is associated with shorter clinical recovery and less severe symptoms in collegiate student-athletes. *The American Journal of Sports Medicine, 46*(6), 1465-1474.

Asken, B. M., Snyder, A. R., Clugston, J. R., Gaynor, L. S. Sullan, M. J., & Bauer, R. M. (2017). Concussion-like symptom reporting in non-concussed collegiate athletes. *Archives of Clinical Neuropsychology, 32*(8), 963-971.

Broglio, S. P., Ferrrara, M. S., Piland, S. G., & Anderson, R. B. (2006). Concussion history is not a predictor of computerised neurocognitive performance. *British Journal of Sports Medicine, 40*, 802-805.

Broglio, S. P., Macciocchi, S. N., & Ferrara, M. S. (2007). Neurocognitive performance of concussed athletes when symptom free. *Journal of Athletic Training, 42*(4), 504-508.

Buckley, T. A., Bryk, K. N., Van Pelt, K. L., Broglio, S. P., East, S. A. Zuckerman, S. L., & Kuhn, A. W. (2019). Concussion and National Hockey League player performance: An advanced hockey metric analysis. *Journal of Athletic Training, 54*(5), 527-533.

Buttner, F., Howell, D. R., Ardern, C. L., Doherty, C., Blake, C., Ryan, J., Catena, R., Chou, L. S., Fino, P., Rochefort, C., Sveistrup, H., Parker, T., & Delahunt, E. (2020). Concussed athletes walk slower than non-concussed athletes during cognitive-motor dual-task assessments but not during single-task assessments 2 months after sports concussion: A systematic review and meta-analysis using individual participant data. *British Journal of Sports Medicine, 54*(2), 94-101.

Caccese, J. B., Eckner, J. T., Franco-MacKendrick, L., Hazzard, J. B., Ni, M., Broglio, S. P., McAllister, T., McCrea, M., Pasquina, P. F., Buckley, T. A. (2020). Clinical reaction time after concussion: Change from baseline versus normative-based cutoff scores. *Journal of Athletic Training*. doi: 10.4085/JAT0457-20

Caffey, A. L., & Dalecki, M. (2021). Evidence of residual cognitive deficits in young adults with a concussion history from adolescence. *Brain Research, 1768*, 147570.

Chin, E. Y., Nelson, L. D., Barr, W. B., McCrory P., & McCrea, M. A. (2016). Reliability and validity of the Sport Concussion Assessment Tool-3 (SCAT3) in high school and collegiate athletes. *The American Journal of Sports Medicine, 44*(9), 2276-2285.

Chow, B. H., Stevenson, A. M., Burke, J. F., & Adelman, E. E. (2019). The effect of concussion on batting performance of major league baseball players. *Open Access Journal of Sports Medicine, 10*, 41-48.

Churchill, N. W., Caverzasi, E., Graham, S. J., Hutchison, M. G., & Schweizer, T. A. (2018). White matter during concussion recovery: Comparing diffusion tensor imaging (DTI) and neurite orientation dispersion and density imaging (NODDI). *Human Brain Mapping, 40*(6), 1908-1918.

Churchill, N. W., Hutchison, M. G., Graham, S. J., & Schweizer, T. A. (2019). Mapping brain recovery after concussion: From acute injury to 1 year after medical clearance. *Neurology, 93*(21), e1980-e1992.

Churchill, N. W., Hutchison, M. G., Graham, S. J., & Schweizer, T. A. (2020). Brain function associated with reaction time after sport-related concussion. *Brain Imaging and Behavior*.

Collie, A., McCrory, P., & Makdissi, M. (2006). Does concussion history affect current cognitive status? *British Journal of Sports Medicine, 40*, 550-551.

Cunningham, J., Broglio, S., Wyse, J., Mc Hugh, C., Farrell, G., Denvir, K., & Wilson, F. (2021). Athlete concussion history recall is underestimated: A validation study of self-reported concussion history among current professional rugby union players. *Brain Injury, 35*(1), 65-71.

Cusimano, M. D. & Zhu, A. (2017). Systematic review of traumatic brain injuries in baseball and softball: A framework for prevention. *Frontiers in Neurology, 8,* 492.

Danna-Dos-Santos, A., Mohapatra, S., Santos, M., & Degani, A. M. (2018). Long-term effects of mild traumatic brain injuries to oculomotor tracking performances and reaction times to simple environmental stimuli. *Scientific Reports, 8*(1)- 4583-11.

Dean, P. J., & Sterr, A. (2013). Long-term effects of mild traumatic brain injury on cognitive performance. *Frontiers in Human Neuroscience, 1*(30), 1-11.

DeCouto, B., Robertson, C. T., Lewis, D., & Mann, D. T. (2019). The speed of perception: the effects of over-speed video training on pitch recognition. Cognitive Processing, *21*, 77-93.

Del Rossi, G. (2017). Evaluating the recovery curve for clinically assessed reaction time after concussion. *Journal of Athletic Training, 52*(8), 766-770.

Dettwiler, A., Murugavel, M., Putukian, M., Cubon, V., Furtado, J., & Osherson, D. (2014). Persistent differences in patterns of brain activation after sports-related concussion: A longitudinal functional magnetic resonance imaging study. *Journal of Neurotrauma, 31*, 180-188.

Echemendia, R. J., Broglio, S. P., Davis, G. A., Guskiewicz, K. M., Hayden, K. A., Leddy, J. J., Meehan, W. P., Putukian, M., Sullivan, S. J., Schneider, K. J., & McCrory, P. (2017). What tests and measures should be added to the SCAT3 and related tests to improve their reliability, sensitivity, and/or specificity in sideline concussion diagnosis? A systematic review. *British Journal of Sports Medicine, 51*, 895-901.

Eckner, J. T., Kutcher, J. S., Broglio, S. P., & Richardson, J. K. (2014). Effect of sport-related concussion on clinically measured simple reaction time. *British Journal of Sports Medicine, 48*(2), 112-118.

Eckner, J. T., Kutcher, J. S., & Richardson, J. K. (2011). Effect of concussion on clinically measured reaction time in NCAA Division I collegiate athletes: A preliminary study. *PM & R, 3*(3), 212-218.

Fino, P. C. (2016). A preliminary study of longitudinal differences in local dynamic stability between recently concussed and healthy athletes during single and dual-task gait. *Journal of Biomechanics, 49*(9), 1983-1988.

Gardner, A., Shores, E. A., Batchelor, J. (2010). Reduced processing speed in rugby union players reporting three or more previous concussions. *Archives of Clinical Neuropsychology, 25*(3), 174-181.

Giza, C. C., & Hovda, D. A. (2014). The new neurometabolic cascade of concussion. *Neurosurgery, 75*, S24-S33.

Gray, R. (2009). A model of motor inhibition for a complex skill: baseball batting. *Journal of Experimental Psychology: Applied, 15*(2), 91-105.

Gray, R. (2017). Transfer of training from virtual to real baseball batting. *Frontiers in Psychology, 8*, 1-11.

Guskiewicz, K. M., McCrea, M., Marshall, S. W., Cantu R. C., Randolph, C., Barr, W., Onate, J. A., & Kelly, J. P. (2003). Cumulative effects associated with recurrent concussion in collegiate football players: The NCAA Concussion Study. *The Journal of American Medical Association, 290*(19), 2549-2555.

Hanninen, T., Parkkari, J., Howell, D. R., Palola, V., Seppanen, A., Tuominen, M., Iverson, G. L., & Luoto, T. M. (2021). Reliability of the Sport Concussion Assessment Tool 5 baseline testing: A 2-week test-retest study. *Journal of Science and Medicine in Sport, 24*(2), 129-134.

Hanninen, T., Parkkari, J., Tuominen, M., Iverson, G. L., Ohman, J., Vartiainen, M., & Luoto, T. M. (2016). Interpreting change on the SCAT3 in professional ice hockey players. *Journal of Science and Medicine in Sport, 20*(5), 424-431.

Hardy, R., Jordan, T., Wolf, A., Johnson, M., & Brand, J. (2017). Concussions and their effects on performance measures of Major League Soccer players: A teaching tool for physical education teachers. *The Physical Educator, 74*(1), 150-163.

Henry, L. C., Elbin, R. J., Collins, M. W., Marchetti, G., & Kontos, A. P. (2016). Examining recovery trajectories after sport-related concussion with a multimodal clinical assessment approach. *Neurosurgery, 78*(2), 232-241.

Howell, D. R., Ostering, L. R., & Chou, L. S. (2018). Detection of acute and long-term effects of concussion: Dual-task gait balance control versus computerized neurocognitive test. *Archives of Physical Medicine and Rehabilitation, 99*(7), 1318-1324.

Hume, P. A., Theadom, A., Lewis, G. N., Quarrie, K. L., Brown, S. R., Hill, R., & Marshall, S. W. (2017). A comparison of cognitive function in former rugby union players compared with former non-contact-sport players and the impact of concussion history. *Sports Medicine, 47*, 1209-1220.

Iverson, G. L., Brooks, B. L., Collins, M. W., & Lovell, M. R. (2006). Tracking neuropsychological recovery following concussion in sport. *Brain Injury, 20*(3), 245-252.

Johnson, R. S., Lempke, L. B., Schmidt, J. D., & Lynall, R. C. (2019). Dynamic reaction time: Jumping into the future of concussion management. *Archives of Clinical Neuropsychology, 34*, 731-794.

Kamins, J., Bigler, E., Covassin, T., Henry, L., Kemp, S., Leddy, J. J., Mayer, A., McCrea, M., Prins, M., Schneider, K. J., Valovich McLeod, T. C., Zemek, R., & Giza, C. C. (2017). What is the physiological time to recovery after concussion? A systematic review. *British Journal of Sports Medicine, 51*, 935-940.

Kuhn, A. W., Zuckerman, S. L., Totten, D., & Solomon, G. S. (2016). Performance and style of play after returning from concussion in the National Hockey League. *The American Journal of Sports Medicine, 44*(8), 2152-2157.

Kumar, N. S., Chin, M., O'Neill, C., Jakoi, A. M., Tabb, L., & Wolf, M. (2014). On-field performance of National Football League players after return from concussion. *The American Journal of Sports Medicine, 42*(9), 2050-2055.

Lempke, L. B., Johnson, R. S., Schmidt, J. D., & Lynall, R. C. (2020). Clinical versus functional reaction time: Implications for postconcussion management. *Medicine and Science in Sports and Exercise, 52*(8), 1650-1657.

Lempke, L. B., Lynall, R. C., Hoffman, N. L., Devos, H., & Schmidt, J. D. (2021). Slowed driving-reaction time following concussion-symptom resolution. *Journal of Sport and Health Science*, *10*(2), 145-153.

Lynall, R. C., Mauntel, T. C., Padua, D. A., & Mihalik, J. P. (2015). Acute lower extremity injury rates increase after concussion in college athletes. *Medicine and Science in Sports and Exercise, 47*(12), 2487-2492.

Martini, D. N., & Broglio, S. P. (2018). Long-term effects of sport concussion and motor performance: A review. *International Journal of Psychophysiology, 132*, 25-30.

Martini, D. N., Eckner, J. T., Meehan, S. K., & Broglio, S. P. (2017). Long-term effects of adolescent sport concussion across the age spectrum. *The American Journal of Sports Medicine, 45*(6), 1420-1428.

Martini, D. N., Sabin, M. J., DePesa, S. A., Leal, E. W., Negrete, T. N., Sosnoff, J. J., & Broglio, S. P. (2011). The chronic effects of concussion on gait. *Archives of Physical Medicine and Rehabilitation, 92*(4), 585-589.

McCrea, M., Broglio, S., McAllister, T., Zhou, W., Zhao, S., Katz, B., Kudela, M., Harezlak, J., Nelson, L., Meier, T., Marshall, S. W., & Guskiewicz, K. M. (2020). Return to play and risk of repeat concussion in collegiate football players: Comparative analysis from the NCAA Concussion Study (1991-2001) and CARE Consortium (2014-2017). *British Journal of Sports Medicine, 54*(2), 102-109.

McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., . . . Vos, P. E. (2017). Consensus statement on concussion in sport- the 5th international conference on concussion in sport held in Berlin, October 2016. *British Journal of Sports Medicine, 51*(21), 1-10.

Meier, T. B., Bergamino, M., Bellgowan, P. S., Teague, T. K., Ling, J. M., Jeromin, A., & Mayer, A. R. (2016). Longitudinal assessment of white matter abnormalities following sports-related concussion. *Human Brain Mapping, 37*, 833-845.

Morris-Binelli, K., Muller, S., & Fadde, P. (2018). Use of pitcher game footage to measure visual anticipation and its relationship to baseball batting statistics. *Journal of Motor Learning and Development, 6*, 197-208.

Mullally, W. J. (2017). Concussion. *The American Journal of Medicine, 130*(8), 885-892.

Nasu, D., Yamaguchi, M., Kobayashi, A., Saijo, N., Kashino, M., & Kimura, T. (2020). Behavioral measures in a cognitive-motor batting task explain real game performance of top athletes. *Frontiers in Sports and Active Living, 2*, 1-9.

Ozen, L. J., & Fernandes, M. A. (2012). Slowing down after a mild traumatic brain injury: A strategy to improve cognitive task performance. *Archives of Clinical Neuropsychology, 27*, 85-100.

Parker, T. M., Ostering, L. R., Van Donkelaar, P., & Chou, L. S. (2006). Gait stability following concussion. *Medicine & Science in Sports and Exercise, 38*(6), 1032-1040.

Patel, N., Bhatia, A., Mullen, C., Bosman, E., & Lear, A. (2021). Professional women's softball injuries: An epidemiological cohort study. *Clinical Journal of Sport Medicine, 31*(1), 63-69.

Peterson, J. G., Tjong, V. K., Terry, M. A., Saltzman, M. D., Gryzlo, S. M., & Sheth, U. (2020). Concussion incidence and impact on player performance in Major League Baseball players before and after a standardized concussion protocol. *The Orthopaedic Journal of Sports Medicine, 8*(4), 1-9.

Powers, K. C., Kalmar, J. M., & Cinelli, M. E. (2013). Recover of static stability following a concussion. *Gait & Posture, 39*(1), 611-614.

Ramkumar, P. N., Navarro, S. M., Haeberle, H. S., Petit, R. W., Miles, T. J., Frangiamore, S. J., Mont, M. A., Farrow, L. D., Schickendantz, M. S. (2018). Short-term outcomes of concussions in Major League Baseball: A historical cohort study of return to play, performance, longevity, and financial impact. *The Orthopaedic Journal of Sports Medicine, 6(*12), 1-7.

Reilly-Boccia, C., Ficklin, T., & Lund, R. (2015). Swing kinematics described in Division I softball players. *Sport Journal*, 7.

Roberts, V. E. (2020). *The use of imagery assisted virtual reality for pitch recognition in NCAA division one softball* (Publication No. 27958025) [Master's thesis, Southern Illinois University at Edwardsville]. ProQuest Dissertations and Theses Global.

Schranz, A. L., Manning, K. Y., Dekaban, G. A., Fischer, L., Jevremovic, T., Blackney, K., Barreira, C., Doherty, T. J., Fraser, D. D., Brown, A., Holmes, J., Menon, R. S., & Bartha, R. (2017). Reduced brain glutamine in female varsity rugby athletes after concussion and in non-concussed athletes after a season of play. *Human Brain Mapping, 39*(4), 1489-1499.

Senthinathan, A., Mainwaring, L. M., & Hutchison, M. (2017). Heart rate variability of athletes across concussion recovery milestones: A preliminary study. *Clinical Journal of Sport Medicine, 27*(3), 288-295.

Strickland, J. S., Crandall, M., & Bevill, G.R. (2019). A retrospective analysis of softball-related head and facial injuries treated in United States emergency departments, 2013-2017. *The Orthopaedic Journal of Sports Medicine, 7*(2), 1-7.

Takamido, R., Yokoyama, K., & Yamamoto, Y. (2022). Hitting movement patterns organized by different pitching movement speeds as advanced kinematic information. *Human Movement Science, 81*, 102908.

Vartiainen, M. V., Holm, A., Lukander, J., Lukander, K., Koskinen, S., Bornstein, R., Hokkanen, L. (2016). A novel approach to sports concussion assessment: Computerized multilimb reaction times and balance control testing. *Journal of Clinical and Experimental Neuropsychology, 38*(3), 293-307.

Washington, J. & Oliver, G. (2018). Kinematic differences between hitting off a tee versus front toss in collegiate softball players. *International Biomechanics, 5*(1), 30-35.

Wasserman, E. B., Abar, B., Shah, M. N., Wasserman, D., & Bazarian, J. J. (2015). Concussions are associated with decreased batting performance among major league baseball players. *The American Journal of Sports Medicine, 43*(5), 1127-1133. doi: 10.1177/0363546515576130

Wasserman, E. B., Register-Mihalik, J. K., Sauers, E. L., Currie, D. W., Pierpoint, L. A., Knowles, S. B., Dompier, T. P., Comstock, D., Marshall, S. W., Kerr, Z. Y. (2019). The first decade of web-based sports injury surveillance: Descriptive epidemiology of injuries in US high school girls' softball (2005-2006 through 2013-2014) and National Collegiate Athletic Association women's softball (2004-2005 through 2013-2014). *Journal of Athletic Training, 54*(2), 212-225.

Werner, S. L., Jones, D. G., Guido, J. A., & Brunet, M. E. (2006). Kinematics and kinetics of elite windmill softball pitching. *The American Journal of Sports Medicine, 34*(4), 597-603.

Wu, Y.C., Harexlak, J., Elsaid, N. M., Lin, Z., Wen, Q., Mustafi, S. M., Riggen, L. D., Koch, K. M., Nencka, A. S., Meier, T. B., Mayer, A. R., Wang, Y., Giza, C. C., DiFiori, J. P., Guskiewicz, K. M., Mihalik, J., LaConte, S. M., Duma, S. M., Broglio, S. P., Saykin, A. J., McCrea, M. A., & McAllister, T. W. (2020). Longitudinal white-matter abnormalities in sports-related concussion: A diffusion MRI study. *Neurology, 95*(7), e781-e792.

Yamashiro, K., Sato, D., Onishi, H., Yoshida, T., Horiuchi, Y., Nakazawa, S., & Mauyama, A. (2013). Skill-specific changes in somatosensory-evoked potentials and reaction times in baseball players. *Experimental Brain Research, 225*(2), 197-203.

Yengo-Kahn, A. M., Zuckerman, S. L., Stotts, J., Zalneraitis, B. H., Gardner, R. M., Kerr, Z. Y., & Solomon, G. S. (2016). Performance following a first professional concussion among National Basketball Association players. *The Physician and Sportsmedicine, 44*(3), 297-303.

Zuckerman, S. L., Kerr, Z. Y., Yengo-Kahn, A., Wasserman, E., Covassin, T., & Solomon, G. S. (2015). Epidemiology of sports-related concussion in NCAA athletes from 2009-2010 to 2013-2014: Incidence, recurrence, and mechanisms. *The American Journal of Sports Medicine, 43*(11), 2654-2662.

Appendices

Appendix A

Informed Consent

Date: October 27, 2021
Study Title: Does concussion history affect softball batting performance in collegiate softball players?

Principal Investigator: Jae Patterson, PhD, Associate Professor
Department of Kinesiology
Brock University
905-688-5550 X3769; jpatterson@brocku.ca

Faculty Supervisor:
Gail Frost, PhD, Associate Professor
Department of Kinesiology
Brock University
905-688-5550 X4497; gfrost@brocku.ca

Principal Student Investigator (PSI):
Kim Uyeno, BSc, Masters Thesis Student
Department of Applied Health Sciences
Brock University
kuyeno@brocku.ca

Co-Investigator:
Michael Holmes, PhD, Associate Professor
Department of Kinesiology
Brock University
905-688-5550 X4398; mholmes2@brocku.ca

INVITATION
You are invited to participate in a research study. The purposes of this study are to compare results from computer reaction time tests to sport-specific reaction time tests and determine if softball batting performance is affected following a concussion.

WHAT'S INVOLVED
As a participant, you will be asked to fill out a Medical History Questionnaire, complete a computerized reaction time task, identify virtual pitches, and complete a virtual batting task. The questionnaire will ask questions about your softball experience, concussion history, and medical history. Your responses from the Medical History Questionnaire will be used to describe the individuals that take part in the study and identify any relationships between concussion history and batting performance. Your responses will not be linked to you, nor will they be shared with anyone outside this research project.

The reaction time task will involve pressing buttons on a keyboard in response to what appears on the screen. The pitch recognition task will involve identifying the type, location, and outcome (i.e., ball or strike) of each pitch, while the batting task will involve swinging in response to virtual pitches. During the batting task, video will be captured of the swings using video cameras and motion capture. Two video cameras will be used to capture video of the swings, one will be placed in front of the batter, and the other behind the batter. During this section, motion capture cameras will also be used to capture the movement at each joint and there are placed all around the room. The motion capture will use small sensors placed on the body to capture the movement of a few joints during each swing.

Participation will take approximately 60 minutes of your time and will be completed in one session.

WHAT TO BRING

On the day of your testing session, please wear of bring the following:

- Athletic clothing or clothes that you can swing a bat in
- Short-sleeve t-shirt or top that shows the elbows and forearms
- Running shoes or turf shows (you'll be swinging inside)
- A bat (preferably the bat that you would use in a game)
- Glasses or contacts (If you normally wear them when you play)
- At least a non-medical face covering (and put it on when you arrive on campus)

POTENTIAL BENEFITS AND RISKS

By participating in this study, you will have the opportunity to use a pitch recognition software to test your ability to accurately recognize incoming pitches. Another possible benefit of participation includes improving our current knowledge of concussions and the impact that they may continue to have on athletes beyond the resolution of symptoms.

There may also be risks associated with participation. Participation in this study will involve swinging in response to pitching videos increasing the risk of possible muscle soreness, muscle strain, and ligament sprain. However, participants will be provided as much time as they need to warm-up prior to starting the batting and pitch recognition task and will be given adequate time between swings. Participants will also be provided plenty of space to swing freely to ensure that both the participants and researchers are safe. It is also possible that answering some the questions on the Medical History Questionnaire may cause feelings of discomfort, anxiety, or embarrassment because you may be remembering personal experiences. You may decline to answer any question(s) that you are asked in the questionnaire, and only the researchers involved in this research project will have access to your responses. Participation is voluntary and your response will not be linked to you.

CONFIDENTIALITY

All information you provide is considered confidential; your name will not be included, or in any other way, associated with the data collected in the study. No data will be shared with your coach, team, or school. The video recordings of the swings will be used to gather outcome variables for the study, and this will be done using a motion analysis software. The videos will be transferred from the motion capture system and video cameras to the PSI's password-protected computer. Once the data has been collected from the videos, they will be deleted from the PSI's password-protected computer. All reports that are written using the data will report group values not individual results. Data collected from this study will be stored on the PSI's and FS's password-protected computers and will be destroyed five years after the results of the study have been published. Access to this data will be restricted to the PI, PSI, and FS.

VOLUNTARY PARTICIPATION

Participation in this study is voluntary. Your participation or non-participation, or your choice to withdraw from the study, will not affect your standing with your team, coach, or school. If you wish, you may decline to answer any questions or participate in any component of the study. Further, you may decide to withdraw from this study at any time and may do so without any penalty or loss of benefits to which you are entitled. If you decide to withdraw from the study, please contact Kim Uyeno (Principal Student Investigator) or Dr. Jae Patterson (Principal Investigator) with your participant number stating that you wish to be removed from the study and your data, including video recordings will be removed at that time. In the case that you cannot remember your participant number, a key code will be kept with all participant's names and participant numbers, in which participants will then have to share their name with the PI or PSI to have their data removed from the study.

PUBLICATION OF RESULTS

Results of this study may be published in professional journals and presented at conferences. Feedback about this study will be available after June 31, 2022 by emailing Kim Uyeno using the contact information provided above.

CONTACT INFORMATION AND ETHICS CLEARANCE

If you have any questions about this study or require further information, please contact Kim Uyeno, Principal Student Investigator or Dr. Jae Patterson, Principal Investigator using the contact information provided above. This study has been reviewed and received ethics clearance through the Research Ethics Board at Brock University (21-XXX). If you have any comments or concerns about your rights as a research participant, please contact the Office of Research Ethics at (905) 688-5550 Ext. 3035, reb@brocku.ca.

Thank you for your assistance in this project. Please keep a copy of this form for your records.

CONSENT FORM

I agree to participate in this study described above. I have made this decision based on the information I have read in the Invitation Letter and Consent Form. I have had the opportunity to receive any additional details I wanted about the study and understand that I may ask questions in the future. I understand that I may withdraw this consent at any time.

Name: ____

Signature: ____ Date:

____

Appendix B

Medical History Questionnaire

This questionnaire asks you to provide information about yourself, your concussion history, and your medical history. This information will be used to describe the individuals that take part in this study and identify any relationships between concussion history and batting performance. Your responses will not be linked to you, nor will they be shared with anyone outside this research project.

Participant Number: _____________

1. How old are you? _________ years
2. Height: _________
3. Approximately how many hours of sleep did you get last night? ______ hours (asked on day of testing)
4. Do you wear glasses or contact lenses? ☐ Yes ☐ No
    a. If so, do you wear them while you play softball? ☐ Yes ☐ No
5. How many years have you played softball? ____________

Concussion History

1. Have you ever been diagnosed with a concussion by a medical professional?
   ☐ Yes ☐ No

If yes:

a. How many times have you been diagnosed with a concussion by a medial professional? ___________
b. When was your last concussion? (mm/year) ____________
c. How long was the recovery for your most recent concussion? ______________
d. Have you been cleared by a doctor to return to full sport activity? ☐ Yes ☐ No
e. Do you consider yourself fully recovered from your last concussion? ☐ Yes ☐ No
f. Have you ever lost consciousness as a result of a concussion? _________

Medical History

1. Do you have a history of any of the following: (Please check all that apply)?

- ☐ Epilepsy
- ☐ Brain surgery
- ☐ Seizures
- ☐ Migraines

2. Have you ever been diagnosed with any of the following? (Please check all that apply?)
   - ☐ Attention deficit/Hyperactivity Disorder
   - ☐ Learning disability
   - ☐ Psychiatric condition
   - ☐ Neurological disorder
   - ☐ Post-Concussion Syndrome

Appendix C
Recruitment Email

Hello,

My name is Kim Uyeno, I am a masters thesis student at Brock University and my thesis advisor is Dr. Gail Frost. For my thesis project, I am conducting a study assessing softball batting performance and reaction time in collegiate softball players. I am emailing you to invite you to take part in our study because you are a part of a collegiate softball team. **We need current university and college softball players or athletes that have played university or college softball in the last 2 years.** We need both players that have sustained a concussion and players that have not sustained a concussion.

Our study will involve one session, during which participants will complete a medical history questionnaire, computerized reaction time test, pitch recognition test, and batting test. Participants will be asked to identify incoming pitches and swing in response to videos of pitchers throwing live pitches. The session will last approximately 60 minutes and will be completed at Brock University.

Participation in this study is completely voluntary, and you can choose to withdraw from the study at any time. Your choice to participate or not, or withdraw from the study will not be shared with any team member or coaching staff, and will not affect your standing with your coach, team, or school. Data will be anonymized, kept confidential, and study reports will only include group values, not individual values.

If you are interested in taking part in our study or would like more information, please email me at kuyeno@brocku.ca.

Thank you for your time.

Kim Uyeno
kuyeno@brocku.ca
Masters Thesis Student
Brock University

Appendix D
Facebook/Instagram Post

Brock University

Want to be involved in softball research?

University and College Softball Players Needed!

Who:
University and college softball players

What's Involved:
1 Visit (75 minutes)
Reaction time test, pitch recognition, virtual batting

Where:
Brock University

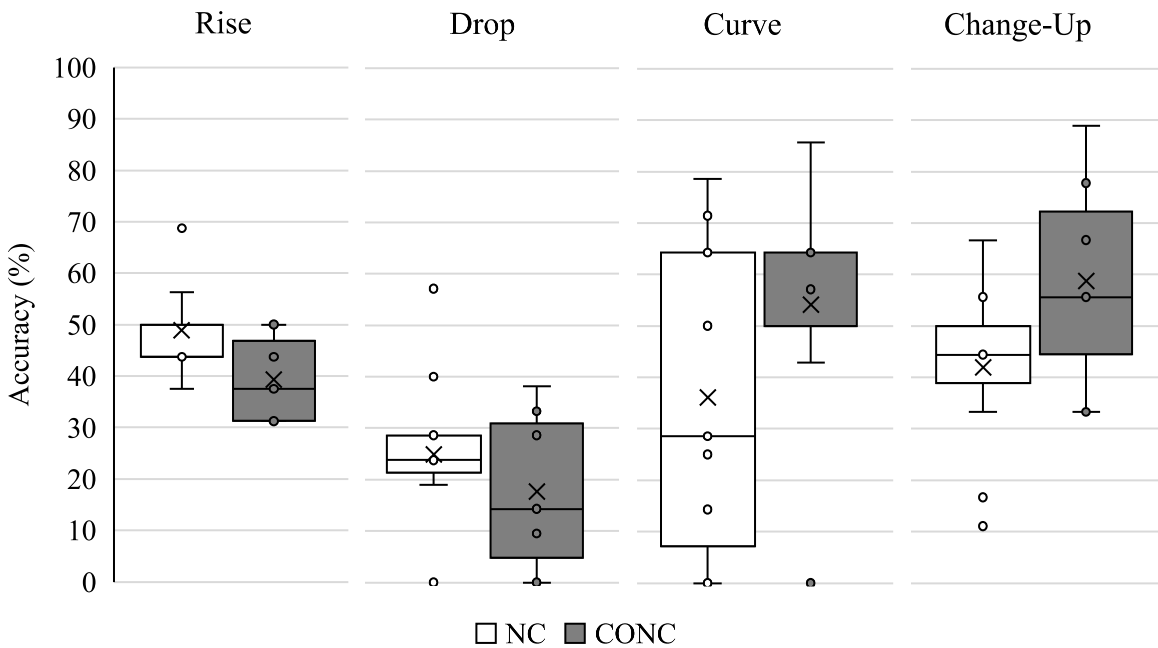
For more information, contact:
Kim Uyeno, Principal Student Investigator
kuyeno@brocku.ca

Cleared by Brock Research Ethics Board (file number: 21-XXX)

Appendix E
Additional PR Figures

Figure E1

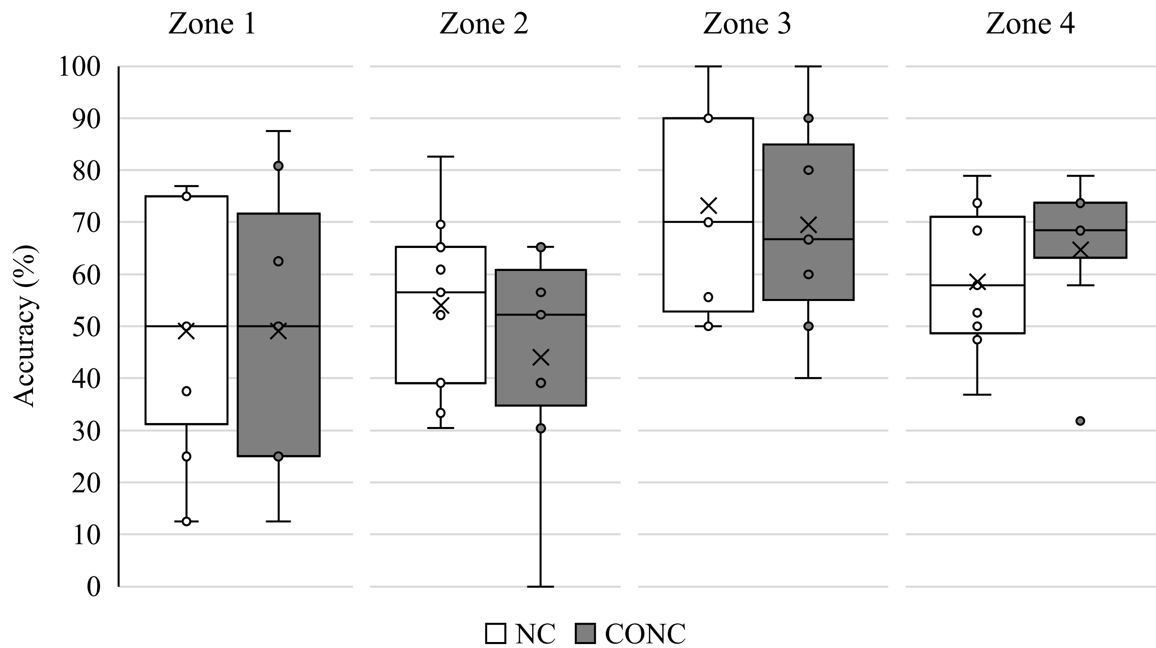
Boxplot of PR by Pitch Type



Note. Individual participant's means are plotted as dots. The horizontal line inside the box represents the median value, the 'X' represents the group mean, box widths represent first (25%) and third (75%) quartiles, and whiskers represent the maximum and minimum.

Figure E2

Boxplot of PR by Pitch Location



Note. Individual participant's means are plotted as dots. The horizontal line inside the box represents the median values, the 'X' represents the group mean, box widths represent first (25%) and third (75%) quartiles, and whiskers represent the maximum and minimum.

Appendix F
Correlation Matrices

Table F1

Concussion History Correlation Table

	Time Since Concussion	Recovery Time
Simple RT	.15	-.19
Choice RT	.32	.41
Go/No-go RT	.72	.42
Incorrect RT	.43	.69
PR Type	.39	.20
PR Outcome	.25	-.30
PR Location	-.26	-.39
PR Total	.25	-.23
Swing Correct	.29	-.53
No Swing Correct	.50	.69
Swing Incorrect	-.62	-.79*
Swing Choice Accuracy	.60	.10
Swing Time	-.42	.11
SRT	.13	-.26
TTC	.59	.24
TTC-E	.56	.20
Swing Termination	-.19	-.31

Note. Pearson correlation coefficients between concussion history variables and RT, PR, and batting outcome variables.

* Indicates significant correlation ($p < 0.05$).

Table F2

Outcome Variables Correlation Coefficients

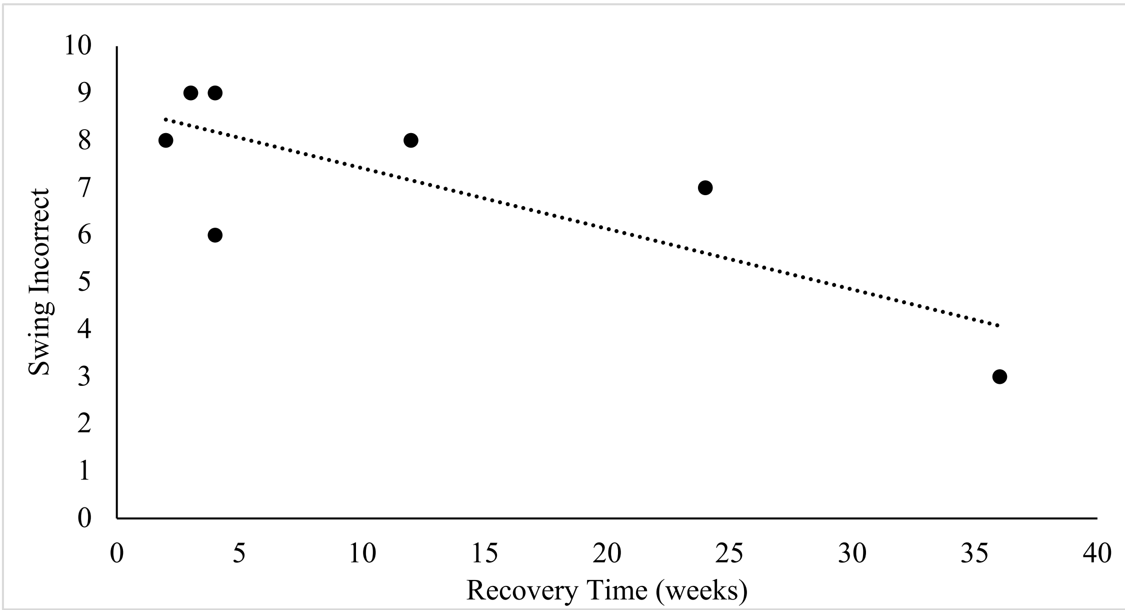
	Choice RT	Go/No-go RT	Incorrect RT	PR Type	PR Outcome	PR Location	PR Total	Swing Correct	No Swing Correct	Swing Incorrect	Swing Choice Accuracy	Swing Time	Swing RT	TTC	TTC-E	Swing Termination
Simple RT	.05	.54	-.57	.12	.42	-.16	.20	-.12	-.13	.18	-.23	-.12	.15	.01	-.04	.13
Choice RT		.36	.39	-.09	-.27	-.72*	-.58	-.17	-.01	.04	-.15	-.23	-.27	-.16	-.24	.28
Go/No-go RT			.04	.48*	.14	-.15	.27	-.10	.12	-.19	.04	.05	-.11	-.07	-.08	.01
Incorrect RT				.31	-.20	-.28	-.07	-.14	.15	-.29	.04	.05	.05	.14	.08	.11
PR Type					.04	.25	.75*	-.46	.21	-.36	-.18	.14	.26	.06	.18	-.04
PR Outcome						-.15	.44	.06	.39	-.28	.44	.02	.11	-.05	-.09	.09
PR Location							0.62*	0.07	-.14	.12	-.08	.43	.06	.04	.13	-.30
PR Total								-.20	.24	-.29	.07	.32	.24	.03	.13	-.14
Swing Correct									-.43	.38	.41	-.11	.14	.34	.24	.03
No Swing Correct										-.93*	.65*	-.08	-.05	.02	.16	.05
Swing Incorrect											-.61	.10	-.18	-.16	-.26	-.17
Swing Choice Accuracy												-.18	.07	.30	.36	.08
Swing Time													-.37	-.37	-.33	.04
SRT														0.65*	.60*	.43
TTC															.89*	.33
TTC-E																.16

* Indicates significant correlation ($p < .05$).

Appendix G
Scatterplots of Significant Correlations

Figure G1

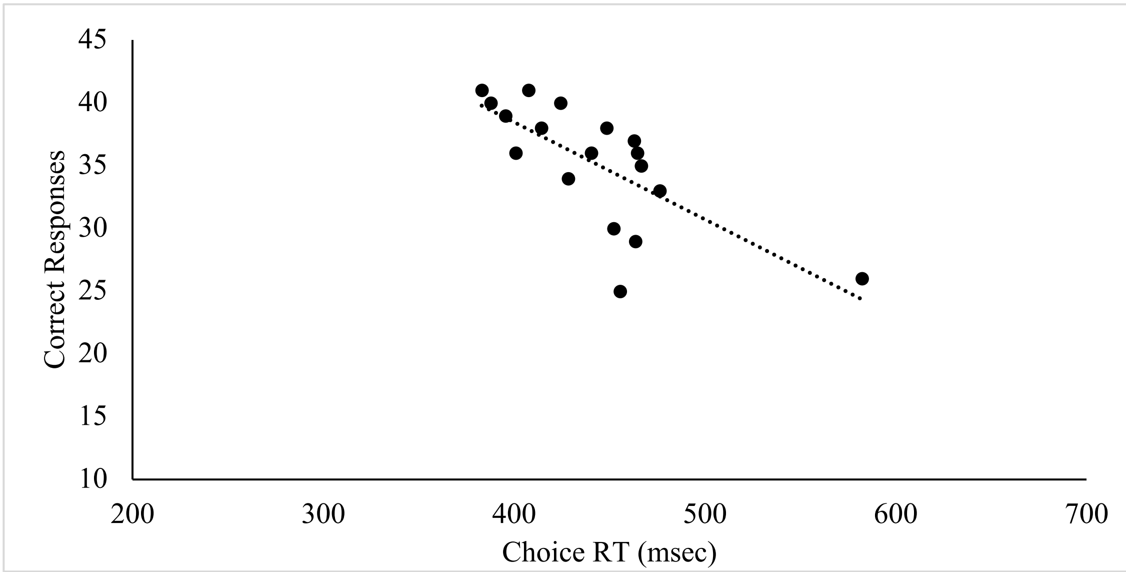
Swing Incorrect and Recovery Time



Note. Scatterplot showing the relationship between swing incorrect and recover time in weeks in those with previous concussion.

Figure G2

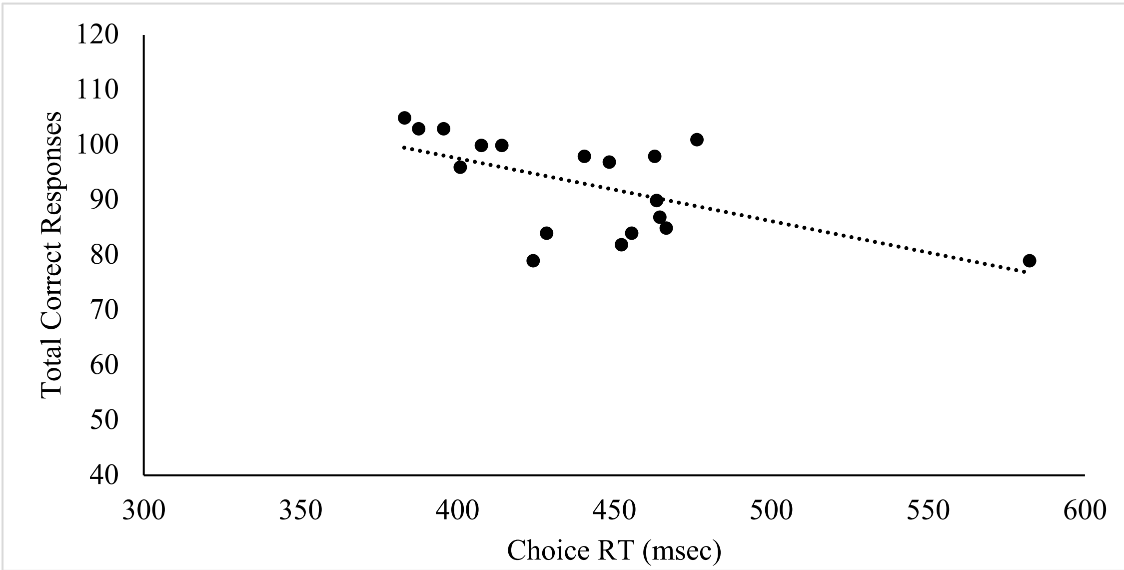
Choice RT and Correct Pitch Location



Note. Scatterplot showing the number of correct pitch location responses and choice reaction time.

Figure G3

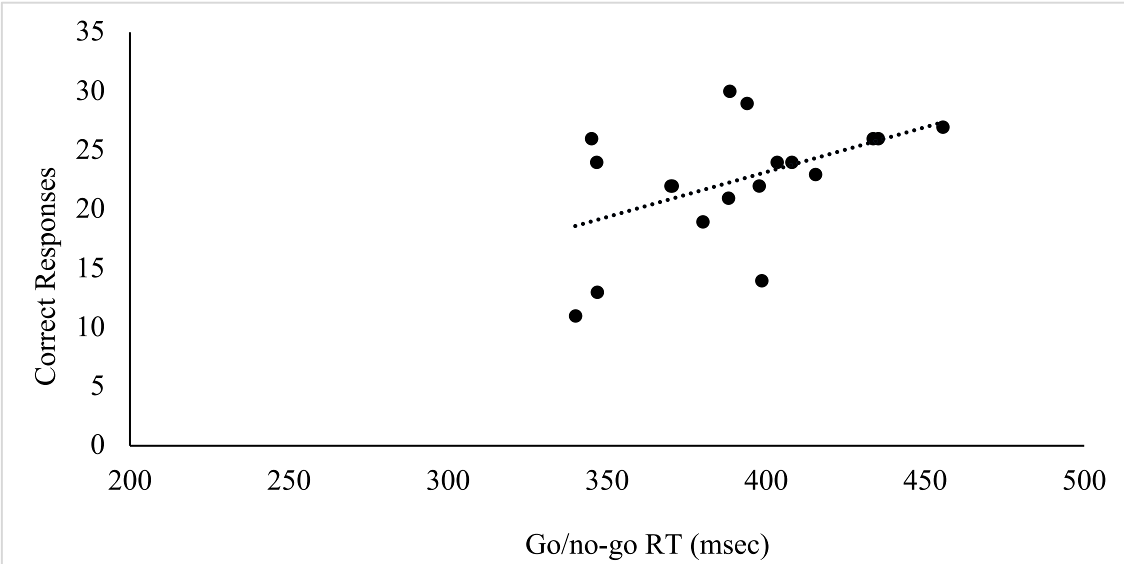
Choice RT and PR Total



Note. Scatterplot showing the number of total correct pitch recognition responses and choice reaction time.

Figure G4

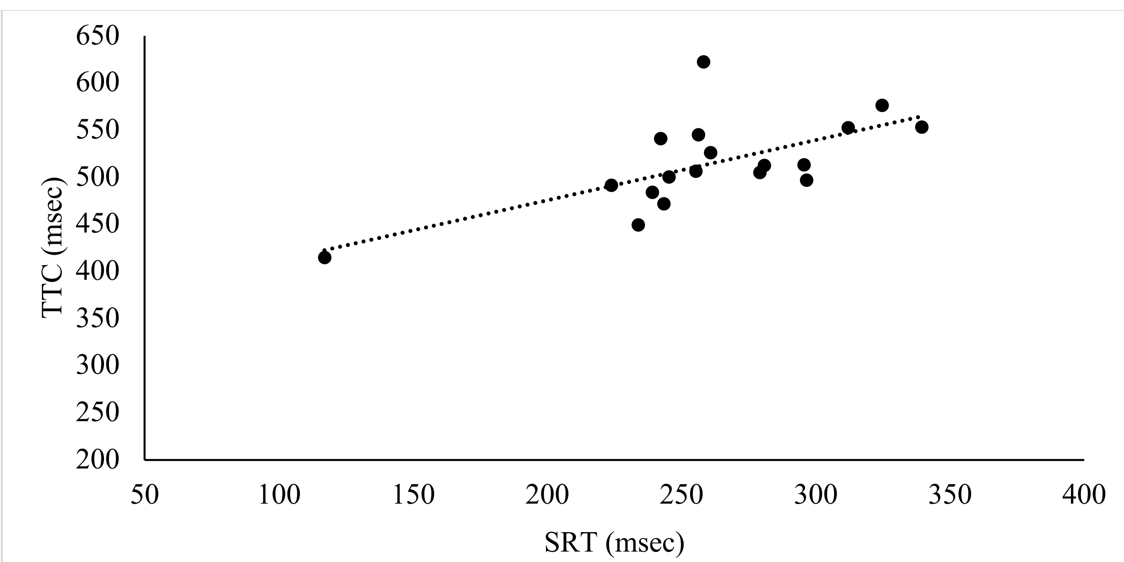
Go/No-go RT and Pitch Type



Note. Scatterplot showing the number of correct pitch type responses and go/no-go reaction time.

Figure G5

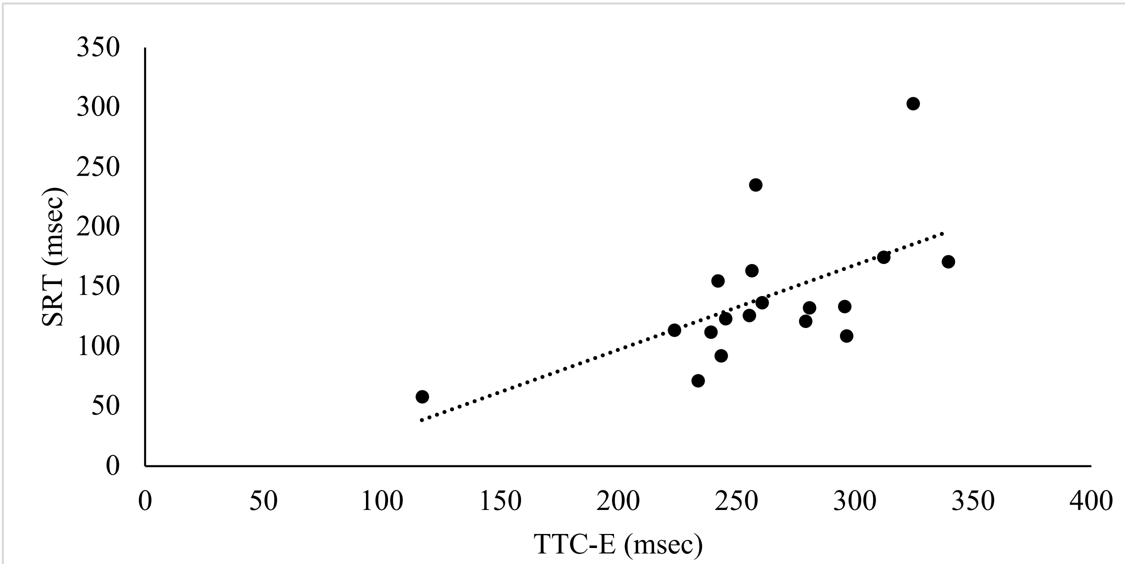
SRT and TTC



Note. Scatterplot showing time to contact (TTC) and swing reaction time (SRT).

Figure G6

SRT and TTC-E



Note. Scatterplot showing swing reaction time (SRT) and time to contact error (TTC-E).

Appendix H
Post-hoc Sample Size

Based on the results from this study and assuming power = 0.95 and $\alpha = 0.05$, if this study were to be replicated, it would require 117 participants per group, for a total sample size of 234 participants for the independent t-test analyses. Based on the results from this study and assuming power = 0.95 and $\alpha = 0.05$, if this study were to be replicated, it would require a total sample size of 168 participants for the Pearson's Correlation analyses.