Predicting Protracted Recovery from Sports-Related Concussion Using Computerized Neurocognitive Test Scores and Symptom Cluster Scores

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PREDICTING PROTRACTED RECOVERY FROM SPORTS-RELATED CONCUSSION USING COMPUTERIZED NEUROCOGNITIVE TEST SCORES AND SYMPTOM CLUSTER SCORES

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PREDICTING PROTRACTED RECOVERY FROM SPORTS-RELATED CONCUSSION USING COMPUTERIZED NEUROCOGNITIVE TEST SCORES AND SYMPTOM CLUSTER SCORES

by

AMANDA SEPULVEDA, BMS

THESIS

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Abstract

Background: A previous study showed that symptom evaluation, in conjunction with computerized neurocognitive testing, improved predictions of protracted recovery in a group of male high school football players. The determination of prognosis following sports-related concussion can be used to facilitate return-to-play and academic decision making in concussion management.

Purpose: The purpose of this study was to replicate and extend previous research in determining the accuracy, sensitivity, specificity, and predictive value of computerized neurocognitive test scores and symptom cluster scores in predicting protracted recovery following sports-related concussion.

Study Design: Systematic replication, Cohort study (prognosis)

Methods: 30 concussed collegiate athletes were followed clinically using the ImPACT test, and were released to return to play once they were asymptomatic and their neurocognitive performance returned to baseline/normative data. The athletes were retrospectively classified as having a short (≤ 14 days) or protracted (> 14 days) recovery based on the number of days they took to return to play. Discriminant function analysis was used to determine how well neurocognitive test scores and symptom cluster scores can predict group membership, and to identify combinations of variables with the highest classification accuracy. Follow-up phone calls were conducted to determine how clinically accurate current return-to-play standards are in predicting recovery of function.

Results: Replication of the Lau et al. (2011) study revealed that computerized neurocognitive test scores and symptom cluster scores classified athletes in the current study into short and protracted recovery groups with 70% accuracy. Two classification models were identified as having the strongest predictive power, one of which resulted in increased classification accuracy compared to the combination of variables used in the Lau et al. study. Follow-up phone calls revealed that 26.7% of athletes experienced symptoms during the return-to-play protocol.

Conclusions: This study extended the Lau et al. (2011) study to a different population of athletes. Four variables identified in the Lau et al. study and two variables identified in the current study were used to identify two models for predicting protracted recovery with the highest classification accuracy, which can be used to facilitate clinical decision making in concussion management.
Keywords: concussion, prognosis, return to play, symptoms, neurocognitive testing, ImPACT
# Table of Contents

Acknowledgements ........................................................................................................... v

Abstract .............................................................................................................................. vi

Table of Contents .............................................................................................................. viii

List of Tables ..................................................................................................................... x

Chapter

1. Literature Review ................................................................................................................. 1

1.1 Introduction ....................................................................................................................... 1

1.2 Natural History of Concussion ......................................................................................... 3

1.3 Neurocognitive Testing and Self-Reported Symptoms ................................................... 5

1.4 Predicting Protracted Recovery ...................................................................................... 9

1.5 Statistical Modeling and Discriminant Function Analysis ............................................... 13

1.6 Purpose of Study ............................................................................................................. 15

2. Methods and Procedures ................................................................................................... 17

2.1 IRB Approval ................................................................................................................... 17

2.2 Study Design .................................................................................................................. 17

2.3 Participants .................................................................................................................... 17

2.4 Instruments ..................................................................................................................... 19

2.5 Procedures ...................................................................................................................... 22

2.6 Statistical Analysis ......................................................................................................... 25

3. Results ............................................................................................................................... 27

3.1 Group Differences .......................................................................................................... 27

3.2 Neurocognitive Performance and Symptom Profiles ..................................................... 30

3.3 Systematic Replication of the Lau et al. (2011) Study .................................................. 33

3.4 Models for Predicting Protracted Recovery .................................................................. 36

3.4.1 Model 1 ....................................................................................................................... 37

3.4.2 Model 2 ....................................................................................................................... 38

3.4.3 Model 3 ....................................................................................................................... 38

3.4.4 Model 4 ....................................................................................................................... 39

3.4.5 Model 5 ....................................................................................................................... 39
3.5 Follow-Up Phone Calls..........................................................................................40

4. Discussion..................................................................................................................45
  4.1 Limitations...............................................................................................................49
  4.2 Future Work..............................................................................................................50
  4.3 Conclusion................................................................................................................51

References....................................................................................................................53

Appendix A.....................................................................................................................58

Curriculum Vita..............................................................................................................59
List of Tables

Table 2.1: Participant Characteristics – El Paso County Collegiate Athletes. ......................18
Table 2.2: Post-Concussion Symptom Scale Symptom Clusters. ..................................................20
Table 2.3: Immediate Post-Concussion Assessment and Cognitive Testing Neurocognitive Composite Scores ..............................................................................................................................21
Table 2.4: ImPACT Reliable Change Deficits – 80% Confidence Interval. .................................22
Table 2.5: Neurocognitive Composite and Symptom Cluster Cutoff Scores for Predicting Protracted Recovery.................................................................................................................................22
Table 2.6: Graduated Return-to-Play Protocol ..................................................................................24
Table 3.1: ImPACT Composite Scores and PCSS Symptom Clusters.............................................30
Table 3.2: Number and Percentage of Athletes with ImPACT Reliable Change Deficits ..........31
Table 3.3: Number and Percentage of Athletes who met the Cutoff at 80% Sensitivity for Each ImPACT Composite Score and PCSS Symptom Cluster Score.............................................32
Table 3.4: Total Number of ImPACT Reliable Change Deficits ......................................................32
Table 3.5: Total Number of 80% Sensitivity Cutoff Scores..............................................................33
Table 3.6: Discriminant Function Analysis: PCSS Symptom Cluster Scores Only.....................34
Table 3.7: Discriminant Function Analysis: ImPACT Neurocognitive Scores Only....................34
Table 3.8: Discriminant Function Analysis: PCSS Symptom Cluster and Neurocognitive Scores Combined........................................................................................................................................35
Table 3.9: Comparison of Discriminant Function Analysis of Combinations of Variables Used in the Lau et al. 2011 Study.................................................................................................................36
Table 3.10: Comparison of Discriminant Function Analysis of Four Models for Predicting Protracted Recovery.........................................................................................................................40
Table 3.11: Patient Profiles of Athletes Who Experienced Difficulties during the Recovery from their Concussion. .................................................................................................................................41
Chapter 1: Literature Review

1.1 Introduction

Concussions pose a significant public health concern. Approximately 1.6 to 3.8 million recreational and sports-related concussions occur in the United States each year, although the true incidence may be even higher (Langlois, Rutland-Brown, & Wald, 2006). A concussion is a bump, blow, or jolt to the head that is typically characterized by natural recovery and resolution of clinical signs and symptoms within a fairly short period of time (see, e.g., Salvatore & Sirmon Fjordbak, 2011). Typical recovery following sports-related concussion occurs within 10 to 14 days of injury (Macciochi et al., 1996; Field et al., 2003; McCrea et al., 2003; Lovell et al., 2003; Lovell et al., 2004; Pellman et al., 2006; Iverson et al., 2006; Makdissi et al., 2010). It is important to decide when it is safe for an athlete to return to play and to the classroom after sustaining a concussion. Premature decisions to release athletes to return to the playing field or to the classroom may result in delayed recovery or more serious consequences, such as diffuse cerebral swelling or second-impact syndrome (Cantu, 1998; Kelly et al., 1991; Saunders & Harbaugh, 1984; Collins et al., 2002; Guskiewicz et al., 2003). Thus, efforts must be made to prevent student athletes from returning to play and school before they have fully recovered.

Research has primarily focused on diagnosing concussion, but few research studies have looked at predicting prognosis. It is difficult to establish guidelines for predicting the length of recovery following a concussion because a concussion is a highly individualized injury. Lau and colleagues (2011) showed that symptom profiles, in conjunction with computerized neurocognitive testing, improved predictions of protracted recovery following sports-related concussion in a group of male high-school football players. Using the same subjects as in their previous study (Lau et al., 2011), Lau and colleagues (2012) implemented receiver-operating characteristic curves to establish clinically objective cutoff scores to help set numerical thresholds for predicting protracted recovery. While Lau and colleagues provided useful information to facilitate clinical decision making in the management of sports-related concussion, the
results from their studies cannot be generalized to female athletes, collegiate athletes, or athletes from other sports because the subjects only included male high school football players. It is also not clear which combinations of neurocognitive composite scores and symptom cluster scores yield the highest classification accuracy. Knowing the most powerful combinations of variables will help clinicians to understand better the effect of variation in performance across neurocognitive test scores and symptom cluster scores on predictions of protracted recovery. Addressing these issues and determining prognosis following sports-related concussion will help clinicians to more confidently address return-to-play and academic decisions, thereby potentially preventing student athletes from returning to play and school before they have fully recovered.

This study seeks to systematically replicate and extend previous research in examining the predictive value of computerized neurocognitive test scores and symptom cluster scores in predicting protracted recovery from sports-related concussion. This study extends the Lau et al. (2011) study to a different population of athletes. Discriminant function analysis is used to determine how well the measures can predict protracted recovery in a group of collegiate athletes. Classification of percent accuracy, sensitivity, specificity, positive predictive value, and negative predictive value are used to examine different classification models for predicting protracted recovery. The current study uses a group of four variables identified in the Lau et al. study (i.e., verbal memory, visual memory, reaction time, and migraine cluster) and a group of two variables identified in the current study (i.e., processing speed and migraine cluster) to establish the models with the strongest predictive power. These models are promising and can potentially be used to facilitate clinical decision making in concussion management. The study also extends the Lau et al. (2012) study by examining differences between the two recovery groups in terms of the number of reliable change deficits and the number of scores that reached the numerical cutoff scores for predicting protracted recovery at the initial post-concussion evaluation. Moreover, follow-up phone calls were conducted to assess how clinically accurate current return-to-play standards are in predicting
recovery of function, based upon whether athletes experienced symptoms during the return-to-play process or thereafter.

1.2 Natural History of Concussion

The Concussion in Sport Group (CISG) defined concussion as “a complex pathophysiological process affecting the brain, induced by biomechanical forces” in the 4th International Conference on Concussion in Sport (McCrory et al., 2013, p. 1). According to the CISG, “(1) concussion may be caused by a direct blow to the head, face, neck or elsewhere on the body with an “impulsive” force transmitted to the head; (2) concussion typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously; (3) concussion may result in neuropathological changes, but the acute clinical symptoms largely reflect a functional disturbance rather than a structural injury; and (4) concussion results in a graded set of clinical symptoms that may or may not involve loss of consciousness” (McCrory et al., 2013, p. 1-2).

Concussions are characterized by immediate physiological changes in the brain (Iverson, 2005). These changes appear to be predominantly metabolic, rather than structural. The majority of the pathophysiology of concussion renders neurons dysfunctional (not destroyed), although a small number of cells might degenerate and die under certain circumstances (Iverson, 2005). The pathophysiology of concussion, also known as the neurometabolic cascade of concussion, is defined as any transient neurologic dysfunction resulting from sufficient biomechanical force (Giza & Hovda, 2001). It is a process of abrupt release of excitatory neurotransmitters, ionic shifts, altered brain metabolism, diminished cerebral blood flow, impaired neuronal activity, and disruption of normal neurotransmission. Animal models suggest that dynamic restoration of the majority of neurometabolic pathophysiology occurs in the hours and days following injury (Giza & Hovda, 2001). This dynamic restoration seems to match the documented recovery patterns of concussed athletes (Macciocchi et al., 1996; Lovell et al., 2003; Lovell et al., 2004; McCrea et al., 2003; McCrea et al., 2002).
Concussed athletes appear to recover relatively quickly and fully in terms of their self-reported symptoms and neurocognitive performance. Due to natural recovery, sports-related concussion is generally not associated with long-term cognitive or neurobehavioral problems (Belanger & Vanderploeg, 2005; Binder, 1997; Carroll, 2004; Iverson, 2005; Rees, 2003; and Schretlen & Shapiro, 2003). The natural history of concussion is characterized by gradual but complete resolution of symptoms, cognition functioning, and postural stability within several days to weeks of injury (McCrea et al. 2003). In a large-scale prospective cohort study, the majority of collegiate athletes’ balance problems, symptoms, and cognitive functioning resolved within 7 days of injury (McCrea et al., 2003). In addition, declines in neuropsychological test performance are not typically seen in athletes past 5 to 10 days (Macciocchi et al., 1996; McCrea et al., 2003; Lovell et al., 2004; Pellman et al., 2004).

In a descriptive epidemiology study, McKeon and colleagues (2013) used time-to-event analysis to develop return-to-play timeline probability estimates after sports-related concussion in a group of high school athletes. They found that 71.3% of the athletes returned to play within 7 to 9 days of injury, and 88.9% of the athletes returned to play within 10 to 21 days following their injury. Overall, the literature suggests that 80-90% of concussed athletes recover in a short 7-to-10 day period (McCrory et al., 2004; McCrory et al., 2013). However, Iverson and colleagues (2006) found that group analyses can obscure slow recovery in some athletes. In the group analysis, performance decrements in neurological testing and symptoms relating to concussion appeared to resolve fully by 10 days. However, individual analysis revealed that 37% of athletes were still showing 2 or more reliable change deficits in their neurocognitive test scores compared to their pre-season scores at 10 days post-injury, thereby highlighting the importance of analyzing individual athletes’ test data (Iverson et al., 2006).

Traditional means of classifying TBI severity, such as computed tomography (CT) and magnetic resonance imaging (MRI), have limited utility in detecting the effects of concussion. These imaging techniques lack sensitivity in evaluating the neurometabolic disruption that occurs in brain physiology
following concussion (McCrea, 2008; McCrory et al., 2013). CT scanning has the poorest sensitivity in diagnosing concussion, even though it is the most commonly used radiologic technique in evaluating traumatic brain injury (McCrea, 2008). Current research suggests that MRI may be more sensitive than CT in detecting structural abnormalities following concussion, and functional MRI (fMRI), in particular, may be more sensitive compared to neuropsychological evaluation alone (Jantzen et al., 2004; Chen et al., 2004; McCrory et al., 2013). Thus, fMRI might potentially provide additional insight into the pathophysiological mechanisms following concussion. Nonetheless, the sensitivity of fMRI and alternative imaging techniques, such as positron emission tomography, diffuse tensor imaging, and magnetic resonance spectroscopy, in detecting the effects of concussion are still in the early stages of development (McCrea, 2008; McCrory et al., 2013).

Since imaging techniques are not sensitive to concussion, healthcare professionals must rely upon other measures to diagnose concussion and decide when it is safe for an athlete to return to play. International guidelines on the management of sports-related concussion recommend that diagnosis of concussion include one or more of the following clinical domains: (1) symptoms; (2) physical signs (loss of consciousness and posttraumatic amnesia); (3) behavioral changes (e.g., irritability); (4) cognitive impairment; and (5) sleep disturbance (McCrory et al., 2013). Current research in the diagnosis and management of concussion encourages the use of a multifaceted-multimodal approach, that includes measures of neurocognitive functioning, postural control, and self-reported symptoms (Stump et al., 2004; Broglio et al., 2007a; Broglio et al., 2007b; Maerlender et al., 2010; Maerlender et al., 2013; Resch et al., 2013; McCrory et al., 2013). Ultimately, the final decision in diagnosing sports-related concussion and in making return-to-play recommendations lies with a medical professional.

1.3 Neurocognitive Testing and Self-Reported Symptoms

Traditionally, diagnosis of sports-related concussion and return-to-play decisions were based solely on an athlete’s self-reported symptoms. However, many athletes may be unaware of concussion-
related symptoms, while others may be reluctant to report symptoms because they do not want to be removed from game play (McCrea et al., 2004). Neurocognitive testing provides an objective measure of whether there has been a change in cognitive processes following an injury. Although some researchers have questioned the clinical usefulness of neurocognitive testing while athletes remain symptomatic (Randolph et al., 2005), the current literature in concussion management supports the added value of neurocognitive testing in diagnosing sports-related concussion (Collins et al., 1999; Broglio et al., 2001a; Broglio et al., 2001b; Grindel et al., 2001; Lovell, 2002; Schatz & Browndyk, 2002; Schatz & Zillmer, 2003; Collie & Maruff, 2001; Collie et al., 2006; Stump et al., 2004; Schatz et al., 2006; Fazio et al., 2007; Makdissi et al., 2010). Van Kampen and colleagues (2006) evaluated the added value of neuropsychological testing relative to self-reported symptoms in a group of 122 concussed high school and collegiate athletes in the U.S. The addition of neurocognitive testing resulted in an increase in sensitivity in diagnosing concussion from 64% to 83% (a net increase of 19%). The CISG describes neurocognitive assessment as a “cornerstone” of concussion management (McCrory et al., 2013).

Neurocognitive testing is a crucial component of a multifaceted-multimodal approach to concussion management. Computerized neurocognitive testing, such as the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT), is commonly used to assess cognition and manage recovery following concussion. The ImPACT is a research-based, computerized neuropsychological screening test battery designed specifically to help clinicians evaluate recovery and track cognition following sports-related concussion. The test consists of six individual test modules that measure different aspects of cognitive functioning including attention, memory, reaction time, and processing speed. Each test module contributes scores to generate 4 composite scores (i.e., verbal memory, visual memory, processing speed, and reaction time). The verbal memory composite evaluates attentional processes, learning, and memory within the verbal domain. The visual memory composite evaluates visual attention and scanning, as well as learning and memory within the visual domain. The visual motor speed (processing speed) composite
evaluates visual processing, learning, and memory, as well as visual-motor response speed. The reaction time composite evaluates average response speed. The test battery also includes an impulse control score that provides a measure of errors on the test (ImPACT Technical Manual, 2011).

In addition, the ImPACT test battery contains a list of 22 commonly reported symptoms called the Post-Concussion Symptom Scale (PCSS). Each symptom is rated using a Likert-type scale ranging from 0 (not currently experiencing) to 6 (most severe) (Aubry et al., 2002; Lovell et al., 2003; Guskiewicz et al., 2004). A total symptom score is obtained by adding up the ratings for each symptom. Pardini et al. (2004) conducted a factor analysis to delineate potential core symptom clusters based on the 22 concussion-related symptoms of the PCSS. The exploratory factor analysis identified a 4-factor solution that contained an 8-item somatic symptoms factor (i.e., migraine symptom cluster), a 7-item cognitive and slowing problems factor (i.e., cognitive symptom cluster), a 2-item sleep problems factor (i.e., sleep symptom cluster), and a 4-item emotionality factor (i.e., neuropsychiatric symptom cluster). The authors concluded that the 4 symptom clusters may reflect different subtypes of concussion (Pardini et al., 2004).

Research suggests that the ImPACT is a reliable (Schatz, 2010; Elbin et al., 2011; Schatz et al., 2013) and valid (Iverson et al., 2003; Iverson et al., 2005; Schatz & Putz, 2006; Maerlender et al., 2010; Allen & Gfeller, 2011; Maerlender et al., 2013) measurement of neurocognitive functioning following sports-related concussion. Studies also show that the ImPACT has a high degree of sensitivity and specificity in diagnosing sports-related concussion (Collins et al., 1999; Barr & McCrea, 2001; Collins et al., 2003; Field et al., 2003; Lovell et al., 2004; Iverson et al., 2005; Iverson et al., 2006; Schatz & Sandel, 2013). Schatz and colleagues (2006) found that the test battery diagnoses concussions with 85.5% accuracy, 81.9% sensitivity, and 89.4% specificity. Only one study stated that the ImPACT lacks sensitivity to detect clinical meaningful cognitive decline following concussion (Echemendia et al., 2012). Another study found that the verbal memory and visual memory composite scores are more variable than the visual-motor (processing) speed and reaction time composite scores (Resch et al., 2013).
Iverson, Lovell, and Collins (2003) provided detailed information regarding interpretation of change on the ImPACT by calculating reliable change confidence intervals for each ImPACT composite score. Proper interpretation of test results requires an understanding of the probable range of measurement error that surrounds test-retest difference scores. Confidence intervals can be used to specify a range of values within which the difference between scores of a test-retest situation lies. A cohort of 56 healthy adolescents and young adults completed the ImPACT 2 times, approximately 7 days apart, in order to estimate test-retest reliability, practice effects, and reliable change parameters. The 80% confidence intervals for interpreting change from baseline to post-concussion included $\pm 9$ points for the verbal memory composite, $\pm 14$ points for the visual memory composite, $\pm 0.06$ s for the reaction time composite, $-3$ points and $+7$ points for the processing speed composite, and $\pm 10$ points for the total PCSS score. It is important to note that there was a significant difference between scores at baseline and retest for the processing speed composite. Approximately 68% of the sample was faster at retest than at baseline (1.7 practice effect). Therefore, the reliable change estimate for the processing speed composite ($\pm 5$ points) was adjusted by two points for the presumed practice effect (Iverson et al., 2003).

In the same study, the researchers applied the derived reliable change indices to 41 amateur athletes who had sustained a sports-related concussion (Iverson et al., 2003). The concussed athletes took the ImPACT test preseason and within 72 hours following their injury. The researchers counted the number of scores that reliably declined from baseline to post-concussion for each athlete. Overall, 24.4% of the athletes showed no decline, 12.2% showed 1 decline, 14.6% showed 2 declines, 17.1% showed 3 declines, 19.4% showed 4 declines, and 12.2% showed 5 declines. The concussed athletes demonstrated significantly lower verbal and visual memory composite scores, slower reaction time and processing speed scores, and reported a higher number of symptoms compared to healthy individuals. In particular, large changes were seen in verbal memory scores, reaction time scores, and self-reported symptoms. The
researchers concluded that the derived reliable change indices allows for more precise determination of deterioration, improvement, and recovery following concussion (Iverson et al., 2003).

1.4 Predicting Protracted Recovery

McCrea (2008) notes that there are several unknowns and clinical dilemmas in diagnosing and managing concussions. There are dilemmas about recovery (i.e., How long should it take to recover after concussion?), prognosis (i.e., What are the acute and subacute predictors of positive and negative outcomes?), and outcome (i.e., What are the best methods to assess recovery and functional outcome after concussion?). With no expectations of recovery time or prognosis following a concussion, teachers and coaches cannot be certain how long a student athlete must be removed from play or the classroom. Recent studies have examined the prognostic value of computerized neurocognitive test scores and symptom profiles in predicting protracted recovery from sports-related concussion (Iverson, 2007; Lau, Lovell, Collins, & Pardini, 2009; Lau, Collins, & Lovell, 2011; and Lau, Collins, & Lovell, 2012).

In 2005, following the Second International Conference on Concussion in Sport, the classification system for sports-related concussion changed to a binary system. Prior to the conference, concussion severity was traditionally rated using a grading scale presented by the American Academy of Neurology (1997). The new classification utilized a 10-day cutoff period to distinguish between a “simple” and “complex” concussion. Iverson (2007) sought to determine if it was possible to predict whether an athlete was going to have a simple or complex concussion within 72 hours of injury on the basis of symptom reporting and neuropsychological testing results. Findings revealed that athletes classified as having a complex concussion performed statistically worse on neuropsychological testing when compared to athletes classified as having a simple concussion. There was a 94% chance that an athlete would have a longer recovery if they displayed 3 of 4 ImPACT composite reliable change deficits, relative to their performance at baseline. Moreover, athletes with complex concussions also reported a higher number of symptoms compared to athletes with simple concussions. This study presented the first preliminary
evidence that suggested that low ImPACT scores and high symptom scores might predict protracted recovery following sports-related concussion (Iverson, 2007).

Lau, Lovell, Collins, and Pardini (2009) sought to identify specific symptom and neuropsychological test patterns that might serve as prognostic indicators of simple and complex concussions in high school athletes. The researchers evaluated the occurrence of the 4 symptom clusters (migraine, cognitive, sleep, and neuropsychiatric) identified in the Pardini et al. (2004) study and their importance in predicting recovery and return to play (Lau et al., 2009). They found that both an athlete’s neuropsychological performance and self-reported symptoms had predictive value in determining length of recovery. Moreover, the researchers found that the ImPACT reaction time composite score and migraine symptom cluster score had the strongest predictive power (Lau et al., 2009).

Following the Third International Conference on Concussion in Sport (2009), the 10-day cutoff to distinguish between simple and complex concussions was no longer supported. Concurrent findings in the literature demonstrated that typical recovery from sports-related concussions occurs within 10 to 14 days of injury (Lovell et al., 2003; Iverson et al., 2006; Makdissi et al., 2010). Subsequent studies adopted a 14-day cutoff period to distinguish between athletes who will have a relatively quick recovery from those who will take longer to recover. Two recent studies (Lau et al., 2011; Lau et al., 2012) utilized this 14-day cutoff period. In one study, Lau and colleagues (2011) sought to quantify how well symptom profiles and computerized neurocognitive test results could predict protracted recovery during the subacute recovery phase (within 2 days) following a sports-related concussion. 108 male high school football players completed the ImPACT test preseason and within 2.23 days of injury. Once the athletes returned to play, they were classified as having either a short (≤ 14 days) or protracted (> 14 days) recovery. The researchers tested five different combinations of variables for their prognostic value (i.e. total symptom score (PCSS) alone, 4 symptom clusters, 4 ImPACT composite scores, 4 symptom clusters in combination with 4 ImPACT composite clusters, and migraine cluster alone).
Lau and colleagues used discriminant function analysis to identify how accurately the combinations of variables could predict protracted recovery from sports-related concussion. Results in the Lau et al. (2011) study showed that the use of the 4 ImPACT composite scores (i.e., verbal memory, visual memory, processing speed, and reaction time) in conjunction with the 4 symptom clusters (i.e., migraine, cognitive, sleep, and neuropsychiatric) had the highest percentage of accuracy, sensitivity, specificity, positive predictive value, and negative predictive value. Together neurocognitive composite scores and symptom cluster scores classified the group of male high school football players with 73.5% accuracy, 65.2% sensitivity, 80.4% specificity, 73.2% positive predictive value, and 73.8% negative predictive value. Canonical coefficient analysis revealed that the migraine cluster, visual memory, verbal memory, and reaction time composite scores were the strongest predictors (Lau et al., 2011). It is important to note that the results in this study cannot be generalized to female athletes, collegiate or professional athletes, or athletes from sports other than football, because the study only included male high school football players.

In a second study, Lau et al. (2012) aimed to build on their previous study by identifying clinically objective cutoff scores to help set numerical thresholds for predicting protracted recovery. Using the same subjects in their previous study, Lau and colleagues implemented receiver-operating characteristic (ROC) curves to determine possible numerical cutoff values for each of the neurocognitive and symptom cluster scores. ROC curves “provide a pure index of [diagnostic] accuracy by demonstrating the limits of a test’s ability to discriminate between alternative states of health over the complete spectrum of operating conditions” (Zweig & Campbell, 1993, p. 561). ROC curves plot sensitivity/specificity pairs at different decision thresholds, thereby creating a powerful way to represent the accuracy of a signal detection system. Once the ROC plot is generated, numerous other assessments, comparisons, indices and analyses can follow (Zweig & Campbell, 1993).
The results in the Lau et al. (2012) study yielded cutoff scores for 75%, 80%, and 85% sensitivity to predict protracted recovery following sports-related concussion. Cutoff scores for the 80% sensitivity are as follows: 64.5 or less for verbal memory, 46 or less for visual memory, 23.5 or less for processing speed, .78 or greater for reaction time, 18 or greater for the migraine cluster, 19 or greater for the cognitive cluster, 4.5 or greater for the sleep cluster, and 3 or greater for the neuropsychiatric cluster. It is important to note that a high percentage of sensitivity was achieved at the expense of specificity. Cutoff scores for the visual memory composite, processing speed composite, cognitive symptom cluster, and migraine symptom cluster were statistically significant in discriminating between athletes who had a short recovery versus those who had a protracted recovery. The researchers concluded that the specific cutoff scores may help to set numerical thresholds for clinicians to predict which concussed athletes will have a protracted recovery. Similar to the Lau et al (2011) study, the Lau et al. (2012) study cannot be generalized to different populations of athletes.

According to the ImPACT Technical Manual (2011), the most accurate evaluation of protracted recovery includes the consideration of each neurocognitive composite score and symptom cluster score. In other words, if all of the scores exceed the cutoff criteria, clinicians can be more confident that the athlete will have a protracted recovery. However, more specific information is needed before these methods can be applied clinically. It is not yet clear which combinations of neurocognitive composite scores and symptom cluster scores yield the highest accuracy in the predictive classification of cases. Athletes may frequently exhibit variation in performance across neurocognitive test scores and symptom cluster scores. For example, an athlete may not report any symptoms, but may perform poorly on the neurocognitive test. Or, an athlete may have average visual memory and verbal memory composite scores, but a below average reaction time score. Similarly, an athlete may have high cognitive and sleep symptom cluster scores, but low migraine and neuropsychiatric symptom cluster scores. Examination of
different classification models for predicting protracted recovery may help clinicians account for variability in performance by identifying combinations of variables with the strongest predictive power.

1.5 Statistical Modeling and Discriminant Function Analysis

The current study seeks to examine different combinations of variables (i.e., “classification models”) that can predict whether a concussed athlete will have a short or protracted recovery. “A statistical model is a probability distribution constructed to enable inferences to be drawn or decisions to be made from data” (Davison, 2003, p. iv). Stated simply, statistical modeling is used to generalize the relationship between variables to make inferences about a population on the basis of a sample (Hopkins, 2001). Discriminant function analysis, also known as categorical modeling, is a multivariate statistical technique used to build a classification model on the basis of cases in which group membership and interval variables are already known (Verma, 2013). Once a classification model is developed, it allows for prediction of group membership of new cases when only the interval variables are known. Discriminant function analysis is also used to study the relationship between group membership and variables used to predict group membership (Verma, 2013).

The primary goal of discriminant function analysis is to determine which variables distinguish between two or more groups, and which combinations of variables can be used to predict group membership (StatSoft, Inc., 2013; Poulsen & French, 2004). Poulsen and French (2004) explain that discriminant function analysis is the reversal of multivariate analysis of variance (MANOVA). That is, in MANOVA the groups are the independent variables and the predictors are the dependent variables, whereas in discriminant function analysis, the predictors are the independent variables and the groups are the dependent variables. Discriminant function analysis is a two-step process that includes testing the significance of a set of discriminative functions (computationally identical to MANOVA) and examining how well classification among groups is achieved (Poulsen & French, 2004).
The following measures can be used to determine the goodness-of-fit of a classification model derived from the discriminant function analysis: eigenvalues, canonical correlation coefficients, Wilks’ Lambda, and p value (Hopkins, 2001). Discriminant function analysis also yields a classification matrix that serves as a measure of the accuracy of a model in predicting group membership (Verma, 2013). The classification matrix shows the number of cases that were correctly classified and those that were misclassified by a classification model (StatSoft, Inc., 2013). Via the classification matrix, discriminant function analysis measures the prognostic value of the independent variables in terms of overall classification accuracy (hit ratio), sensitivity, specificity, positive predictive value, and negative predictive value. These clinical measures can also be regarded as measures of the goodness-of-fit of a classification model (Hopkins, 2001).

Sensitivity refers to the ability of a test or variables to correctly classify an individual as having a “disease”, or in this case as having a protracted recovery. It is calculated by taking the number of true positives and dividing it by the sum of the true positives and false negatives. In other words, it is the probability of testing positive when the “disease” is present (Parikh et al., 2008). Specificity refers to the ability of a test or variables to correctly classify an individual as “disease free”, or in this case as having a short recovery. It is calculated by taking the number of true negatives and dividing it by the sum of true negatives and false positives. In other words, it is the probability of testing negative when the “disease” is absent (Parikh et al., 2008). Positive predictive value (PPV) refers to the percentage of individuals who tested positive who actually have a “disease”. It is calculated by taking the number of true positives and dividing it by the sum of the true positives and false positives. It can also be described as the probability of an individual having the “disease” when the test is positive (Parikh et al., 2008). Negative predictive value (NPV) refers to the percentage of individuals who tested negative who do not have a “disease”. It is calculated by taking the number of true negatives and dividing it by the sum of the
false negatives and true negatives. The NPV is the probability of an individual not having the “disease” when the test is negative (Parikh et al., 2008).

Overall, discriminant function analysis is a useful tool for identifying discriminating variables between different groups and for determining classification models that classify cases into different groups with a better than chance accuracy (StatSoft, Inc., 2013). A high overall percentage of classification accuracy indicates that the classification model is valid (Verma, 2013). One way to evaluate the classification accuracy of a model is to ascertain whether the groups are classified at a percentage higher than expected by chance (Humberty, 1984). This can be done by calculating the proportional by chance accuracy rate or the maximum by chance accuracy rate. Model accuracy must be 25% better than chance criteria using either the proportional chance criterion or the maximum chance criterion (Classification accuracy chance criteria, n.d.; Huberty, 1984).

### 1.6 Purpose of Study

The purpose of this study was to further explore the predictive value of computerized neurocognitive test results and self-reported symptoms in predicting protracted recovery from sports-related concussion. This study aimed to systematically replicate and extend previous research by examining the classification accuracy, sensitivity, specificity, and predictive value of neurocognitive test scores and symptom cluster scores in predicting protracted recovery in a group of collegiate athletes. This study investigated which classification models for predicting protracted recovery resulted in the most successful outcomes. This study also examined potential differences between the short and protracted recovery groups in terms of the number of scores that met the cutoff criteria and the number of reliable change deficits at the first post-concussion evaluation. Furthermore, this study evaluated how clinically accurate current return-to-play standards are in predicting recovery of function as determined by whether athletes experienced symptoms during the return-to-play process or thereafter.
The research questions asked included: (1) Can the results of the Lau et al. (2011) study be replicated to a different population of athletes? (2) Which combinations of computerized neurocognitive test scores and symptom cluster scores (classification models) have the highest classification accuracy? (3) Do athletes classified as having a short recovery differ in the number of reliable change deficits and cutoff scores for predicting protracted recovery compared to athletes classified as having a protracted recovery? (4) How accurate are current return-to-play standards in determining whether athletes will be symptom-free during the return-to-play process?

The results of this study will help to determine the reliability and generality of computerized neurocognitive testing and symptom evaluation results in predicting protracted recovery from sports-related concussion. The findings will potentially support clinical decision making in concussion management by identifying specific models for predicting protracted recovery. In addition, the follow-up phone call interviews will provide insight into the clinical success of current return-to-play standards in determining recovery of function. For the purposes of this study, recovery is defined as resolution of clinical signs and symptoms and neurocognitive performance that has returned to baseline or is within the average range of performance based on the normative data; and, protracted recovery is defined as recovery that took longer than 14 days. Addressing these issues will help clinicians to more confidently address return-to-play and academic decisions, thereby potentially preventing athletes from returning to play and school before they have fully recovered.
Chapter 2: Methods and Procedures

2.1 IRB Approval

The university’s institutional review board for human subjects approved this study.

2.2 Study Design

This study is a systematic replication of the Lau et al. (2011) study with a change in participants. It is a cohort study (prognosis) that is used to replicate and extend previous research to a different population of athletes in order to further examine the classification accuracy of computerized neurocognitive test scores and symptom cluster scores in predicting protracted recovery. In this study, athletes were followed clinically until they were released to their athletic trainers to initiate the graduated return-to-play protocol. It is important to note that the concussed athletes’ symptoms and neurocognitive test scores were tracked and monitored until they met criteria for clinical recovery, and that the athletes were retrospectively classified as having a short recovery (≤ 14 days) or a protracted recovery (> 14 days) based on the number of days they took to return to play.

2.3 Participants

Participants were selected from a pre-existing database in the UTEP Concussion Management Clinic (CMC). A total of 66 collegiate athletes from the El Paso Metropolitan area were referred to the UTEP CMC for post-concussion evaluation between 2008 and 2014. All athletes in participating schools who sustained an injury to the head during this time were referred to the UTEP CMC regardless of perceived severity. Only 1 of the athletes who was referred to the clinic was not concussed. Of the 65 athletes who sustained a concussion, 30 athletes (46.3%) were seen in the UTEP CMC until they were released to initiate the graduated return-to-play protocol and were successfully contacted via follow-up phone calls. 10 athletes (15.4%) did not return for their follow-up appointments. 11 athletes (16.9%) did not have documented contact information in their folders. 11 athletes (16.9%) had documented contact information that included a phone number that was either the wrong number, disconnected, could not be
completed as dialed, or was not accepting incoming calls. 2 athletes (3.1%) did not answer the phone, and 1 athlete (1.5%) was on military leave.

Of the 30 collegiate athletes, 9 athletes were classified as having a short recovery (≤ 14 days; mean = 10.56 days to recover) and 21 athletes were classified as having a protracted recovery (> 14 days; mean = 23.33 days to recover). Table 2.1 presents the demographic information for the subject sample used in this study. The subjects in the current study differed from the subject sample in the Lau et al. (2011) study. The subject sample in the Lau et al. (2011) study was more exclusive, consisting entirely of male subjects from Pennsylvania high-school football programs, whereas the current study included both male and female athletes from various sports programs in a university and community college in El Paso, TX.

Table 2.1: Participant Characteristics – El Paso County Collegiate Athletes

<table>
<thead>
<tr>
<th></th>
<th>Short Recovery (≤ 14 days)</th>
<th>Protracted Recovery (&gt; 14 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of athletes (%)</td>
<td>9 (30%)</td>
<td>21 (70%)</td>
</tr>
<tr>
<td>No. of days to initial evaluation</td>
<td>3.56 (SD = 2.30, range = 1 to 8)</td>
<td>4.10 (SD = 3.18, range = 0 to 13)</td>
</tr>
<tr>
<td>No. of days to recover</td>
<td>10.56 (SD = 2.30, range = 8 to 14)</td>
<td>23.33 (SD = 8.32, range = 15 to 42)</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male (%)</td>
<td>6 (66.7%)</td>
<td>14 (66.7%)</td>
</tr>
<tr>
<td>Female (%)</td>
<td>3 (33.3%)</td>
<td>7 (33.3%)</td>
</tr>
<tr>
<td>Average Age</td>
<td>20 (SD = 1.32, range = 18 to 22)</td>
<td>19.95 (SD = 1.24, range = 18 to 23)</td>
</tr>
<tr>
<td>Years of education</td>
<td>13 (SD = 1.32, range = 12 to 15)</td>
<td>12.95 (SD = 1.07, range = 12 to 15)</td>
</tr>
<tr>
<td>Years of college sport experience</td>
<td>1.44 (SD = 2.13, range = 0 to 6)</td>
<td>1.29 (SD = 1.49, range = 0 to 4)</td>
</tr>
</tbody>
</table>
History
ADHD 0 1
Repeated a grade 1 0
Received speech therapy services 0 1
Received special education services 0 1
Headaches 2 4
Meningitis 1 0
Migraines 1 2

History of concussion
None (0) 3 (33.3%) 11 (52.4%)
1 5 (55.6%) 6 (28.6%)
2 1 (11.1%) 2 (9.5%)
3 0 (0%) 1 (4.8%)
4 0 (0%) 1 (4.8%)

Sport
Football (%) 2 (22.2%) 12 (57.1%)
Softball (%) 1 (11.1%) 1 (4.8%)
Baseball (%) 3 (33.3%) 2 (9.5%)
Soccer (%) 1 (11.1%) 2 (9.5%)
Basketball (%) 2 (22.2%) 3 (14.3%)
Cheerleading (%) 0 (0%) 1 (4.8%)

Acute Injury Characteristics
Anterograde amnesia 0 (0%) 2 (10.5%)
Retrograde amnesia 1 (12.5%) 5 (26.3%)
Loss of consciousness 1 (12.5%) 8 (42.1%)

2.4 Instruments

The current study used Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) software to monitor the recovery of athletes who sustained a concussion and were referred to the UTEP CMC. As previously discussed, the ImPACT test battery has a high degree of sensitivity and specificity in diagnosing sports-related concussion, and serves as a reliable and valid measurement of neurocognitive functioning during recovery following sports-related concussion (Schatz et al., 2006; Schatz, 2009; Elbin et al., 2011; Schatz et al., 2013; Iverson et al., 2003; Iverson et al., 2005; Schatz & Putz, 2006; Maerlender et al., 2010; Allen & Gfeller, 2011; Maerlender et al., 2013; Collins et al., 1999; Barr & McCrea, 2001;
Collins et al., 2003; Field et al., 2003; Lovell et al., 2004; Iverson et al., 2005; Iverson et al., 2006; Schatz & Sandel, 2013). The ImPACT test battery takes approximately 20 to 30 minutes to complete and requires the use of a computer screen, mouse, and keyboard. The test consists of three sections: demographic profile and health history questionnaire, current concussion symptoms and conditions, and the neurocognitive test.

For the first part of the test, the student athlete is asked to provide basic demographic and descriptive information, such as age, weight, sex, sport, position, history of concussion, and relevant medical history. Next, the athlete is required to use a 7-point Likert-type scale to rate the presence and severity of 22 concussion-related symptoms. The Post-Concussion Symptom Scale (PCSS) is a “state” measure of perceived symptoms associated with concussion (i.e., the athlete is asked to report their current symptoms at the time of each post-concussive evaluation). The 4 symptom clusters (migraine, cognitive, sleep, and neuropsychiatric) established in the Pardini et al. (2004) study and the individual symptoms that make up each cluster are summarized in Table 2.2. Finally, the athlete must complete 6 neurocognitive modules (Word Memory, Design Memory, X’s and O’s, Symbol Match, Color Match, and Three Letter Memory). Scores from the 6 neurocognitive modules generate 4 composite scores (verbal memory, visual memory, processing speed, and reaction time). The individual tests and the construction of composite scores are summarized in Table 2.3.

Table 2.2: PCSS Symptom Clusters

<table>
<thead>
<tr>
<th>Migraine Cluster</th>
<th>Cognitive Cluster</th>
<th>Sleep Cluster</th>
<th>Neuropsychiatric Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headaches</td>
<td>Fatigue</td>
<td>Difficulty falling asleep</td>
<td>Feeling more emotional</td>
</tr>
<tr>
<td>Visual problems</td>
<td>“Mental fogginess”</td>
<td>Sleeping less than usual</td>
<td>Sadness</td>
</tr>
<tr>
<td>Dizziness</td>
<td>Drowsiness</td>
<td>Sleeping more than usual</td>
<td>Nervousness</td>
</tr>
<tr>
<td>Sensitivity to noise</td>
<td>Difficulty</td>
<td></td>
<td>Irritability</td>
</tr>
<tr>
<td>Sensitivity to light</td>
<td>concentrating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nausea/vomiting</td>
<td>Difficulty remembering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balance problems</td>
<td>Feeling slowed down</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Numbness/tingling</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*aSymptom clusters first described by Pardini et al. (2004)*
Table 2.3: ImPACT Neurocognitive Composite Scores*a

<table>
<thead>
<tr>
<th>Verbal Memory</th>
<th>Visual Memory</th>
<th>Processing Speed</th>
<th>Reaction Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Word Memory</td>
<td>- Design Memory</td>
<td>- Total Number Correct/ 4 during</td>
<td>- Average Correct RT of Interference</td>
</tr>
<tr>
<td>(module 1) Total</td>
<td>(module 2) Total</td>
<td>Interference of X’s and O’s (module 3)</td>
<td>Stage of X’s and O’s (module 3)</td>
</tr>
<tr>
<td>Percent Correct</td>
<td>Percent Correct</td>
<td>- Average Counted Correctly*3 from</td>
<td>- Symbol Match (module 4) Average</td>
</tr>
<tr>
<td>- Symbol Match</td>
<td>- X’s and O’s</td>
<td>Countdown Phase of Three Letters</td>
<td>Correct RT (module 4) Average</td>
</tr>
<tr>
<td>(module 4) (Total</td>
<td>(module 3) (Total</td>
<td>(module 6)</td>
<td>- Color Match (module 5) Average</td>
</tr>
<tr>
<td>Correct Hidden)/9*100</td>
<td>Correct Memory)/12*100</td>
<td></td>
<td>Correct RT</td>
</tr>
<tr>
<td>- Three Letters</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(module 6) Percent</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Total Letters</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Percent Correct</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Correct</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*aComposite scores as described in the ImPACT Test Technical Manual (2011)

After referral to the UTEP CMC, the athletes were followed clinically using the ImPACT and PCSS to monitor their neurocognitive status and self-reported symptoms throughout their recovery. All baseline and post-concussion evaluations were collected using the same version of the ImPACT test battery. Athletes’ neurocognitive test scores and symptom cluster scores at the first post-concussion evaluation were used to replicate and extend the Lau et al. (2011) study. In addition, this study compared the predictive value of previously established reliable change indices (Iverson et al., 2003) and cutoff scores for predicting protracted recovery (Lau et al. 2012). Table 2.4 shows the reliable change difference scores for the 4 ImPACT neurocognitive composite scores (verbal memory, visual memory, processing speed, and reaction time). Table 2.5 shows cutoff scores for the 4 ImPACT neurocognitive composite scores and the 4 PCSS symptom clusters (migraine, cognitive, sleep, and neuropsychiatric) at the 75%, 80%, and 85% sensitivity.
Table 2.4: ImPACT Reliable Change Deficits – 80% Confidence Interval

<table>
<thead>
<tr>
<th>Composite</th>
<th>Reliable Change Deficit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal Memory</td>
<td>–9 points</td>
</tr>
<tr>
<td>Visual Memory</td>
<td>–14 points</td>
</tr>
<tr>
<td>Processing Speed</td>
<td>–3 points</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>+ 0.06 s</td>
</tr>
<tr>
<td>PCSS</td>
<td>+ 10 points</td>
</tr>
</tbody>
</table>

*Reliable change deficits first described by Iverson et al. (2003)

Table 2.5: Neurocognitive Composite and Symptom Cluster Cutoff Scores for Predicting Protracted Recovery

<table>
<thead>
<tr>
<th>Variable</th>
<th>75% Sensitivity</th>
<th>80% Sensitivity</th>
<th>85% Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal Memory</td>
<td>66.5</td>
<td>64.5</td>
<td>60.5</td>
</tr>
<tr>
<td>Visual Memory</td>
<td>48.0</td>
<td>46.0</td>
<td>44.5</td>
</tr>
<tr>
<td>Processing Speed</td>
<td>24.5</td>
<td>23.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>.72</td>
<td>.78</td>
<td>.86</td>
</tr>
<tr>
<td>Migraine</td>
<td>15</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Cognitive</td>
<td>18</td>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td>Sleep</td>
<td>3</td>
<td>4.5</td>
<td>6</td>
</tr>
<tr>
<td>Neuropsychiatric</td>
<td>2.5</td>
<td>3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

*Neurocognitive composite and symptom cluster cutoff scores first described by Lau et al. (2012)

2.5 Procedures

The UTEP CMC concussion management protocol adheres to international return-to-play standards for the clinical management and care of concussed athletes. Specific details of current international return-to-play standards can be found in the consensus statements on concussion in sport that summarize the recommendations following the 1st (Vienna 2001), 2nd (Prague 2004), 3rd (Zurich 2008), and 4th (Zurich 2012) International Conferences on Concussion in Sport (Aubry et al., 2002; McCrory et al., 2005; McCrory et al., 2009; McCrory et al., 2013). Under agreement with participating schools’ athletic trainers, all athletes must complete baseline neurocognitive testing through the UTEP CMC before beginning practice and training with their respective teams. The participating schools’ athletic trainers also agreed that student athletes who sustained a concussion would not be permitted to return-to-play until
the UTEP CMC recommended the athletes initiate the return-to-play protocol once they met clinical
return-to-play criteria.

All of the athletes in the current study underwent preseason neurocognitive evaluation using the
ImPACT and the PCSS – with the exception of 2 athletes who did not take the test preseason. Similar to
the Lau et al. (2011) study, concussed athletes were followed clinically rather than according to a
controlled research protocol. The ImPACT and the PCSS were administered during the initial evaluation
and at each post-concussion evaluation. Post-concussion evaluations were conducted approximately 1, 2,
3, and 4 weeks post-injury, and more if it was necessary. Athletes were evaluated by undergraduate and
graduate research assistants who were volunteering/working in the UTEP CMC, and supervised by an
experienced and ASHA certified speech-language pathologist.

Athletes had to meet two clinical criteria before being released to return to play. First, an athlete’s
neurocognitive performance had to return to their performance at baseline. If an athlete did not have
available baseline data, their neurocognitive scores were compared to age-specific normative data (i.e., an
athlete’s scores had to be at least in the average performance range). Second, international protocols
require that an athlete must be asymptomatic at rest before progression through a stepwise exertional
program with subsequent increasing levels of physical activity. No athlete was released from the UTEP
CMC until their total PCSS score was less than 7. Iverson and colleagues (2003) noted that 76% of
nonconcussed adolescents and young adults had a total symptom score of 6 or less, with a large proportion
having a score of 0 (40.5%). Previous studies used the same threshold requiring an athlete to have a total
PCSS score of less than 7 before returning to play (Iverson, 2007; Lau et al., 2009; Lau et al., 2011; Lau
et al., 2012).

After meeting the two clinical criteria, the athletes were released to their athletic trainers for
progression through the graduated return-to-play protocol. The UTEP CMC recommended that each
athlete successfully complete the graduated return-to-play protocol without experiencing symptoms at any
level before returning to play. The graduated return-to-play protocol requires an athlete to gradually increase the amount of physical exertion over a 5 days so long as they remained asymptomatic (McCrory et al., 2013). The graduated return-to-play protocol is outlined in Table 2.6. If an athlete reports experiencing any post-concussion symptoms during the stepwise progression, the athlete is required to drop back to the previous level and attempt to progress again after they have rested for 24 hours (McCrory et al., 2013). All physical activity was monitored by the collegiate athletes’ athletic trainers.

Table 2.6: Graduated Return-to-Play Protocol

<table>
<thead>
<tr>
<th>Rehabilitation Stage</th>
<th>Physical Exertion Activity</th>
<th>Objective of Each Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No activity</td>
<td>Total rest protocol (no physical or mental exertion)</td>
<td>Recovery</td>
</tr>
<tr>
<td>2. Light aerobic</td>
<td>Walking, swimming, or stationary cycling keeping intensity &lt; 70% maximum permitted heart rate (no resistance training)</td>
<td>Increase heart rate</td>
</tr>
<tr>
<td>exercise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Sport-specific</td>
<td>Skating in ice hockey or running in soccer (no head-impact activities)</td>
<td>Add movement</td>
</tr>
<tr>
<td>exercise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Non-contact</td>
<td>Progression to more complex training drills, such as passing drills in football, ice hockey, and soccer (may start progressive resistance training)</td>
<td>Exercise, coordination and cognitive load</td>
</tr>
<tr>
<td>training skills</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Full-contact</td>
<td>Regular drills and normal training activities after medical clearance</td>
<td>Restore confidence and assess functional skills by coaching staff</td>
</tr>
<tr>
<td>practice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Return to play</td>
<td>Regular game play</td>
<td></td>
</tr>
</tbody>
</table>

As part of the UTEP CMC protocol, information obtained during baseline and post-concussion evaluations, including ImPACT and PCSS scores, were entered in a pre-existing database. The database is located in the UTEP CMC on a password protected computer. The investigator conducted follow-up phone calls between 3 months to 5 years post-injury to obtain athletes’ consent to use their data in the current study. The investigator asked the athletes specific questions about the recovery from their concussion (See Appendix A for the telephone script used in this study). First, the athletes were asked when they started the graduated return-to-play protocol. Then, they were asked how many days they took
to complete the return-to-play protocol before they returned to play. This information was used to document each athlete’s exact return-to-play date and to calculate the length of recovery following their injury. The athletes were then retrospectively classified as having a short recovery ($\leq 14$ days) or a protracted recovery ($> 14$ days) based on the number of days they took to return to play.

### 2.6 Statistical Analysis

SPSS version 20.0 software was used in this study. A series of $t$ tests were used to examine the possible differences between the short and protracted recovery groups for factors such as age, gender, years of education, years of collegiate sport experience, history of concussion, history of migraine, history of treatment for headache, and presence/absence of attention deficit hyperactivity disorder. A series of $t$ tests were also used to determine the difference between the two groups with regard to the presence/absence of loss of consciousness and posttraumatic amnesia (i.e., anterograde and retrograde amnesia). Multivariate analysis of variance (MANOVA) and univariate analysis of variance (ANOVA) were conducted to determine between and within group differences with regard to the 4 ImPACT neurocognitive composite scores (verbal memory, visual memory, processing speed, and reaction time) and 4 PCSS symptom cluster scores (migraine, cognitive, sleep, and neuropsychiatric). The 4 neurocognitive scores and 4 symptom clusters constituted the dependent variables, and the short and protracted recovery groups constituted the independent variables. In addition, a series of $t$ tests were also used to determine the potential differences between the short and protracted recovery groups in terms of the number of reliable change deficits and the number of scores that met the 75%, 80%, and 85% sensitivity cutoff criteria for predicting protracted recovery.

Discriminant function analysis was performed with the 4 PCSS symptom clusters and the 4 ImPACT neurocognitive scores separately, then combined. Discriminant function analysis was also used to investigate different combinations of variables that had the highest classification accuracy. In all of the discriminant function analyses, the recovery groups (short versus protracted) constituted the
dependent variables, and the different neurocognitive composite and symptom cluster scores constituted the independent variables. Classification accuracy was calculated for each discriminant function analysis to examine how well neurocognitive composite scores and symptom cluster scores can predict protracted recovery from sports-related concussion. Model accuracy was evaluated using the maximum chance criterion (Classification accuracy chance criteria, n.d.; Huberty, 1984).

Sensitivity, specificity, positive predictive value, and negative predictive value were also calculated to assess the goodness-of-fit for each model. Similar to the Lau et al. (2011) and Lau et al. (2012) studies, sensitivity refers to the ability of the tested variables to accurately identify athletes who will have a protracted recovery, when they indeed have a protracted recovery (i.e., they do not recover within 14 days). Specificity refers to the ability of the variables to accurately identify athletes who will not have a protracted recovery, when they indeed have a short recovery (i.e., they recover within 14 days, not protracted recovery = short recovery). The positive predictive value is the proportion of athletes correctly classified as having a protracted recovery who actually have a protracted recovery. The negative predictive value is the proportion of athletes correctly classified as not having a protracted recovery, who actually did not have a protracted recovery.
Chapter 3: Results

This study was designed to systematically replicate and extend previous research in examining the predictive value of computerized neurocognitive test scores and symptom cluster scores in predicting protracted recovery following sports-related concussion. Data was collected and analyzed using the collegiate athletes’ preseason and initial post-concussion evaluation Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) and Post-Concussion Symptom Scale (PCSS) scores. Athletes were retrospectively classified as having a short recovery (≤ 14 days) or a protracted recovery (> 14 days) based on the number of days they took to return to play. Potential differences between the two recovery groups were explored. Discriminant function analysis was used to investigate how well the neurocognitive test scores and symptom cluster scores could predicting group membership. Classification of accuracy, sensitivity, specificity, positive predictive value, and negative predictive value were used to identify which models (combinations of variables) for predicting protracted recovery had the most successful outcomes. Furthermore, follow-up phone calls were conducted to obtain specific details of each athlete’s recovery process in order to determine how accurate current return-to-play standards are in determining recovery of functioning.

3.1 Group Differences

Of the 30 collegiate athletes, 9 athletes (30% of the subjects, 6 males and 3 females) were classified as having a short recovery (≤ 14 days), and 21 athletes (70% of the subjects, 14 males and 7 females) were classified as having a protracted recovery (> 14 days). Subject demographic information is provided in Table 2.1. There was no significant difference between the two groups in terms of the mean time from when the injury occurred to the initial evaluation ($t = -0.46, p = .650$). Initial evaluation typically occurred within 4 days from injury (short recovery group = 3.56, protracted recovery group = 4.10). There was a significant difference between the short recovery group and the protracted recovery group with regard to average length of recovery ($t = 6.07, p = .000$). The mean length of recovery for the short recovery group
was significantly shorter (mean = 10.56 days, SD = 2.30) than the mean length of recovery for the protracted recovery group (mean = 23.33 days, SD = 8.32). It should be noted that 3 athletes classified as having a protracted recovery were not included in this analysis because they had prolonged return-to-play dates due to factors other than not meeting the clinical criteria to initiate the graduated return-to-play protocol. Specifically, one athlete did not return to play until after she graduated from college, one athlete’s return-to-play date was prolonged due to a knee injury, and another athlete’s return-to-play date was prolonged due to missed follow-up appointments. Overall, the average length of recovery in this sample of concussed athletes was 19 days. The two groups did not differ significantly with regard to age ($t = .09, p = .926$), education ($t = .10, p = .918$), or collegiate sport experience ($t = .24, p = .816$). The average age for the athletes was 19.97 years old (short recovery group = 20, protracted recovery group = 19.95). The short recovery group completed an average of 13 years of education and had an average of 1.44 years of collegiate sport experience, whereas the protracted recovery group completed an average of 12.95 years of education and had 1.29 years of collegiate sport experience.

A series of $t$ tests were also used to examine the potential significance of factors such as history of headache, migraine, and presence or absence of attention deficit hyperactivity disorder on recovery time: headache ($t = .19, p = .849$), migraine ($t = .13, p = .899$), ADHD ($t = -.65, p = .522$). There were no significant differences noted between the short and protracted recovery groups. Overall, six athletes reported receiving treatment for headaches (short recovery group = 2, protracted recovery group = 4), three athletes reported receiving treatment for migraines (short recovery group = 1, protracted recovery group = 2), and only one athlete in the protracted recovery group reported being diagnosed with ADHD. There was also no significant difference between the two groups in terms of athletes who reported receiving speech therapy ($t = -.65, p = .522$) or special education services ($t = -.65, p = .522$). Only one athlete in the protracted recovery group reported receiving speech therapy, and a different athlete in the protracted recovery group reported receiving special education services. Moreover, the athletes in the two
recovery groups did not differ with respect to reporting having received treatment for meningitis \((t = 1.00, p = .347)\) or having to repeat a grade level \((t = 1.00, p = .347)\). Only one athlete in the short recovery group reported having a history of receiving treatment for meningitis, and a different athlete in the short recovery group reported having to repeat a grade level. None of the athletes reported having a learning disability, nor did they report having a history of having brain surgery or receiving treatment for substance abuse, epilepsy, or a psychological condition.

Independent-samples \(t\) tests were also used to compare the concussion history of each group. There was no significant difference between the short and protracted recovery groups with regard to history of concussion \((t = .94, p = .355)\) or number of previous concussions \((t = -.08, p = .938)\). Overall, 16 athletes (53.3%) reported sustaining one or more concussions prior to their involvement in the study. There were 6 (66.7%) and 10 (47.6%) athletes who reported a history of concussion in the short and protracted groups, respectively. The majority of athletes in this study were football players \((n = 14; 46.7\%)\), followed by baseball players \((n = 5; 16.7\%)\), softball players \((n = 5; 16.7\%)\), soccer players \((n = 3; 10\%)\), basketball players \((n = 2; 6.7\%)\), and cheerleaders \((n = 1; 3.3\%)\). A higher percentage of football players were classified as having a protracted recovery \((12 \text{ out of } 14; 85.7\%)\), compared to those classified as having a short recovery \((2 \text{ out of } 14; 14.3\%)\). This information is presented in Table 2.1.

In addition, a series of \(t\) tests were also used to determine the difference between the two groups with regard to acute injury characteristics (i.e., loss of consciousness, anterograde amnesia, and retrograde amnesia). Only 27 out of the 30 athletes in the study had documented information for the three variables during the initial post-concussion evaluation (short recovery = 8, protracted recovery = 19). There was no significant difference between the two groups with regard to any of the acute injury characteristics: loss of consciousness \((t = 1.73, p = .099)\), anterograde amnesia \((t = 1.46, p = .163)\), and retrograde amnesia \((t = .77, p = .450)\). Nonetheless, a greater number and percentage of athletes in the protracted recovery group reported experiencing these three symptoms at the time of injury, compared to athletes in the short
recovery group. Only 1 athlete in the short recovery group reported experiencing LOC, compared to 8 athletes in the protracted recovery group (42.1%). None of the athletes in the short recovery group reported experiencing anterograde amnesia, whereas 2 athletes in the protracted recovery group did (10.5%). Only one athlete in the short recovery group reported experiencing retrograde amnesia, while 5 athletes in the protracted recovery group reported experiencing this symptom (26.3%).

3.2 Neurocognitive Performance and Symptom Profiles

Table 3.1 displays the neurocognitive composite scores and symptom cluster scores for the short and protracted recovery groups. Although the athletes in the protracted recovery group performed worse on the neurocognitive test and reported a higher number of symptom scores compared to athletes in the short recovery group, multivariate analysis of variance (MANOVA) – with the recovery groups as the independent variable and with the 4 ImPACT composite scores and the 4 PCSS symptom cluster cutoff scores as the dependent variables – was not significant ($F = .90, p = .531$). Univariate analyses of variance showed significant differences between the short and protracted recovery groups on the visual motor speed (processing speed) composite score ($F = 7.30, p = .012$). The visual memory composite score approached significance ($F = 4.17, p = .051$). The other variables were not significantly different: verbal memory ($F = 2.51, p = .124$), reaction time ($F = 2.64, p = .116$), migraine cluster ($F = 2.70, p = .111$), cognitive cluster ($F = 2.32, p = .139$), sleep cluster ($F = 1.25, p = .274$), and neuropsychiatric cluster ($F = .20, p = .660$).

Table 3.1: ImPACT Composite Scores and PCSS Symptom Cluster Scores

<table>
<thead>
<tr>
<th></th>
<th>Short Recovery (≤ 14 days)</th>
<th>Protracted Recovery (&gt; 14 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal Memory</td>
<td>88.33 (SD = 12.48)</td>
<td>78.86 (SD = 15.91)</td>
</tr>
<tr>
<td>Visual Memory</td>
<td>80.89 (SD = 10.95)</td>
<td>68.38 (SD = 16.83)</td>
</tr>
<tr>
<td>Processing Speed</td>
<td>41.38 (SD = 4.74)</td>
<td>34.31 (SD = 7.71)</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>.56 (SD =.08)</td>
<td>.64 (SD =.13)</td>
</tr>
<tr>
<td>Total Symptom Score</td>
<td>12.33 (SD = 15.30)</td>
<td>22.62 (SD = 16.41)</td>
</tr>
<tr>
<td>Migraine Symptom Cluster</td>
<td>5.78 (SD = 6.50)</td>
<td>10.19 (SD = 6.83)</td>
</tr>
<tr>
<td>Cognitive Symptom Cluster</td>
<td>3.44 (SD = 4.88)</td>
<td>7.19 (SD = 6.63)</td>
</tr>
<tr>
<td>Sleep Symptom Cluster</td>
<td>1.33 (SD = 1.66)</td>
<td>2.57 (SD = 3.12)</td>
</tr>
<tr>
<td>Neuropsychiatric Symptom Cluster</td>
<td>1.78 (SD = 3.90)</td>
<td>2.52 (SD = 4.33)</td>
</tr>
</tbody>
</table>
Differences between the two recovery groups in terms of previously described ImPACT reliable change indices and ImPACT neurocognitive composite and PCSS symptom cluster cutoff scores for predicting protracted recovery were also examined. Table 3.2 shows the number and percentage of athletes with reliable change deficits on the 4 ImPACT composite scores (verbal memory, visual memory, processing speed, and reaction time) and on the total PCSS score. It is important to note that this information does not include the 2 athletes who did not have available baseline data. A higher percentage of athletes classified in the protracted recovery group had reliable change deficits across all of the neurocognitive composite scores compared to athletes classified in the short recovery group. The total PCSS score was the most frequently occurring reliable change deficit from baseline to initial post-concussion evaluation for both groups (short recovery group = 33.3%, protracted recovery group = 68.4%). Athletes classified in the protracted recovery group were also more likely to meet cutoffs at 80% sensitivity for the 4 ImPACT composite scores (verbal memory, visual memory, processing speed, and reaction time) and 4 PCSS symptom clusters (migraine, cognitive, sleep, and neuropsychiatric), compared to athletes classified in the short recovery group. This information is presented in Table 3.3.

Table 3.2: Number and Percentage of Athletes with ImPACT Reliable Change Deficits

<table>
<thead>
<tr>
<th></th>
<th>Short Recovery</th>
<th>Protracted Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(≤ 14 days)</td>
<td>(&gt;14 days)</td>
</tr>
<tr>
<td>Verbal Memory</td>
<td>2 (22.22%)</td>
<td>5 (26.32%)</td>
</tr>
<tr>
<td>Visual Memory</td>
<td>0 (0%)</td>
<td>3 (15.79%)</td>
</tr>
<tr>
<td>Processing Speed</td>
<td>1 (11.11%)</td>
<td>6 (31.58%)</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>1 (11.11%)</td>
<td>7 (36.84%)</td>
</tr>
<tr>
<td>PCSS</td>
<td>3 (33.33%)</td>
<td>13 (68.42%)</td>
</tr>
</tbody>
</table>

Short recovery group (n = 9), protracted recovery group (n = 19)
Table 3.3: Number and Percentage of Athletes who met the 80% Sensitivity Cutoff Criteria for Each ImPACT Composite Score and PCSS Symptom Cluster Score

<table>
<thead>
<tr>
<th></th>
<th>Short Recovery (≤ 14 days)</th>
<th>Protracted Recovery (&gt;14 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal Memory</td>
<td>1 (11.11%)</td>
<td>3 (14.29%)</td>
</tr>
<tr>
<td>Visual Memory</td>
<td>0 (0%)</td>
<td>2 (9.52%)</td>
</tr>
<tr>
<td>Processing Speed</td>
<td>0 (0%)</td>
<td>3 (14.29%)</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>0 (0%)</td>
<td>4 (19.05%)</td>
</tr>
<tr>
<td>Migraine Cluster</td>
<td>0 (0%)</td>
<td>3 (14.29%)</td>
</tr>
<tr>
<td>Cognitive Cluster</td>
<td>0 (0%)</td>
<td>1 (4.76%)</td>
</tr>
<tr>
<td>Sleep Cluster</td>
<td>0 (0%)</td>
<td>6 (28.57%)</td>
</tr>
<tr>
<td>Neuropsychiatric Cluster</td>
<td>1 (11.11%)</td>
<td>6 (28.57%)</td>
</tr>
</tbody>
</table>

Table 3.4 shows the frequency of the total number of ImPACT reliable change deficits for the short and protracted recovery groups. The difference between the short recovery group and the protracted recovery groups in terms of the number of reliable change differences including the total PCSS score was not statistically significant ($t = -1.73$, $p = .096$). The difference between the two recovery groups approached significance when the total PCSS score was not included ($t = -2.02$, $p = .054$). Over half of the athletes classified as having a short recovery demonstrated 0 ImPACT reliable change deficits from baseline to the first post-concussion evaluation ($n = 5; 55.6\%$), while less than half of athletes demonstrated 1 or more reliable change deficits ($n = 4; 44.4\%$). Conversely, the majority of athletes classified as having a protracted recovery demonstrated 1 or more reliable change deficits ($n = 14; 73.7\%$), while fewer athletes demonstrated 0 reliable change deficits ($n = 5; 26.3\%$).

Table 3.4: Total Number of ImPACT Reliable Change Deficits

<table>
<thead>
<tr>
<th></th>
<th>Short Recovery (≤ 14 days)</th>
<th>Protracted Recovery (&gt;14 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5 (55.56%)</td>
<td>5 (26.32%)</td>
</tr>
<tr>
<td>1</td>
<td>2 (22.22%)</td>
<td>5 (26.32%)</td>
</tr>
<tr>
<td>2</td>
<td>2 (22.22%)</td>
<td>3 (15.78%)</td>
</tr>
<tr>
<td>3</td>
<td>0 (0%)</td>
<td>4 (21.05%)</td>
</tr>
<tr>
<td>4</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>5</td>
<td>0 (0%)</td>
<td>2 (10.53%)</td>
</tr>
</tbody>
</table>

Short recovery group ($n = 9$), protracted recovery group ($n = 19$)
There was a significant difference between the two groups with regard to the number of ImPACT scores and PCSS symptom cluster scores that met the 80% sensitivity cutoff criteria \( t = -2.86, p = .008 \). The majority of athletes in the short recovery group did not have any scores that met the 80% sensitivity cutoff criteria \( n = 8; 88.9\% \). Only 1 athlete in the short recovery group had two scores that met the cutoff criteria. Athletes with a protracted recovery, on the other hand, were much more likely to have at least one score that met the 80% sensitivity cutoff criteria \( n = 13; 61.9\% \). This information is shown in Table 3.5.

Independent \( t \) tests were also used to determine the difference between the two groups with regard to scores that met the 75% sensitivity and 85% sensitivity cutoff criteria. There was not a significant difference between the two groups when the 75% sensitivity criteria was employed \( t = -1.77, p = .087 \), but there was a significant difference between the two groups when the 85% sensitivity criteria was used \( t = -2.56, p = .017 \).

<table>
<thead>
<tr>
<th></th>
<th>Short Recovery ( \leq 14 \text{ days} )</th>
<th>Protracted Recovery ( &gt;14 \text{ days} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8 (88.89%)</td>
<td>8 (38.1%)</td>
</tr>
<tr>
<td>1</td>
<td>0 (0%)</td>
<td>5 (23.81%)</td>
</tr>
<tr>
<td>2</td>
<td>1 (11.11%)</td>
<td>4 (19.05%)</td>
</tr>
<tr>
<td>3</td>
<td>0 (0%)</td>
<td>2 (9.52%)</td>
</tr>
<tr>
<td>4</td>
<td>0 (0%)</td>
<td>1 (4.76%)</td>
</tr>
<tr>
<td>5</td>
<td>0 (0%)</td>
<td>1 (4.76%)</td>
</tr>
<tr>
<td>6</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>7</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>8</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
</tbody>
</table>

### 3.3 Systematic Replication of the Lau et al. (2011) Study

Discriminant function analysis of the 4 PCSS symptom clusters (migraine, cognitive, sleep, and neuropsychiatric) was not significant \( p = .572 \). Statistics for each symptom cluster are included in Table 3.6. Even though there was no significant difference, the analysis classified the collegiate athletes into short and protracted recovery groups with 63.3% accuracy, 61.9% sensitivity, 66.7% specificity, 81.3%
positive predictive value, and 42.9% negative predictive value. The results of this analysis are similar to the results found in the Lau et al. (2011) study in which the 4 symptom cluster scores alone classified high school athletes into short and protracted recovery groups with 63.2% accuracy, 46.9% sensitivity, 77.2% specificity, 63.9% positive predictive value, and 62.9% negative predictive value.

Table 3.6: Discriminant Function Analysis: PCSS Symptom Cluster Scores Only

<table>
<thead>
<tr>
<th>Symptom Cluster</th>
<th>Wilks’ Lambda</th>
<th>F</th>
<th>P</th>
<th>Canonical Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Migraine</td>
<td>.912</td>
<td>2.703</td>
<td>.111</td>
<td>.629</td>
</tr>
<tr>
<td>Cognitive</td>
<td>.924</td>
<td>2.315</td>
<td>.139</td>
<td>.442</td>
</tr>
<tr>
<td>Sleep</td>
<td>.957</td>
<td>1.245</td>
<td>.274</td>
<td>.192</td>
</tr>
<tr>
<td>Neuropsychiatric</td>
<td>.993</td>
<td>.198</td>
<td>.660</td>
<td>–.217</td>
</tr>
</tbody>
</table>

Discriminant function analysis of the 4 ImPACT neurocognitive composite scores (verbal memory, visual memory, processing speed, and reaction time) was not significant ($p = .175$). Statistics for each composite score are included in Table 3.7. Although there was not a significant difference, the analysis classified the collegiate athletes into the two recovery groups with 63.3% accuracy, 57.1% sensitivity, 77.8% specificity, 85.7% positive predictive value, and 43.8% negative predictive value. The results of this analysis are also similar to the results found in the Lau et al. (2011) study, in which the 4 neurocognitive composite scores alone classified high school athletes into the two recovery groups with 65.4% accuracy, 53.2% sensitivity, 75.4% specificity, 64.1% positive predictive value, and 66.2% negative predictive value.

Table 3.7: Discriminant Function Analysis: ImPACT Neurocognitive Scores Only

<table>
<thead>
<tr>
<th>ImPACT Scores</th>
<th>Wilks’ Lambda</th>
<th>F</th>
<th>P</th>
<th>Canonical Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal Memory</td>
<td>.918</td>
<td>2.511</td>
<td>.124</td>
<td>–.281</td>
</tr>
<tr>
<td>Visual Memory</td>
<td>.870</td>
<td>4.166</td>
<td>.051</td>
<td>.354</td>
</tr>
<tr>
<td>Processing Speed</td>
<td>.793</td>
<td>7.296</td>
<td>.012</td>
<td>.951</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>.914</td>
<td>2.638</td>
<td>.116</td>
<td>.038</td>
</tr>
</tbody>
</table>
The combined discriminant function analysis with the 4 ImPACT neurocognitive composite scores and 4 PCSS symptom cluster scores was not significant ($p = .525$). Statistics for the variables are included in Table 3.8. Even though there was no significant difference between the two groups, the analysis classified the collegiate athletes into short and protracted recovery groups with 70% accuracy, 66.7% sensitivity, 77.8% specificity, 87.5% positive predictive value, and 50% negative predictive value. The results of this analysis are also similar to the results found in the Lau et al. (2011) study in which the 4 ImPACT neurocognitive composite scores combined with the 4 PCSS symptom cluster scores classified high school athletes into the two recovery groups with 73.5% accuracy, 65.2% sensitivity, 80.4% specificity, 73.2% positive predictive value, and 73.8% negative predictive value.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Wilks’ Lambda</th>
<th>$F$</th>
<th>$P$</th>
<th>Canonical Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal Memory</td>
<td>.918</td>
<td>2.511</td>
<td>.124</td>
<td>-.214</td>
</tr>
<tr>
<td>Visual Memory</td>
<td>.870</td>
<td>4.166</td>
<td>.051</td>
<td>.226</td>
</tr>
<tr>
<td>Processing Speed</td>
<td>.793</td>
<td>7.296</td>
<td>.012</td>
<td>.917</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>.914</td>
<td>2.638</td>
<td>.116</td>
<td>.201</td>
</tr>
<tr>
<td>Migraine</td>
<td>.912</td>
<td>2.703</td>
<td>.111</td>
<td>-.216</td>
</tr>
<tr>
<td>Cognitive</td>
<td>.924</td>
<td>2.315</td>
<td>.139</td>
<td>-.302</td>
</tr>
<tr>
<td>Sleep</td>
<td>.957</td>
<td>1.245</td>
<td>.274</td>
<td>-.108</td>
</tr>
<tr>
<td>Neuropsychiatric</td>
<td>.993</td>
<td>.198</td>
<td>.660</td>
<td>.234</td>
</tr>
</tbody>
</table>

Similar to the Lau et al. (2011) study, discriminant function analyses were also conducted for the total PCSS score alone and the migraine cluster alone. The discriminant function analysis for the total PCSS score alone was not significant ($p = .120$). The analysis classified the collegiate athletes with 60% accuracy, 57.1% sensitivity, 66.7% specificity, 80% positive predictive value, and 40% negative predictive value. Similarly, the PCSS score alone correctly classified 61.7% of the high school athletes in the Lau et al. (2011) study. The discriminant function analysis for the migraine cluster alone was also not significant ($p = .111$). The analysis classified the collegiate athletes with 63.3% accuracy, 61.9%
sensitivity, 66.7% specificity, 81.3% positive predictive value, and 42.9% negative predictive value. Similarly, the migraine cluster alone correctly classified 63.2% of the high school athletes in the Lau et al. (2011) study. See Table 3.9 for a comparison of the discriminant function analyses of the same combinations of variables used in the Lau et al. (2011) study.

Table 3.9: Comparison of Discriminant Function Analysis of Combinations of Variables Used in the Lau et al. 2011 Study

<table>
<thead>
<tr>
<th></th>
<th>Total Symptom Score</th>
<th>Migraine Cluster Score Only</th>
<th>Symptom Cluster Scores Only</th>
<th>Neurocognitive Scores Only</th>
<th>Neurocognitive and Symptom Cluster Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilks’ lambda</td>
<td>.916</td>
<td>.912</td>
<td>.894</td>
<td>.783</td>
<td>.744</td>
</tr>
<tr>
<td>P</td>
<td>.120</td>
<td>.111</td>
<td>.572</td>
<td>.175</td>
<td>.525</td>
</tr>
<tr>
<td>Accuracy, %</td>
<td>60</td>
<td>63.3</td>
<td>63.3</td>
<td>63.3</td>
<td>70</td>
</tr>
<tr>
<td>Sensitivity, %</td>
<td>57.1</td>
<td>61.9</td>
<td>61.9</td>
<td>57.1</td>
<td>66.7</td>
</tr>
<tr>
<td>Specificity, %</td>
<td>66.7</td>
<td>66.7</td>
<td>66.7</td>
<td>77.8</td>
<td>77.8</td>
</tr>
<tr>
<td>PPV, %</td>
<td>80</td>
<td>81.3</td>
<td>81.3</td>
<td>85.7</td>
<td>87.5</td>
</tr>
<tr>
<td>NPV, %</td>
<td>40</td>
<td>42.9</td>
<td>42.9</td>
<td>43.8</td>
<td>50</td>
</tr>
</tbody>
</table>

*Sensitivity, specificity, positive predictive value, and negative predictive value are given in relation to ability to predict protracted recovery.

A discriminant function analysis for the processing speed composite score alone was conducted because it was the only variable in which there was a significant difference between the two groups. The discriminant function analysis for the processing speed composite score alone was significant (p = .012). The analysis correctly classified 66.7% of athletes, with 61.9% sensitivity, 77.8% specificity, 86.7% positive predictive value, and 46.7% negative predictive value.

### 3.4 Models for Predicting Protracted Recovery

As an extension to the Lau et al. (2011) study, different models for predicting protracted recovery were investigated to identify combinations of variables with the highest classification accuracy. Seventeen models were evaluated, and five models were identified as having the most successful outcomes. To evaluate the predictive value of all eight variables, the first model included the 4 ImPACT composite scores and the 4 PCSS symptom cluster scores. The second model consisted of the 4 ImPACT composite scores and the migraine symptom cluster score, because previous research suggests that the migraine
cluster is a strong predictor of protracted recovery (Lau et al., 2009; Lau et al., 2011). The third model only contained 2 ImPACT composite scores (visual memory and processing speed) and the migraine symptom cluster score. As previously stated, there was a significant difference between the two recovery groups in terms of the processing speed composite score in the current study, and the visual composite score approached significance. The fourth model contained 3 ImPACT composite scores (verbal memory, visual memory, and reaction time) and the migraine symptom cluster score, because these variables were found to have the strongest predictive power in the Lau et al. (2011) study. Lastly, the fifth model contained the processing speed composite score and the migraine symptom cluster score, because these variables were the strongest contributors in the majority of the models examined in the current study.

3.4.1 Model 1

The results from the discriminant function analysis for Model 1 (4 ImPACT composite scores and 4 PCSS symptom clusters) were discussed in the previous section. This model had the highest canonical correlation coefficient and the lowest Wilks’ lambda value compared to the other models. The canonical correlation for Model 1 was .506, which indicates that approximately 25.6% of the variation in the two groups is explained by the discriminant model. The value of the Wilks’ lambda was .744; therefore, 74.4% of the variance is not explained by the model. The $p$ value for Model 1 was not significant ($p = .525$). Based on the requirement that model accuracy be 25% better than chance criteria, the standard for assessing the model’s accuracy is 62.5%. The model’s accuracy rate of 70% exceeds this standard. In addition, Model 1 classified the collegiate athletes into short and protracted recovery groups with 66.7% sensitivity, 77.8% specificity, 87.5% positive predictive value, and 50% negative predictive value. Standardized canonical discriminant function coefficient analysis revealed that the most important variables in predicting group membership were the processing speed composite score (.917) and the cognitive cluster score (−.302).
3.4.2 Model 2

The discriminant function analysis for Model 2 (4 ImPACT composite scores and migraine cluster) revealed a canonical correlation of .490, which indicates that approximately 24% of the variation in the two groups is explained by the model. The value of the Wilks’ lambda was .760; therefore, 76% of the variance is not explained by the model. The $p$ value for Model 2 was not significant ($p = .220$). Based on the requirement that model accuracy be 25% better than chance criteria, the standard to use for comparing the model’s accuracy is 62.5%. The model’s accuracy rate of 70% exceeds this standard. Model 2 yielded the highest sensitivity compared to the other models. The model classified the collegiate athletes into the two recovery groups with 71.4% sensitivity, 66.7% specificity, 83.3% positive predictive value, and 50% negative predictive value. Standardized canonical discriminant function coefficient analysis revealed that the most important variables in predicting group membership were the processing speed composite score (.928) and the migraine symptom cluster score (−.381).

3.4.3 Model 3

The discriminant function analysis for Model 3 (visual memory, processing speed, and migraine cluster) revealed a canonical correlation of .484, which indicates that approximately 23.4% of the variation in the two groups is explained by the model. The value of the Wilks’ lambda is .766; therefore, 76.6% of the variance is not explained by the model. The $p$ value for Model 3 approached significance ($p = .070$). Based on the requirement that model accuracy be 25% better than chance criteria, the standard to use for comparing the model’s accuracy is 62.5%. The model’s accuracy rate of 70% exceeds this standard. In addition, Model 3 classified the collegiate athletes into short and protracted recovery groups with 66.7% sensitivity, 77.8% specificity, 87.5% positive predictive value, and 50% negative predictive value. Standardized canonical discriminant function coefficient analysis revealed that the most important variables in predicting group membership were the processing speed composite score (.806) and the migraine symptom cluster score (−.374).
3.4.4 Model 4

The discriminant function analysis for Model 4 (verbal memory, visual memory, reaction time, and migraine cluster) revealed a canonical correlation of .409, which indicates that approximately 16.7% of the variation in the two groups is explained by the model. The value of the Wilks’ lambda is .833; therefore, 83.3% of the variance is not explained by the model. The $p$ value for Model 4 was not significant ($p = .313$). However, this model had the highest classification accuracy, specificity, and predictive value compared to the other models. The model’s accuracy rate of 73.3% exceeds the standard used to compare the model’s accuracy (62.5%). In addition, Model 4 classified the collegiate athletes into the two recovery groups with 66.7% sensitivity, 88.9% specificity, 93.3% positive predictive value, and 53.3% negative predictive value. Standardized canonical discriminant function coefficient analysis revealed that the most important variables in predicting group membership were the visual composite score ($-0.534$) and the migraine symptom cluster score ($0.419$).

3.4.5 Model 5

The discriminant function analysis for Model 5 (processing speed and migraine cluster) revealed a canonical correlation of .483, which indicates that approximately 23.3% of the variation in the two groups is explained by the model. The value of the Wilks’ lambda is .767; therefore, 76.7% of the variance is not explained by the model. Model 5 was the only model that had a significant $p$ value ($p = .028$), indicating that the model is good. Based on the requirement that model accuracy be 25% better than chance criteria, the standard to use for comparing the model’s accuracy is 62.5%. The model’s accuracy rate of 70% exceeds this standard. In addition, Model 5 classified the collegiate athletes into the two recovery groups with 66.7% sensitivity, 77.8% specificity, 87.5% positive predictive value, and 50% negative predictive value. Standardized canonical discriminant function coefficient analysis revealed that the most important variable in predicting group membership was the processing speed composite score (.845).
Table 3.10 compares the results from the discriminant function analyses for the 5 models for predicting protracted recovery.

Table 3.10: Comparison of Discriminant Function Analysis of Four Models for Predicting Protracted Recovery

<table>
<thead>
<tr>
<th></th>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canonical Correlation</td>
<td>.506</td>
<td>.490</td>
<td>.484</td>
<td>.409</td>
<td>.483</td>
</tr>
<tr>
<td>Wilks’ Lambda</td>
<td>.744</td>
<td>.760</td>
<td>.766</td>
<td>.833</td>
<td>.767</td>
</tr>
<tr>
<td>P</td>
<td>.525</td>
<td>.220</td>
<td>.070</td>
<td>.313</td>
<td>.028</td>
</tr>
<tr>
<td>Accuracy, %</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>73.3</td>
<td>70</td>
</tr>
<tr>
<td>Sensitivity, %</td>
<td>66.7</td>
<td>71.4</td>
<td>66.7</td>
<td>66.7</td>
<td>66.7</td>
</tr>
<tr>
<td>Specificity, %</td>
<td>77.8</td>
<td>66.7</td>
<td>77.8</td>
<td>88.9</td>
<td>77.8</td>
</tr>
<tr>
<td>PPV, %</td>
<td>87.5</td>
<td>83.3</td>
<td>87.5</td>
<td>93.3</td>
<td>87.5</td>
</tr>
<tr>
<td>NPV, %</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>53.3</td>
<td>50</td>
</tr>
</tbody>
</table>

*Sensitivity, specificity, positive predictive value, and negative predictive value are given in relation to ability to predict protracted recovery.

3.5 Follow-Up Phone Calls

The investigator conducted follow-up phone calls to obtain consent to use the athletes’ data in the current study and to document more detailed information about the recovery from their concussion. Once the athletes gave the investigator permission to use their data in the current study, they were asked specific questions about the recovery from their injury. See Appendix A for the complete telephone script used in the study. The athletes were first asked if they remembered discussing the graduated return-to-play protocol with members of the UTEP CMC team when they were released to their athletic trainers to begin the stepwise progression. The athletes specified whether they started the return-to-play protocol the day they were released or the day after. The athletes were then asked if they successfully completed the protocol with their athletic trainer over a span of 5 days (as recommended). Overall, the concussed athletes completed the graduated return-to-play protocol in less than 5 days (mean = 4.38, range = 2 to 7 days). There was no significant difference between the short and protracted recovery groups in regard to the number of days it took to complete the graduated return-to-play protocol ($t = 1.43, p = .164$). The short
recovery group completed the protocol in an average of 4.78 days (SD = .667), and the protracted recovery group completed the protocol in an average of 4.20 days (SD = 1.508).

Next, the athletes were asked if they remembered having any problems or experiencing any symptoms during the graduated return-to-play protocol. 5 of the athletes (short recovery group = 1, protracted recovery group = 4) reported experiencing symptoms during the stepwise progression. The athletes were also asked if they experienced any symptoms after completing the graduated return-to-play protocol. 4 athletes (short recovery group = 1, protracted recovery group = 3) reported experiencing symptoms sometime after completing the return-to-play protocol. Finally, the athletes were asked if they felt like they had fully recovered from their concussion. 3 athletes (short recovery group = 1, protracted recovery group = 2) felt that they had not fully recovered from their injury. Overall, out of the 30 collegiate athletes in the study, 8 (26.7%) reported experiencing symptoms sometime after being released to initiate the return-to-play protocol. Table 3.11 shows the patient profiles of the 8 athletes who experienced difficulties – as defined by the persistence of concussion-related symptoms after being released to initiate the return-to-play protocol – during the recovery from their concussion.

Table 3.11: Patient Profiles of Athletes Who Experienced Difficulties during the Recovery from their Concussion

<table>
<thead>
<tr>
<th>Participant Number</th>
<th>Length of Recovery From Injury to Follow-up Phone Call</th>
<th>Days to Complete RTP Protocol</th>
<th>Symptoms During the RTP Protocol</th>
<th>Symptoms After Completing the RTP Protocol</th>
<th>Fully Recovered From Injury</th>
<th>Patient Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14 days (short recovery group)</td>
<td>4 years</td>
<td>5</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Yes</td>
<td></td>
<td>The athlete reported that he feels like he “never fully recovered”. He reported that flashing lights bother him especially when he is driving at night. He also reported having migraines from time to time.</td>
</tr>
<tr>
<td></td>
<td>Recovery Group Time</td>
<td>Recovery Group Duration</td>
<td>Number of Days</td>
<td>Did Not RTP That Season</td>
<td>Did Not Complete RTP Protocol</td>
<td>Return to Play That Season</td>
</tr>
<tr>
<td>---</td>
<td>---------------------</td>
<td>-------------------------</td>
<td>----------------</td>
<td>-------------------------</td>
<td>-------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>2</td>
<td>20 days (protracted recovery group)</td>
<td>1 year</td>
<td>3 or 4</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>10 days (short recovery group)</td>
<td>6 months</td>
<td>5</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>Did not RTP that season (protracted recovery group)</td>
<td>2 years</td>
<td>Did not complete the RTP protocol</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>17 days (protracted recovery group)</td>
<td>2 years</td>
<td>2 or 3</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
The athletes reported that she did not begin the stepwise progression when she was released from the UTEP CMC because she was still experiencing symptoms (e.g., headache, nausea, and sensitivity to light). According to the athlete, she did not fully express the symptoms she was experiencing to the concussion management team because she wanted to return to play as soon as possible. The athlete also reported that although she was no longer experiencing symptoms during the Christmas break, she did not start the RTP protocol due to a knee injury. She reported that she returned to normal physical activity upon returning from the Christmas break. She stated that at this time, she felt “100%” and was no longer experiencing any symptoms. It should be noted that the athlete also reported that her neurologist had diagnosed her with post-concussion syndrome.
| 7 | 25 days (protracted recovery group) | 3 months | 5 | Yes | Yes | Yes | The athlete reported that she felt a little tired after the second day of the graduated return-to-play protocol. The athlete also reported that she felt dizzy the day she did sprints, so the athletic trainer sent her home to rest. The athlete reported that she had difficulty remembering when taking quizzes and doing school work up until a week and a half after completing the stepwise progression, even though she was not experiencing symptoms during physical activity at this time. According to the athlete, her symptoms completely resolved 7 weeks post-injury. |
|---|---|---|---|---|---|---|
| 8 | 30 days (protracted recovery group) | 1 year | 5 | No | Yes | No | The athletes reported experiencing symptoms after completing the stepwise protocol (i.e., headache). He also reported that about 2 months after his concussion he was in a car accident. According to the athlete he has been experiencing constant headaches since then and he does not feel like he has fully recovered from the injury. The athlete also noted that he never returned to play after his car accident. |
Chapter 4: Discussion

The purpose of this study was to systematically replicate and extend previous research in examining how well computerized neurocognitive test scores and symptom cluster scores can predict length of recovery following sports-related concussion. This study aimed to determine the classification accuracy, sensitivity, specificity, and predictive value of the tested variables in predicting protracted recovery in a group of collegiate athletes. To restate the research questions, the investigator hoped to answer the following questions: (1) Can the results of the Lau et al. (2011) study be replicated to a different population of athletes? (2) Which combinations of computerized neurocognitive test scores and symptom cluster scores (classification models) have the highest classification accuracy? (3) Do athletes classified as having a short recovery differ in the number of reliable change deficits and cutoff scores for predicting protracted recovery compared to athletes classified as having a protracted recovery? (4) How accurate are current return-to-play standards in determining whether athletes will be symptom-free during the return-to-play process? Addressing these issues will help clinicians to more confidently address return-to-play and academic decisions, thereby potentially preventing athletes from returning to play and school before they have fully recovered.

A notable finding in this study is that the average recovery period for this group of collegiate athletes was 19 days. Moreover, 70% of the athletes were classified as having a protracted recovery. This finding is counter to the evidence that suggests the majority of athletes recover within 10 to 14 days of injury (Macciochi et al., 1996; Field et al., 2003; McCrea et al., 2003; Lovell et al., 2003; Lovell et al., 2004; Pellman et al., 2006; Iverson et al., 2006; Makdissi et al., 2010). It suggests that the average recovery period following sports-related concussion may frequently extend longer than two weeks. Also noteworthy, is that the two recovery groups did not differ in terms of experiencing loss of consciousness, anterograde amnesia, or retrograde amnesia when their injury occurred. There is mixed evidence in the literature on the relationship between recovery time following concussion and acute injury characteristics,
such as loss of consciousness and posttraumatic amnesia. McCrea and colleagues (2012) found that prolonged recovery following sports-related concussion was associated with unconsciousness and posttraumatic amnesia in high school and college athletes. Meehan and colleagues (2013), on the other hand, found that loss of consciousness and amnesia at the time of injury were not associated with prolonged recovery after sports-related concussion. The findings in the current study suggest that there is no association between the presence or absence of acute injury characteristics and length of recovery following sports-related concussion.

The primary objective of this study was to further examine how well self-reported symptoms and neurocognitive test scores together can predict protracted recovery from sports-related concussion by systematically replicating the Lau et al. (2011) study with a change in participants. The current study extended the Lau et al. (2011) study to a different population of athletes. Even though the results of the discriminant function analyses were not statistically significant, classification of overall accuracy, sensitivity, specificity, positive predictive value, and negative predictive value for each combination of variables almost matched those found in the Lau et al. (2011) study. In the current study, the 4 neurocognitive test scores and 4 symptom cluster scores accurately classified 70% of the collegiate athletes as having a short recovery or a protracted recovery. In the Lau et al., (2011) study, these measures correctly classified 73.5% of male high school football players into the two recovery groups. Moreover, similar to the Lau et al. (2011) study, the 4 neurocognitive composite scores and 4 symptom cluster scores combined yielded the highest classification accuracy, sensitivity, specificity, positive predictive value, and negative predictive value, compared to either measure alone.

As an extension to the Lau et al. (2011) study, classification models for predicting protracted recovery were investigated to identify specific combinations of variables with the strongest predictive power. Five models resulted in the most successful outcomes. Model 1 (4 ImPACT composite scores and 4 PCSS symptom clusters) had the highest canonical correlation coefficient (.506) and the lowest Wilks’
lambda value (.744), indicating that the model has greater discriminatory ability compared to the other models. However, the $p$ value of this model was not significant ($p = .525$), and therefore fails to reject the null hypothesis that the variables have no discriminating ability. Model 2 (4 ImPACT composite scores and migraine cluster) had the overall highest percent sensitivity (71.4%). However, this model also failed to reject the null hypothesis ($p = .220$). Model 3 (visual memory, processing speed, and migraine cluster) approached significance ($p = .070$), but failed to reject the null hypothesis as well.

Although Model 4 (verbal memory, visual memory, reaction time, and migraine cluster) also failed to reject the null hypothesis ($p = .313$), this model had the most successful outcomes in terms of classification. Model 4 resulted in the highest classification accuracy (73.3%), specificity (88.9%), positive predictive value (93.3%), and negative predictive value (53.3%). It is not surprising that this combination of variables resulted in the highest classification accuracy. In the Lau et al. (2011) study, canonical coefficient analysis showed that the verbal memory composite score, visual memory composite score, reaction time composite score, and migraine symptom cluster score contributed the most to discriminating between the two recovery groups (i.e., short versus protracted recovery groups). The findings in the current study provide further insight into the symptom and neurocognitive testing profiles of athletes who are at a greater risk of having a protracted recovery. That is, if an athlete has lower verbal and visual memory scores and higher reaction time and migraine cluster scores, a clinician can say with 73.3% confidence that the athlete will have a protracted recovery.

Model 5 (processing speed and migraine cluster) was the only model that had a significant $p$ value ($p = .028$). Therefore, the null hypothesis can be rejected and it may be inferred that the model is good. Canonical coefficient analysis showed that the processing speed composite score and the migraine symptom cluster score had the largest absolute values in the majority of the classification models. This indicates that the two variables have greater discriminative power in predicting group membership (i.e., short versus protracted recovery group) compared to the other variables. It should also be noted that Model
yielded the same classification results as Model 1: 70% accuracy, 66.7% sensitivity, 77.8% specificity, 87.5% positive predictive value, and 50% negative predictive value. The results of the discriminant function analyses for Model 4 and Model 5 suggest that specific subsets of variables can predict protracted recovery as well as or better than the use of all 4 ImPACT composite scores and 4 PCSS symptom cluster scores. Model 4 and Model 5 can potentially facilitate clinical decision making in concussion management by providing a better understanding of the role that variation in performance plays in predicting protracted recovery. Therefore, these two models can be labeled as ones worth pursuing.

As an extension to the Lau et al. (2012) study, the current study also investigated potential differences between the two recovery groups in terms of the number of reliable change deficits and neurocognitive and symptom cluster scores that met the 75%, 80%, and 85% sensitivity cutoff criteria for predicting protracted recovery at the initial post-concussion evaluation. There was no significant difference between the two recovery groups with regard to the number of reliable change deficits \((p = .054)\) or the number of neurocognitive and symptom cluster scores that met the 75% sensitivity cutoff criteria \((p = .087)\). This suggests that these two measures may not be sensitive enough to distinguish between athletes who will have a short recovery from those who will have a protracted recovery. There was, however, a significant difference between the two recovery groups in terms of the number of scores that met the 80% sensitivity cutoff criteria \((p = .039)\) and 85% sensitivity cutoff criteria \((p = .017)\). In addition, the majority of the athletes in the short recovery group did not have any scores that met the 80% sensitivity cutoff criteria (88.89%), whereas the majority of the athletes in the protracted recovery group had at least one score that met the 80% sensitivity cutoff criteria (61.9%). It is important to note that the reliable change indices only apply to the ImPACT composite scores, whereas the cutoff scores take into consideration both ImPACT composite scores and PCSS symptom cluster scores. This finding further supports that the combination of neurocognitive test scores and symptom profiles yields the highest predictive value in predictions of protracted recovery, compared to either measure alone. Nonetheless,
more research is needed to determine the accuracy of pre-established cutoff scores in predicting protracted recovery following sports-related concussion.

Furthermore, follow-up phone calls revealed that 26.7% of the collegiate athletes in the study experienced symptoms during the return-to-play protocol or thereafter. Moreover, the information provided by the athletes during the follow-up phone calls suggests that international return-to-play guidelines and clinical recommendations are not always being followed. Several athletes reported completing the graduated return-to-play protocol and returning to play in less than 5 days, despite continuing to experience post-concussive symptoms. Perhaps the most concerning finding is that some of the athletes reported downplaying their symptoms because they wanted to return-to-play as quickly as possible. Since athletes are highly motivated to return to play, it is not uncommon for them to underreport concussion-related symptoms. It is for this reason that clinicians involved in the management of sports-related concussion should adopt a conservative approach when making return-to-play decisions to avoid delayed recovery and the possible long-term adverse effects and catastrophic consequences that may ensue if an athlete sustains a second injury before fully recovering from a previous injury.

4.1 Limitations

This study is not without limitations. To begin with, follow-up appointments were conducted on a weekly basis and athletes were retrospectively classified into short and protracted recovery groups. Therefore, it is possible that some of the athletes classified as having a protracted recovery actually recovered within 14 days but were not cleared until after this time. In addition, this study did not use an experimental design. It was an ex post facto, retrospective case study, and therefore, the methodology did not allow for experimental control of factors, such as precise assessment intervals or requiring athletes to complete a specific number of assessments. Athletes were followed clinically and were released to return to play based on two clinical criteria, rather than a specific time after their injury. Other limitations include a small sample size, particularly the short recovery group, and the potential biases of self-reported
symptoms. As previously stated, athletes are highly motivated to return-to-play and may therefore choose not to report any symptoms they may be experiencing at the fear of being held out for a longer period of time. In addition, the extended length of time between when the injury occurred and when the follow-up phone calls were conducted may have limited the athletes’ ability to accurately recall details from their recovery process. It should also be noted that although self-reported symptoms may not be reliable, they were used to create the statistical models in the current study. The results of this study may have been affected by these limitations, and should therefore be interpreted with caution. Moreover, the subjects in this study only included collegiate athletes. Thus, the findings cannot be generalized beyond this population of athletes.

4.2 Future Work

Further research is necessary to better understand the clinical utility of computerized neurocognitive test and symptom evaluation results in predicting protracted recovery from sports-related concussion. It should be noted that 26.7% to 30% of the athletes in the study were incorrectly classified. Thus, caution should be used in predicting protracted recovery from sports-related concussion until more research is conducted. Moreover, since the models in the study were developed on the basis of a small sample size and self-reported symptoms, the level of classification accuracy may not hold for all future classification of new cases. Therefore, future studies should investigate how well neurocognitive test scores and symptom cluster scores can predict protracted recovery following a concussion using larger sample sizes and different populations of athletes, such as semi-professional athletes and female high school athletes, as well as athletes from different sports.

The results for Model 4 (verbal memory, visual memory, reaction time, and migraine cluster) and Model 5 (processing speed and migraine cluster) are promising, indicating that these models are worth pursuing due to their successful outcomes and high classification accuracy. It should be noted that if one wants to classify cases predictively, it is necessary to collect new data to “try out” the utility of a
classification model. Therefore, once powerful classification models such as these are validated, future studies can test the models’ ability to predict group membership (short recovery versus protracted recovery) when only the interval variables (or in this case, neurocognitive test scores and symptom cluster scores) are known.

In addition, future research should investigate the predictive value of pre-established ImPACT neurocognitive composite and PCSS symptom cluster cutoff scores for predicting protracted recovery at the 80% sensitivity, specifically which combinations of cutoff scores have the strongest predictive power. Researchers may also attempt to look at the raw scores from each neurocognitive test module, or compare the change in severity of ImPACT composite scores from baseline to the initial post-concussion evaluation when investigating potential predictors of positive and negative outcomes following sports-related concussion. Furthermore, future studies should include more precise and detailed documentation of each athlete’s recovery process. Clinicians should follow-up with athletes throughout the return-to-play process to monitor athletes’ symptoms and document the athletes’ exact return-to-play date. Moreover, future research may potentially investigate whether the average recovery time following sports-related concussion, and the cutoff criteria for distinguishing between a short recovery and a protracted recovery, should be extended from 2 to 3 weeks post-injury.

4.3 Conclusion

Concussions pose a significant public health concern. Premature decisions to release athletes to return to the playing field or to the classroom may result in delayed recovery or more serious consequences. The purpose of this study was to replicate and extend previous research in determining the classification accuracy, sensitivity, specificity, and predictive value of computerized neurocognitive test scores and symptom cluster scores in predicting protracted recovery following sports-related concussion. This study extended the Lau et al. (2011) study to a different population of athletes and identified combinations of variables (classification models) with the strongest predictive power that can be used to
facilitate clinical decision making in the management of sports-related concussion. Furthermore, this study revealed that some athletes may experience difficulties during the recovery from a concussion. Thus, a conservative approach to concussion management should be taken to prevent athletes from returning to play before they have fully recovered.
References


Appendix A

Telephone Script
Hello, my name is Amanda Sepulveda. I am a graduate student research assistant from the UTEP Concussion Management Clinic may I please speak to (name of athlete).

Our records show that you were seen in our clinic in (month and year). I would like your permission to use your test results for my research project and I would also like to ask you a couple of questions about the recovery following your concussion.

- Do I have permission to use your test results? Yes No
- May I ask you a couple of questions about your recovery? Yes No

(Note: If the athlete said no, say thank you for your time and discontinue the phone call. If athlete said yes, continue with the script.)

On (date) we told you that you could start the stepwise progression return-to-play protocol, where you gradually increased your physical activity over a 5 day period until you were ready to play again.

- Do you remember us explaining this protocol to you?
- Can you remember if you started the protocol on that day or the day after?
- Did you successfully complete the protocol within 5 days?
- Do you remember having any problems or experiencing any symptoms during that time?
- Have you had any symptoms since then?
- Do you think you have fully recovered from your concussion?

Please recall that your results and your name will remain anonymous. Thank you for giving me permission to use your test results for my research project and taking the time to answer my questions, it is greatly appreciated. Have a nice day.

____________________________  __________________________  __________________________
Signature of Examiner        Date                          Time
Curriculum Vita

Amanda Sepulveda was born in El Paso, Texas. The second daughter of Marcy Sepulveda and Robert Sepulveda, she graduated from Fabens High School in the spring of 2009 and entered The University of Texas at El Paso in the fall with the Presidential Excellence Scholarship and the Top 10% Scholarship. While pursuing a bachelor’s degree, she worked as a high school math tutor at Fabens High School, and later as a research assistant at the University of Texas at El Paso after receiving the Campus of Undergraduate Research Initiatives Research Award in 2012. As an undergraduate student, she published two papers in the Early Child Development and Care journal. After graduating summa cum laude with her Bachelor of Multidisciplinary Studies from The University of Texas at El Paso in the summer of 2013, she entered the Graduate School at The University of Texas at El Paso in the fall with the Jimmie-Vokes Bernard Memorial Endowed Scholarship, and later received the Sandy Tyler Endowed Fellowship in Health Sciences. She continued to work as a research assistant from 2013 to 2014. During this time she published a paper in the Seminars in the Speech and Language journal, and she presented her research at the 2014 American Speech-Language Hearing Association Convention in Orlando, Florida.

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This thesis was typed by Amanda Sepulveda.