CLINICAL USEFULNESS OF OCULAR TESTS FOR DIAGNOSING CONCUSSIONS

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Abstract

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Doctor of Philosophy

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Dysfunctions of ocular motor and binocular vision are some of the most commonly observed problems in patients with severe traumatic brain injury. Secondarily, subjective complaints of compromised vision and ocular motor functions are also sometimes reported in mild traumatic brain injuries (mTBI). Simple ocular/vision assessments such as near point of convergence (NPC), the King-Devick Test (KDT), and stereoacuity can be performed to identify and assess these deficits, but their diagnostic accuracy has yet to be thoroughly investigated. The purpose of this study was to determine if differences exist in NPC, KDT, and stereoacuity test scores between concussed and control athletes, and to determine the diagnostic accuracy of these tests.

A multicenter control group design was utilized. The independent variable was group (control vs. concussed). The

dependent variables were the ocular test scores from the NPC, KDT, and stereoacuity tests. Participants were recruited from several collegiate athletic programs. In total 34 healthy, non-concussed controls (21 male, 13 female) aged 19 $\pm$ 1.5 years and 19 concussions (11 male, 8 female) aged 20.42 $\pm$ 1.5 years participated in the study. A concussion was operationally defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces, that was diagnosed by a health care professional through the use of signs and symptoms scales, balance and neurocognitive testing.

Data were analyzed using descriptive and inferential statistics. T-tests and chi-squares were performed to ensure there were no significant differences between groups on specific demographic or relevant prognostic variables (sport, sex, and concussion history). T-tests were employed to identify significant differences between groups on ocular test scores. Then clinical and statistical cutoffs for all three tests were determined. Based off of these cutoffs sensitivity, specificity, and likelihood ratios were determined for each assessment. Furthermore, receiver operating characteristic (ROC) curves were calculated to help determine the diagnostic accuracy of these assessments. The alpha level was set at $p \leq .05$ and the

SPSS for Windows, Version 21.0, statistical program (IBM, Inc., Armonk, NY) was used for all data analysis.

Significant differences were found between groups for all three ocular assessments. NPC demonstrated a statistical cutoff of 5.5 cm, which provided a sensitivity of 79% and specificity of 76% and an AUC of 0.827. For the KDT, a statistical cutoff time of 49.5s demonstrated a sensitivity of 58% and specificity of 72% with an AUC of 0.658. Lastly, for stereoacuity a statistical cutoff point of 28.50 arc sec was found which produced a sensitivity of 65% and specificity of 54% with a maximum AUC of 0.706. All three tests demonstrated their potential to positively contribute to the diagnosis of a concussion.

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CHAPTER 1

CLINICAL USEFULNESS OF OCULAR TESTS FOR DIAGNOSING CONCUSSIONS

Introduction

Concussions are a growing problem in sports; 30% of retired collegiate athletes report they have suffered at least one concussion during their college athletic career (Llewellyn, Joyner, & Buckley 2014). This number grows to 50% when including unreported and unrecognized concussions. Reported cases have risen in emergency rooms as well as within high school and college sports (Hootman, Dick, & Agel, 2007; Lincoln, Caswell, & Dunn, 2011; Selassie et. al., 2013) possibly due to an actual increase in the incidence of concussion or possibly due to the increased education, awareness, reporting, and diagnosis of the injury. Not taken into account in this estimate of incidence are the undiagnosed concussions that occur. A recent study (Meehan, Mannix, & O’brien, 2013) found that of 486 patients, 30.5% reported having previously suffered a head impact that resulted in concussion symptoms, indicating a large portion of these injuries remain undiagnosed. This may be due to athletes hiding their symptoms in order to continue participating or because they are unaware of the symptoms associated with a concussion.

Because of the many possible long-term effects of concussion (Broglio, Cantu, Gioia, Guskiewicz, & Kutcher, 2012; De Beaumont et al., 2009; Guskiewicz, 2005; Guskiewicz, 2007; Vanderploeg et al., 2007), it’s imperative for this injury to be properly diagnosed and treated. This can prove problematic for athlete’s masking or hiding symptoms, which is why it’s important to incorporate objective assessment tools in a concussion evaluation. Furthermore, to increase sensitivity of diagnosis the use of a battery of tests, including such tools as signs and symptoms scales, balance, and neurocognitive testing has been recommended (Broglio & Pietz, 2008; Lau, Lovell, Collins, & Pardini, 2011; McCrory et al., 2013). Even with a battery of tests, diagnosing a concussion can prove to be difficult because of its complex symptomatology. Not all athletes present with the same symptoms, and certain factors may increase the incidence of this injury.

Many different factors can influence the risk of concussion such as sex (Covassin, Swanik, & Sachs, 2003; Gessel, Fields, & Collins, 2007; Lincoln et al., 2011; Marar, McIlvain, & Fields, 2012), concussion history

(Colvin, Mullen, & Lovell, 2009; Guskiewicz et al., 2003; Guskiewicz 2007; Hollis, Stevenson, & McIntosh, 2009; Schulz, Marshall, & Mueller, 2004), and what sport and position is being played by the athlete (Crisco et al., 2010; Hootman et al., 2007; Pellman et al., 2004). In addition, many areas of the brain can be affected by a concussion, requiring assessment of several different brain functions.

Ocular assessment for sport concussion has traditionally included simply smooth pursuits (e.g., H-test) and pupil reflex to examine cranial nerve function and the presence of intracranial bleeding (Starkey, & Ryan, 1996). It is estimated that up to 65% of concussion patients present with ocular motor dysfunction (Capo-Aponte, Urosevich, Temme, Rarbett, & Sanghera, 2012). Consequently, more robust ocular motor screenings are starting to be incorporated into a concussion assessment battery (Mucha et al., 2014). Different aspects of vestibular and ocular functioning such as smooth pursuits, saccades, convergence, vestibular ocular reflex, and visual motion sensitivity have proven useful in assessing a concussion and identifying athletes in need of special treatment (Collins, Kontos, Reynolds, & Murawski, 2014; Mucha et al., 2014), but these tools have not been thoroughly investigated with concussion. These tests, in addition to other ocular assessments (e.g., stereoacuity), need further investigation to determine their clinical usefulness in assessing a concussion.

Capo-Aponte et al. (2012) investigated the occurrence of visual dysfunctions and symptoms associated with mild traumatic brain injury (TBI). They reported that those diagnosed with a mild TBI exhibited normal eye health measurements (e.g., normal visual fields, pupil responses, intraocular pressure) while presenting with several deficits in vergence, stereopsis, pursuits and saccadic eye movements. These deficits can be identified by using ocular near point of convergence (NPC), the King-Devick test (KDT), and a stereoacuity assessment.

Convergence specifically involves simultaneous adduction of the eyes to focus them on an object of interest. Assessing one's NPC measures the closest point a person can maintain focus on an object moving slowly towards them, before diplopia or deviation of an eye occurs. Convergence insufficiency, or dysfunction in coordination of adduction of the eyes medially, can result in blurred vision, diplopia, problems reading, headache, and eyestrain (Ciuffreda & Tannen, 1995). NPC can be significantly receded in severe (Cohen, Groswasser, Barchadski, & Appel, 1989) and mild TBI patients (Capo-Aponte et al., 2012; Hellerstein, Freed, & Maples, 1995; Szymanowicz et al., 2012). Recently, it was reported to be receded in those whom had a sport-related concussion (Mucha et al., 2014). There is disagreement however, in the normative values (Appendix A).

The King-Devick Test (KDT) was originally developed to assess impaired ocular motor function and its relation to learning disabilities (Oride et al., 1986). This simple ocular test involves reading a pattern of numbers on separate cue cards as quickly as possible. The skill of reading is a complex task, which requires the integration of many visual systems; in particular fixations, saccades, and pursuits are challenged during this task (Ciuffreda & Tanen, 1995). Abnormal saccades, or rapid movements of the eyes, can contribute to a lowered score on the KDT and have been found to be indicative of compromised brain function (Heitger et al., 2009).

The KDT has been investigated in the sports setting and is reported to have high reliability with an intra-class correlation (ICC) of .97 (Galetta, Brandes et al., 2011). Furthermore, scores of this test have been shown to worsen after concussion (Brughelli et al., 2013; Galleta, Barrett et al., 2011; Galetta, Brandes et al., 2011;

Galetta et al., 2013; King et al., 2012; King et al., 2013; King, Hume, Gissane, & Clark, 2015; Leong et al., 2015; Seidman et al., 2015), indicating it may be sensitive to deficits associated with concussion, but this has yet to be thoroughly investigated.

Stereoacuity, another simple ocular test, measures stereopsis. Binocular perception, or stereopsis, involves the fusion of visual fields from each eye. The different images seen by each eye are joined to form one fused image improving depth perception. Abnormal binocular vision may occur when a scene is viewed with both eyes yet there is difficulty in perceiving a single fused image. Limited stereopsis can be due to a lack of coordination between extraocular muscles, or as a result of damage to areas of the brain involved with neural processing of this information such as the occipital lobe, parietal cortex, or corpus callosum. Stereopsis can be measured through a random-dot stereogram, which uses a series of imprinted shapes on a card printed in a way that when viewed with special lenses they appear to be raised from the card, similar to a hologram (Snowden et al., 2006).

Significant deficits in stereoacuity have been identified in severe (Cohen et al., 1989; Miller et al., 1999) and mild (Capo-Aponte et al., 2012; Hellerstein et al., 1995, Szymanowicz et al., 2012) TBI patients. Although the mild TBI populations did involve injuries classified similar to sport concussion in that patients scored $\geq$ 13 on the Glasgow Coma Scale, experienced < 30 min. unconsciousness, and suffered a mechanism of injury correlating to brain injury, they were not sports related in nature. The populations consisted of military blast induced mild TBI (Capo-Aponte et al., 2012) or were recruited from optometric centers (Hellerstein et al., 1995; Szymanowicz et al., 2012) where they were referred due to their symptomology after suffering injuries related to falls, motor vehicle accidents, or through other non sport-related mechanisms. Stereoacuity has not been investigated thoroughly with an athletic population.

Unlike stereoacuity, NPC and the KDT have been investigated in the athletic population but their diagnostic accuracy has yet to be determined. All three of these tests can be performed within a short period of time, without costly equipment, and could be easily incorporated into a concussion assessment. To date, no study has examined the use of stereoacuity in sport related concussion, and furthermore, no study has investigated the diagnostic accuracy of all of these tests. The purpose of this study was to determine if differences exist in NPC, KDT, and stereoacuity scores between concussed athletes and controls and to determine the diagnostic accuracy of these tests. These tests have the potential of being clinically useful in the assessment of a concussion to identify visual dysfunctions as markers of concussion in addition to ensuring a more appropriate course of rehabilitation.

Statement of the Purpose

The primary purpose of this study was to investigate the effect of concussion on selected ocular tests. The secondary purpose was to evaluate the diagnostic accuracy of these tests in their diagnosis of concussion.

Aims and Hypotheses

Aim 1

To assess the effect of concussion on ocular test scores (NPC, KDT, and stereoacuity).

Research Hypothesis for Aim 1

Hypothesis 1. Concussed athletes will score significantly worse on all ocular tests compared to controls. Specifically, they will have a more remote NPC, longer reading times for the KDT, and greater arc seconds for stereoacuity than the controls.

Aim 2

To assess the diagnostic accuracy (i.e., sensitivity, specificity, and positive and negative likelihood ratios) of selected ocular tests in diagnosing concussion.

Research Hypothesis for Aim 2

Hypothesis 2-1. The ocular tests will have a sensitivity and specificity of $\geq$ 60% compared to the diagnosis from an appointed health care professional who used a standard concussion assessment protocol.

Hypothesis 2-2. Positive likelihood ratios will be greater than two, exemplifying at least a small (2 to 5) to large (> 10) shift in probability that a concussion is present (Deneger, CR, & Fraser, 2006).

Hypothesis 2-3. Negative likelihood ratios will be $\leq$ 0.5 indicating a small (0.2 -.5) shift in probability that a concussion has occurred (Deneger et al., 2006).

Hypothesis 2-4. Receiver operating characteristic (ROC) curves will have a ($\geq$ 70) fair area under the curve(Carter, Pan, Rai, & Galandiuk, 2016).

Methodology

Research Design

A multicenter control group design was utilized. The independent variable was group (control vs. concussed). A concussion was operationally defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces. Diagnosis of a concussion was made by a NATA BOC athletic trainer or physician based on signs and symptoms, balance testing, and neurocognitive assessment scores. The dependent variables were the ocular test scores from the NPC, KDT, and stereoacuity. Possible variables that could influence the risk of concussion were also collected (sport, sex, and concussion history). Sport was categorized according to impact (high vs. low). High impact sports included football, ice hockey, and rugby while low impact sports included all others.

Participants

Subjects were recruited from Temple University club and varsity sports teams, Temple University's Motion Action Perception (MAP) lab, Drexel University club sports teams, and Widener University varsity athletics teams. All subjects were currently an active participant in a sport. Potential participants were excluded if they self-reported an unresolved ocular disorder (e.g., ocular hypertension, and gaze disorders). Control subjects were also screened and excluded for having a concussion by self-reporting no recent mechanism of injury. In total 34 controls were collected (21 male, 13 female) aged 19 $\pm$ 1.5 years. The sample of concussed athletes consisted of 19 patients (11 male, 8 female) aged 20.42 ± 1.5 years whom were seen 3.88 ± 3.51 days post injury. The concussed athletes were collected from Temple University’s club sports (n = 8), varsity sorts (n = 3), and MAP lab (n = 7), and Drexel University’s club sports (n = 1).

Instrumentation

Ocular Assessment Battery

Near Point of Convergence Assessment. An accommodative ruler (Figure 1; Bernell Incorp. Mishawaka, IN) was used to assess NPC. NPC measures the closest point in space where a patient can see one target with binocular vision. During testing the participant was seated with their head upright and facing forward. An accommodative ruler was placed to rest on the participant’s upper lip, and an accommodative target (i.e., reduced snellen chart including 8pt, 10pt, and 12pt font) was moved down the length of the ruler, towards their face, at a rate of approximately one to two cm/s. The participant was asked to signal once they experience diplopia and could no longer see a single target, which caused the examiner to stop moving the target and record the distance between the participant and object in centimeters. The test takes approximately 1 min to complete. The inter-rater reliability of this test was assessed through a pilot study in our lab where three testers performed NPC assessments on 10 young, healthy, active subjects (Pearson r = .981).

Figure 1. Accommodative Ruler

King-Devick Test. Four different test cards (Figure 3; KDT, Oakbrook Terrace, IL) were used to assess ocular-motor function. Each card contains a different series of single-digit numbers spanning from left to right (Figure 3). This test measures ocular-motor, speech, and decision-making brain functions by assessing the speed of rapid number naming in participants. First, each participant is shown a card and asked to practice the concept of reading aloud the digits displayed on the card. Once this is completed and the participant feels comfortable with the procedure, the test begins. Three other cards are then given to the participant and they are asked to read the digits located on the card as quickly as possible. The participants are timed, and errors are recorded. The test takes less than two min to complete and was found in a pilot study performed by the investigator at Temple University to have a high degree of inter (r = .941) and intra (r = .939) rater reliability.

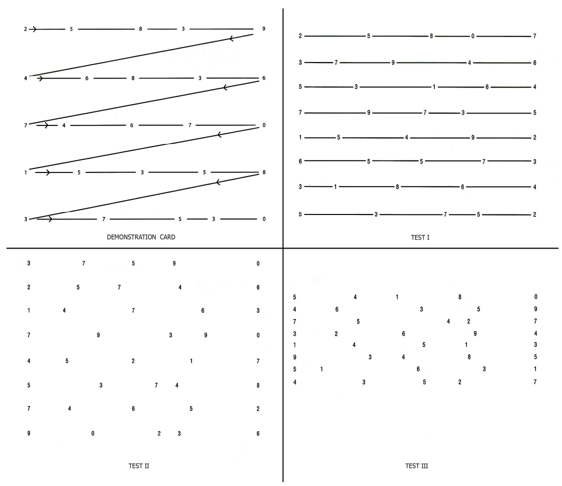

Figure 2. The King-Devick Test

Stereoacuity Test. Stereopsis was assessed with subjects wearing a pair of polarized glasses (Stereo Optical, Chicago, IL) while examining a card held about 14 inches from them, with different circle designs (Figure 3). Stereopsis occurs when the two retinal images, slightly disparate because of the normally different views provided by the horizontal separation of the two eyes, are cortically integrated. The subject was guided through 12 items of graded difficulty, each having three circle designs. The subject was asked to identify which circles look as though they are raised from the background of the card. Each circle design has an associated arc seconds. The arc seconds associated with the last circle within a design to be correctly identified as being raised from the surface by the participant was recorded. The test takes approximately two minutes to complete. Within the pilot study performed by the investigator, inter (r = .999) and intra (r = .932) rater reliability of this test was found.

Figure 3. Stereoacuity Test

Concussion Assessment Battery

Over the course of the season, athletes who were suspected of having a head injury (i.e., had an appropriate mechanism of injury and were reporting signs and symptoms indicative of a concussion) completed a site-specific standardized concussion evaluation. Each site’s battery of assessments included at least a detailed history of event mechanism, signs and symptoms assessment and the Balance Error Scoring System (BESS) test.

History of event mechanism and symptoms. With the assessment of a concussion, the athletes were asked to characterize the mechanism by which their injury occurred (e.g., head to head contact with another player or hit the ground with their head). Then they were asked to identify the extent to which they were experiencing any concussion signs and symptoms. These abnormal subjective feelings may have included dizziness, headache, irritability, difficulty concentrating, etc. Their concussion symptom severity was subjectively graded with a scale, and the progress of their resolution of symptoms was tracked through their recovery. Identification of these symptoms and scores has shown to have 89% sensitivity and 100% specificity at the time of injury (McCrea et al., 2005).

The Balance Error Scoring System. The BESS is an objective balance measure that involves posing in three different positions of graduated difficulty (double-leg standing, single-leg standing, and tandem stance) for 20 seconds on a firm then foam surface (Alcan Airex, Sins, Switzerland). The athlete closed their eyes and maintained the appropriate position for 20 seconds. If they fell out of the position in any way (e.g., stumbled, or opened their eyes) an error was recorded. Ultimately, all errors from each of the six poses were added up to provide the BESS test score. A study (Iverson et al., 2013) examining the modified BESS test (hard surface only) developed normative reference scores for this test. Adults aged 20 to 29 who exhibit 1 to 4 errors are categorized as normal, 5 to 6 as below average, 7 to 10 as poor, and 11 or more errors as very poor. This particular balance test has a 34% sensitivity and 91% specificity (McCrea et al., 2005) for concussion when used as an assessment tool at the time of injury.

Procedures

The principal investigator met with all athletic trainer’s at the involved sites. Protocols were explained in detail, and athletic trainers involved with collecting data were trained as to the proper testing procedures. All data collectors were provided with an educational handout (Appendix B) to refer to after having run through all the tests with the principal investigator. These appointed personnel then recruited athletes involved in team sports at their institution through flyers and e-mail advertisements (Appendix C). The data collectors then explained the consent process and discussed the study as well as answered any questions the possible participants had. If the athlete decided to participate they signed the appropriate institutional review board (IRB) consent and Health Insurance Portability and Accountability Act (HIPAA) forms (Appendix D). Normal baseline testing measurements were taken for all control athletes (e.g., BESS scores), with the addition of these three ocular tests, prior to the athlete’s season. When an athlete sustained a concussion during their season, they underwent ocular assessment (NPC, KDT, and stereoacuity) in addition to their normal concussion assessment battery. The sports medicine staff conducted the assessment and managed the injury as normal.

Data Analysis

Data were analyzed using descriptive and inferential statistics. The groups were investigated to ensure significant differences existed in the variables that defined a concussion (signs and symptoms and BESS test scores). The data were further inspected for any outliers within the dependent variable scores of the control group, which could alter the standard deviations of scores. Only the control group was examined for outliers because outliers within the concussion group could reflect a natural response to suffering a concussion. Observing a boxplot identified these outliers; any data points beyond 1.5 times the interquartile range, indicated they were possible outliers. The data were further inspected for normality after the removal of all outliers. The distributions of scores were examined through the Shapiro-Wilke test. Any data distributions that were found to be abnormal or skewed were transformed by taking the natural logarithm of scores. After that, the data were re-examined to identify if normal distributions existed.

Prior to performing analysis for the aim 1, the characteristics of participants were compared between the two groups (control vs. concussed) to identify any possible group disparities. T-tests were performed on the continuous variables of BESS test and total symptom scores to determine if the concussed and control group were significantly different when using the gold standard concussion assessment tools (Signs and symptoms, BESS test). Chi-squares were performed on certain categorical variables (i.e., sport, sex, and concussion history). Next, linear regressions were executed to determine if these variables contributed to the prediction of the ocular exam scores. First, an unadjusted linear regression was executed to evaluate the group effect on each outcome. Next, adjusted linear regressions were performed where potential confounding factors were added to the model and the group effect was re-evaluated after controlling for these covariates.

To evaluate Aim 1, t-tests were performed using the log-transformed data to determine if significant group differences exist for any ocular measures. For variables with a non-normal distribution, the nonparametric Mann-Whitney U test was performed.

To evaluate aim 2, diagnostic accuracy, sensitivity, specificity, and positive and negative likelihood ratios of these ocular tests were calculated. The standard to which these ocular tests were compared was a concussion diagnosis by either a certified athletic trainer or physician through use of signs and symptoms scales, balance testing, and neurocognitive testing (Broglio et al., 2007).

Clinical cutoffs for differentiating between a positive and negative ocular test were created by defining a positive test, or a test indicative of concussion, as being 1.0 standard deviation from the mean of all baseline scores (Broglio et al., 2007). Statistical cutoffs were also determined through the use of receiver operating characteristic (ROC) curve. The ROCs were depicted by plotting sensitivity on the y axis and 1 - specificity on the x axis, or the true positive rate versus the false positive rate (Bewick et al., 2004). The area under the curve (AUC) was also identified. An area of .90 - 1 exemplifies an excelled AUC while .80 - .89 is good, .70 - .79 is fair, .60 - .69 is poor, and .50 - .59 represents a failed test.

Sensitivity and specificity were calculated by (Denegar et al., 2012):

$$Sensitivity = \frac{Number\ of\ True\ Positives}{Number\ of\ True\ Positives + Number\ of\ False\ Negatives}$$

$$Specificity = \frac{Number\ of\ True\ Negatives}{Number\ of\ True\ Negatives + Number\ of\ False\ Positives}$$

Positive and negative likelihood ratios were calculated to further determine the diagnostic accuracy of these assessments without the prevalence of concussion affecting these values. Since data were collected from athletes who are more likely to sustain a concussion due to the sport they play, likelihood ratios enable a better estimate of injury. Likelihood ratios were determined by the following (Denegar et al., 2012):

+LR = Sensitivity / (1 - specificity)

-LR = (1 – Sensitivity) / Specificity

After calculating these ratios, they were interpreted using previously determined guidelines. For positive likelihood ratios 1 - 2 indicates a very small, usually unimportant shift in the possible presence of the injury while 2 - 5 is also a small shift, but sometimes important. Values ranging from 5 - 10 indicate a moderate shift, and > 10 indicates a large, often conclusive shift. For negative likelihood ratios 0.5 - 1 indicates a very small, usually unimportant shift while 0.2 - 0.5 is also a small, but sometimes important shift. From 0.1 - 0.2 is a moderate shift, and values less then 0.1 represent a large, often conclusive shift in the likelihood the injury is present (Denger et al., 2006). The alpha level was set at $p \leq 0.05$ and the SPSS for Windows, Version 21.0, statistical program (IBM, Inc., Armonk, NY) was used for all data analysis.

Results

Statistical tables are presented in Appendix G. Raw data are presented in Appendix H. First, the control and concussion groups were examined for significant differences in signs and symptoms, and balance test scores (Table 1). The concussion group significantly differed from our control group in the amount of symptoms they were experiencing; however, when BESS test scores were compared there was no significant difference between the two groups.

Table 1. Group Comparison of Scores on Standard Concussion Assessment Tools

Test	Control M	Control SD	Concussion M	Concussion SD	Statistical Analysis t	Statistical Analysis P
Total Symptoms	1.72 ±	3.84	18.26 ±	20.70	-4.424	<.001
BESS	16.29 ±	8.69	15.11 ±	11.09	.421	.329

Note. BESS (Balance Error Scoring System), M (mean), SD (standard deviation), and p (probability level).

Next, the data were investigated for any potential outliers within the control group. Three outliers were observed for NPC with scores of 17.5, 19, and 19.5 cm. Within the stereoacuity scores, three outliers were also found, each with a score of 100 arc seconds. These outliers were removed for the remainder of the analysis for each individual assessment. No outliers were identified in the KDT data.

Upon investigation of the normality of distributions, the data for NPC (W = 0.952, p = 0.205) and KDT (W = 0.972, p = .548) both demonstrated normal distributions as demonstrated by the Shapiro-Wilk statistic; however stereoacuity proved to have a non-normal distribution (W=0.775, p <0.001). After natural logarithmic transformation of all stereoacuity scores, these data still demonstrated a non-normal distribution (W=0.881, p=0.004). Accordingly, non-parametric statistical analyses were performed.

Chi-squares indicated there was no significant association between group (control vs. concussion) and sex, ($x^2(1)= 0.011$, $p = 0.917$; Table 2). Significant associations were identified between group and sport ($x^2(1)= 16.742$, $p < 0.001$; Table 3), and group and concussion history ($x^2(1)= 6.653$, $p = 0.010$; Table 4).

To further investigate these variables and their contribution to the ocular assessment scores, linear regressions were performed (Table 5). Stereoacuity was not investigated with a regression analysis as it demonstrated a non-normal distribution. With a model containing the variables group, sex, and sport, only group significantly predicted the score of the NPC assessment. After adjusting for sex and sport, the mean of NPC scores are higher by 7.09 cm in the concussion group as compared to the control group. Although not significant, this model also showed that athletes with a history of concussion scored 2.267 cm more on this test than those athletes with no history of concussion. The goodness of fit for this model was weak ($R^2 = .307$).

Table 2. Association between Group and Sex

Group	Male	Female	x^2	*p*
Control	*19(37.3%)*	*11(21.6%)*	*.011*	*.917*
Concussion	*13(25.5%)*	*8(15.7%)*		

Note. x^2 *(chi-square), p (probability level), and df=1.*

Table 3. Association between Group and Sport

Group	High Impact	Low Impact	x^2	*p*
Control	*30(58.8%)*	*8(15.7%)*	*16.742*	*.000**
Concussion	*2(3.9%)*	*11(21.6%)*		

Note. x^2 *(chi-square), p (probability level), and df=1.*

Table 4. Association between Group and Concussion History

Group	No Hx	Concussion Hx	x^2	*p*
Control	*10(19.6%)*	*13(25.5%)*	*6.653*	*.010**
Concussion	*22(43.1%)*	*6(11.8%)*		

Note. Hx (History), x^2 *(chi-square), p (probability level), and df=1.*

Table 5. Univariate Regression Analysis of Risk Factors for Concussion on Prediction of NPC Scores

Parameter	*B*	SE(B)	*p*
Group	7.090	1.899	.001
Sex	-.316	1.641	.848
Sport	-.263	2.251	.908
Concussion Hx	-2.267	1.606	.165

Note. B (coefficient for the constant), SE (Standard Error), *p* (probability level), and hx (history).

For the KDT, group was again the only factor that significantly predicted scores (Table 6). The control participants were faster by 6.307 s compared to the concussed group after controlling for sex and sport; however the goodness of fit in the current model was weak (R^2 = .165).

Differences Between Groups

A significant difference was found between groups for all three ocular assessments; therefore, all were investigated for diagnostic accuracy (Table 7).

Table 6. Univariate Regression Analysis of Risk Factors for Concussion on Prediction of KDT Scores

Parameter	*B*	SE(B)	*p*
Group	6.307	2.950	.038
Sex	4.401	2.483	.083
Sport	-5.041	3.503	.157
Concussion Hx	-2.936	2.478	.242

Note. B (coefficient for the constant), SE (Standard Error), *p* (probability), and hx (history).

Table 7. Ocular Assessment Scores by Group

	Control		Concussion		Statistical Analysis	
Test	M	SD	M	SD	t	*p*
NPC	4.78 ±	2.03	10.96 ±	7.70	-4.538	.000*
KDT	45.32 ±	7.28	50.18 ±	9.45	-2.063	.044*
Stereoacuity	28.59 ±	13.01	39.47 ±	14.13		.019*

Note. * statistically significant at $p \leq .05$. M (mean), SD (standard deviation), and *p* (probability level).

Diagnostic Accuracy

NPC

Utilizing the control group’s clinical scores, a cutoff point of 6.81 cm was calculated, which demonstrated a sensitivity of 63% and specificity of 79% (Table 8; Table 9). A positive likelihood ratio of 3 and negative likelihood ratio of 0.47 were then determined. These results indicate a small shift in probability that a concussion is present for a patient with a NPC score of $\geq$ 6.81 cm. The ROC analyses demonstrated a maximum AUC of 0.827. A sensitivity of 79% and specificity of 76% were used to identify a statistical cutoff point of 5.50 cm for this test (Table 10).

KDT

Using the clinical scores for this test from the control group, a cutoff time of 52.59 s was used to determine sensitivity (47%) and specificity (89%) (Table 9). A positive likelihood ratio of 4.27 and negative likelihood ratio of 0.60 were then determined. This indicated that should a patient score $\geq$ 52.59 s on the KDT, there is a small shift in the probability they have suffered a concussion. The ROC analyses demonstrated a maximum AUC of 0.658. A sensitivity of 58% and specificity of 72% were used to identify a statistical cutoff point of 49.5 s for this test (Table 10).

Stereoacuity

A clinical cut-off point of 41.6 arc sec was found using the control participants' scores (Table 9), which produced a sensitivity of 29% and specificity of 89% with a positive likelihood ratio of 2.64 and negative likelihood ratio of 0.80. This indicates a small to very small shift in probability a concussion has occurred given this clinical cutoff score on stereoacuity. A maximum AUC of 0.706 was found with the ROC analysis, which yielded a cutoff point of 28.5 arc sec. This was associated with 65% sensitivity and 54% specificity (Table 10).

Table 8. Clinical and Statistical Cutoffs Sensitivity and Specificity for NPC, KDT, and Stereoacuity

	Clinical		Statistical	
Test	Sensitivity	Specificity	Sensitivity	Specificity
NPC	63%	79%	79%	76%
KDT	47%	89%	58%	72%
Stereo	29%	89%	65%	54%

Table 9. Diagnostic Accuracy of Ocular Exams Based on Clinical Cut-Points

Test	Cut-Off	Sen.	Spec.	PLR	NLR
NPC	6.81	63%	79%	3.00	.47
KDT	52.59	47%	89%	4.27	.60
Stereo	1.60	29%	89%	2.64	.80

Note. PLR (Positive Likelihood Ratio), NLR (Negative Likelihood Ratio), AUC (Area Under the Curve).

Table 10. Diagnostic Accuracy of Ocular Exams Based on Statistical Cut-Points

Test	Cut-Off	Sen.	Spec.	PLR	NLR	AUC
NPC (cm)	5.5	79%	76%	3.29	.28	.827
KDT (s)	49.5	58%	72%	2.07	.60	.658
Stereo (deg)	28.50	65%	54%	1.41	.65	.706

Note. PLR (Positive Likelihood Ratio), NLR (Negative Likelihood Ratio), AUC (Area Under the Curve).

Discussion

The results of this study suggest that NPC, KDT, and stereoacuity are all tests that can positively contribute to accurately assessing a sport-related concussion. All three of these tests proved to have significantly worse scores in concussed athletes compared to healthy athletes. The cutoff scores determined for each test indicated sensitivity and specificity comparable to other concussion assessment tests (Broglio et al., 2007). Considering all of these tests are simple to learn, easy to implement, and cost effective, they may prove useful for clinicians in the field when assessing a concussion.

When a concussion occurs several identifying signs and symptoms follow, including confusion, amnesia, loss of consciousness, headache, dizziness, nausea, poor concentration, and/or poor balance that are considered to be indicative of injury (Herring et al., 2011). Many of these signs and symptoms, such as blurred vision, headache, or trouble reading could be attributed to ocular motor dysfunction. An athlete with these symptoms may have a normal field of vision and normal static visual acuity. Ostensibly, it is important to use tests which are specific to these ocular deficits, otherwise the concussion may go undetected. Ocular-motor dysfunction resulting from a concussion has been reported to occur in up to 65% of patients (Capo-Aponte et al., 2012) and could be an indication that one of the many areas of visual integration within the brain has been injured.

Differences Between Groups

When first determining if the concussion group performed significantly poorer on certain typical concussion assessments, it was found that they did have significantly more signs and symptoms than the control group (1.72 $\pm$ 3.84 vs. 18.26 $\pm$ 20.70). However, they did not perform significantly worse on the BESS test (14.66 $\pm$ 6.16 vs. 15.11 $\pm$ 11.10 errors). Although this was not expected, it does not indicate that our groups were not good representations of a healthy or concussed population. Variation in the diagnostic accuracy of the BESS test has been cited within the literature. Even though it may not be a strong test in terms of accuracy (34% sensitivity; McCrea et al., 2005) it is still a common tool employed to assess a concussion because it is objective, and because there are not many other affordable and practical balance assessment tools available to athletic trainers and health care professionals.

Near Point of Convergence

Near point of convergence is largely controlled within the midbrain. It is thought that delays in afferent signaling to this region regarding depth estimation from retinal disparity could lead to an abnormal NPC (Stark, Keynyon, & Krishnan, 1980). Furthermore, the pons, cerebellum, parietal lobes (Gamlin, 2002), frontal eye fields (Gamlin; Gamlin & Yoon, 2000), and the primary visual cortex (Trotter, Celebrini, Stricanne, & Imbert, 1996) are all involved in the neural pathway of vergence. Because so many areas of the brain are involved with the processing of this ocular motor function, it is not surprising concussion alters NPC in the present study.

NPC was significantly receded in the concussion athletes compared to the healthy non-concussed control athletes (10.96 ± 7.70 vs. 4.78 ± 2.03 cm). This is similar to the findings of several other studies (Capo-Aponte et al., 2012; Cohen et al., 1989; Hellerstein et al., 1995; Mucha et al., 2014; Szymanowicz et al., 2012). However only one of these former studies was similar to the present study in that it investigated sport-related concussion in the athletic population (Mucha et al., 2014). The remainder of these studies investigated non-athletic populations, including severe TBI (Cohen et al., 1989); and mild TBI (13 – 15 score on the Glasgow Coma Scale) incurred through non-sports mechanisms (Capo-Aponte et al., 2012; Hellerstein et al., 1995; Szymanowicz et al., 2012) compared to healthy counterparts.

Capo-Aponte et al. (2012) investigated the occurrence of visual dysfunctions and associated symptoms in active duty warfighters who experienced blast-related mTBI. Upon comparison to a healthy non-concussed control group, NPC (9.95 $\pm$ 7.43 vs. 2.9 $\pm$ 2.43mm), pursuit, and saccadic eye movements were all significantly more defective in the mTBI group. Furthermore, these patients presented with significantly more symptoms such as blurred vision, diplopia, headaches, and reading problems, which could all be related to disturbances in convergence (Capo-Aponte et al., 2012; Hellerstein et al., 1995).

Similar studies (Hellerstein et al., 1995; Szymanowicz et al., 2012) have reported comparable results when assessing NPC in mTBI patients. Hellerstein et al. found significantly receded measures in NPC between mTBI patients and age-matched control subjects; however, this measurement was taken using a different instrument (phoroptor), which possibly produced different results compared to the current study in which an accommodative ruler was utilized. Szymanowicz et al. found significantly receded NPC measurements in mTBI patients compared to age-matched controls (13.98 $\pm$ 2.06 vs. 7.03 $\pm$ 0.33cm). Both of these studies used optometry students as control subjects. It has been reported previously that anticipatory eye movements may alter vergence measurements (Kumar, Ramat, & Leigh, 2002), and therefore, using subjects who are knowledgeable of the testing process and anticipated outcomes may not serve as the best control subjects. Furthermore, these studies (Hellerstein et al., 1995; Szymanowicz et al., 2012) recruited participants from optometric centers where patients were referred for visual symptoms related to their injuries. This may imply their deficits are more pronounced than most patients, resulting in these findings not being generalizable to all mTBI patients.

The current study investigated sport-related concussion. In particular, the population was of college age (19.53 $\pm$ 1.47 yrs). Recently, Mucha et al. (2014) investigated NPC in a similar athletic population. They studied sixty-two patients (13.9 ± 2.5 yrs) who had suffered s port-related concussion by using a new tool called the Vestibular Ocular Motor Screening (VOMS) assessment. This battery of tests included NPC and the results were compared to a control group (12.9 ± 1.6 yrs). NPC was found to be significantly receded within the concussion group (p <.001) with a mean difference between groups of 4.0 cm (1.9 ± 3.2 cm vs. 5.9 ± 7.7 cm). The scores for both of these groups are smaller than those found within the current study; however, the population examined within the current study is comparatively older in age.

There has been some disagreement in the literature as to whether age may contribute to differences seen in normative values for NPC. Some investigators (Chen, O'Leary & Howell 2000; Hayes, Cohen, Rouse & De Land, 1998) have reported that elementary school-aged norms do differ from those of adults in that younger ages produce smaller measurements. In contrast, Adler et al. (2007) found no difference in scores with several different age groups (6 – 9, 11 – 13, and 20 – 30 yrs). Possible differences produced because of age have been suggested to be the result of the change in inter-pupillary distance, which increases with aging (Chen & O'Leary, 1997).

The difference in NPC scores among studies could also be attributed to differences in administration of the test. In the current study, the examiner performed the test by using an accommodative ruler and moving a target towards the athlete’s face until a positive test was noted either by the observation of mal-alignment of the eyes or by the athlete stating they were now seeing double. Mucha et al. (2014) performed this test by having the athlete move the target towards their own face until diplopia or mal-alignment was observed. Mucha et al. did not disclose the placement of the ruler on the athlete’s face, although they did note they measured the distance to the tip of the nose. Several other studies have failed to disclose the procedures in which this test was performed, which could affect an athlete’s results (Phillips & Tierney, 2015).

The diagnostic accuracy of NPC was also investigated in the current study. A clinical cutoff of 6.81 cm and statistical cutoffs of 5.5 cm were determined to identify a concussion. The statistical cutoff produced slightly stronger results in terms of sensitivity (79%) compared to the clinical cutoffs (63%). While both cutoffs produced similar results for specificity (76% for statistical, 79% for clinical). The statistical cutoff that was found in the current study is similar to the cutoff point of 5 cm used by Mucha et al. This previous study based this cutoff on two previous studies (Scheiman et al., 2003; Shippman, Infantino, Cimbol, Cohen, & Weseley, 1983). Scheiman et al. used optometry patients who had been diagnosed with convergence insufficiency and compared their results to a control group of optometry students. Differences were identified between these groups (2.49 $\pm$ 1.74 vs. 9 $\pm$ 6.74 cm). Shippman et al. used a similar population, and also found a difference between the groups with an average of 7.9 cm for the convergence insufficiency group and 5 cm for the control group. The authors stated that convergence insufficiency could be defined by an abnormal NPC of 10 cm or more (Shippman et al. 1983). It was noted that both groups tested within the accepted range of normalcy, and no suggested cutoff was provided; however the control group did have an average of 5 cm for this assessment. It should be noted that the cutoff used by Mucha et al. was not determined by using the same methods as in the current study.

Although the cutoff used by Mucha et al. (2014) was found by using averages of scores, they did implement ROC curves to determine the usefulness of their VOMS assessment. A curve specific to NPC and specificity of this test were not reported. The current study found a sensitivity of 63% and a specificity of 79% for NPC based on the clinical scores, which produced a positive likelihood ratio of 3. This indicates a small shift in probability that a concussion is present for a patient with an NPC score of $\geq$ 6.81 cm. Hayes et al. (1998) previously suggested a similar cutoff of 6 cm after having found that 85% of their healthy subjects had an NPC of $\leq$ 6 cm with an accommodative target. Mucha et al. reported that a cutoff of $\geq$ 5 cm resulted in sensitivity of 84% and a positive likelihood ratio of 5.8, indicating a moderate but usually important shift in probability that the condition is present. The difference in sensitivities and cutoffs between previous studies (Hayes et al., 1998; Mucha et al., 2014) and the current study could be attributed to the differences in averages reported for the populations investigated, differences in ages of the populations investigated, and also because NPC was not specifically used for the ROC analysis performed by Mucha et al. Taking everything into account, NPC could positively contribute to an assessment of concussion.

King-Devick Test

The KDT assesses how quickly an athlete can read a set a numbers from three cards. This procedure requires the generation of saccades, or quick movements of the eye from one number and line of numbers to the next. The production of these specific eye movements involves complex pathways within the brain. First, visuospatial information concerning the numbers on the cue card being viewed have to be relayed to the occipital lobe. From there, information is sent to the parietal cortex. The mapping of the eye movements are then produced in the frontal eye fields, dorsolateral prefrontal cortex, and several other motor areas (Heitger et al., 2004; Hutton, 2008). If any of these many areas are damaged, latency in the production of these eye movements can occur, resulting in the numbers to be read slower during the KDT.

This latency effect was demonstrated in the current study’s results as the concussion group performed significantly slower (50.18 $\pm$ 9.45 sec) than the control group (45.33 $\pm$ 7.23 sec) which is in agreement with the findings of other studies (Galetta et al., 2015; Galleta, Barett, et al., 2011; Galetta, Brandes, et al., 2011; King et al., 2015; Leong et al., 2015; Seidman et al., 2015) that have reported scores to worsen after head injuries. Even though there seems to be an agreement in the literature that KDT scores worsen with a concussion, there is great variability in what constitutes a normal range of time to complete the KDT. Appendix A-2 displays the variability in normal averages reported for this test, and also illuminates some of the possible causes for this variability.

The aforementioned KDT studies have investigated a range in ages and athletic levels. Small sample sizes (e.g., $\leq$ 12) have typically been used and in some investigations (Galetta et al., 2011; Galetta et al., 2015; King et al., 2012; King et al., 2015; Leong et al., 2015; Seidman et al., 2015; Vernau et al., 2015) an ambiguous definition of concussion was also employed when defining their groups. Several of these studies included “unwitnessed” concussions in which the mechanism of injury was not observed by a health care professional, or failed to reveal their concussion assessment protocol (King et al., 2012; King et al., 2015). Unstandardized methods of diagnosing a concussion within the literature, small sample sizes, and differences in age ranges could all attribute to different data and a large variance in KDT scores.

Within the current study, a sensitivity and specificity for KDT of 47% and 89% were found for a clinical cutoff of 52.59 sec. Only one previous study (King et al., 2015) investigated the diagnostic accuracy of the KDT, and reported the test having a sensitivity of 100% and specificity of 94%. These numbers are much higher compared to both the clinical and statistical numbers established in the current study. This could be attributed to how the concussion group was identified in the previous study (King et al., 2015). All who had a witnessed ($n = 8$) or unwitnessed ($n = 44$) mechanism of injury were tested using the KDT and then the Sport Concussion Assessment Tool 3 (SCAT3). If these rugby athletes scored > 3 s of their pre-match testing they were referred to a physician who confirmed the concussion using unknown methods (King et al., 2015). Because limited assessment tools were employed in this evaluation process, there may have been an inflation of sensitivity. In the current study, an NATA BOC athletic trainer or physician diagnosed the concussion based on mechanism of injury, signs and symptoms, balance testing, and neurocognitive assessment scores, which is in accordance with the National Athletic Trainers Association position statement on concussion (Broglio et al., 2014).

Even though the sensitivity of the KDT may not be strong, this test may still be useful as a concussion diagnosis and assessment tool within sport. For this tool to be useful, it may be important that baseline scores are first recorded to ensure a higher sensitivity in diagnosing a concussion. With a high degree of test-retest reliability, and worsening and graduated improvement of scores within previously concussed athletes (Galetta, Brandes, et al., 2011; King et al., 2012; Tjarks et al., 2013), this evaluation tool could even be used as a recovery assessment tool when tracking an athletes return to baseline during rehabilitation. Because it has demonstrated potential for diagnosing unwitnessed concussions (King et al., 2015), it should be investigated for its ability to detect subconcussion impacts.

Stereoacuity

Stereopsis is the ability to perceive depth through the integration of each individual eyes’ visual field. It is one of the processes that helps us to perceive 3-D depth. This process involves many of the same brain structures and pathways utilized in NPC and the KDT function. Initially, the retinas receive visual information for each eye and the information from each visual hemi-field is carried through the optic nerves to the contralateral occipital lobe via the geniculocalcarine tract where horizontal disparities between the two images are processed. Adjacent regions of the parietal cortex then interpret this information. For interpretation of objects in front of, or past the fixation point, different regions of the retina are involved where monocular information is eventually sent to separate hemispheres. Binocular integration then occurs by transmission of the information across the corpus callosum from the parietal and occipital regions (Howard & Rogers, 1995). Ultimately, through these different pathways binocular information is processed within the visual areas of the cortex and depth perception is perceived. Abnormal binocular vision occurs when a scene is viewed with both eyes yet depth is not perceived. This disorder can be due to a lack of coordination between extraocular muscles or as a result of damage to areas of the brain involved with neural processing of this information.

Within the current study, stereopsis was significantly affected by concussion (28.59 $\pm$ 13.01 vs. 39.47 $\pm$ 14.13 arc sec). The literature pertaining to this particular test is very limited. Investigations including an astereopsis test following brain injury have been performed within the severe TBI population (Miller et al., 1999). Subjects suffered traumatic brain injuries (33.05 $\pm$ 13.69 yrs) and were admitted to an emergency department for their injury. A Glasgow Coma Scale score of 13 to 15 and length of post-traumatic amnesia characterized diagnosis. Stereoacuity was evaluated using a six item raised circle test of graded difficulty, with each item being worth a point for scoring (6 = highest score achievable). The TBI group scored significantly lower (3.85 ± 2.2) than the control group (5.33 ± 1.09).

Two similar studies (Miller et al., 1999; Szymanowicz et al., 2012) examined stereoacuity within a population of patients suffering from mild TBI. Miller et al. reported significantly (p = 0.001) reduced stereoacuity within the TBI group compared to matched controls. Likewise, Szymanowicz et al. reported significant (p = 0.010) differences in stereoacuity between the TBI (38.8 ± 3.8 arc sec) and matched control group (20.5 ± 0.5 arc sec). Both of these studies, however, recruited brain injury patients from optometric centers, where they were referred because of their visual symptoms due to their head injuries. Accordingly, the findings from this population may not be generalizable to a typical sample of mild TBI patients. Nonetheless, it still provides insight into visual deficits that can be produced through a brain injury.

The randot stereoacuity test was used for this measurement in the study by Szymanowicz et al. (2012) and also in the current investigation. Compared to the previous investigation, in the current study somewhat similar scores for both the control and concussion groups (28.59 ± 13.01 vs. 39.47 ± 14.13 arc sec). This is the first time stereoacuity has been investigated in the sports-related concussion population and has shown potential to be incorporated into a concussion assessment battery.

Limitations

This study was not without limitations. The small concussion sample size may have limited the interpretation of this data. However, the sample size was large enough to identify statistically significant results. Additionally, in the future it would be beneficial to perform a similar investigation with a pre- post-test design where the same participants are baseline tested before the sports season begins and tested again after having suffered a concussion. This would account for individual variations that may occur due to unique physiological characteristics of individuals. Lastly, it would be valuable to clinicians to gather more data pertaining to normative values for these tests to ensure easy interpretation of injury values.

Decisions on Aims and Hypotheses

Based on the results of this study, the following decisions on the hypotheses were made:

Aim 1

Hypothesis 1

There were statistically significant differences found between concussed athletes and controls on the three ocular test scores. Specifically, the concussion group scored significantly worse on all tests with a more remote NPC, longer reading times for the KDT, and greater arc seconds for stereoacuity testing. Hypothesis 1 was accepted.

Aim 2

Hypothesis 2-1.

The diagnostic measures of all tests can be seen for the clinical cutoffs in table 9 and the statistical cutoffs in table 10. It was hypothesized that all tests would have a sensitivity and specificity $\geq$ 60%. All statistical sensitivities were close to or greater than 60% so Hypothesis 2-1 was partially accepted.

Hypothesis 2-2.

It was hypothesized that Positive likelihood ratios would be greater than 2 exemplifying at least a small shift in probability that a concussion is present (Deneger et al., 2006). All tests demonstrated positive likelihood ratios greater than 2, except for the statistical positive likelihood ratio of stereoacuity. Hypothesis 2-2 was partially accepted.

Hypothesis 2-3.

Negative likelihood ratios were hypothesized to be $\leq$ 0.5 indicating at least a small shift in probability that a concussion has occurred (Deneger et al., 2006); which none of the tests reached. Only the NPC met the threshold as the other tests had negative likelihood ratios ranging from .60 - .80 indicating very small and usually unimportant shifts in probability that a condition is present. Hypothesis 2-3 was rejected.

Hypothesis 2-4.

Receiver operating characteristic (ROC) curves were hypothesized to have a large area under the curve, exemplifying at least a fair indicator of diagnostic performance of $\geq$ .70 (Carter et al., 2016). The areas under the curves ranged from .658 - .827 indicating almost fair to good accuracies. Hypothesis 2 was not partially accepted.

Conclusion

Recently, a new trend in concussion diagnosis has emerged which consists of identifying different clinical trajectories that present secondary to a concussion. These clinical trajectories or pathologies such as cervical, vestibular, and ocular-motor pathology present with different signs and symptoms and should all be treated differently according to the underlying pathology. Foremost, it is important that clinicians are able to recognize and differentiate each of the trajectories (Collins et al., 2013; Ellis et al., 2013; Leddy et al., 2012). Once the correct trajectory or pathology has been identified a more targeted form of rehabilitation can be initiated. Ocular testing has the potential for contributing to the identification of the correct concussion trajectory.

This is the first study to investigate concurrent clinical and statistical diagnostic accuracies of NPC, the KDT, and stereoacuity in a sport-concussion population. All of these tools demonstrate their clinical usefulness through their diagnostic accuracy measures, and therefore could be useful additions in a concussion assessment protocol. Although the tools exhibited low to high sensitivity and specificity, no single tool should be used as a standalone assessment during a concussion assessment. Instead, it is appropriate to continue investigations of new tools that may aid in the detection of the diverse signs and symptoms associated with a concussion, such as ocular motor dysfunction. The current study’s findings highlight the viability of supplementing the current concussion protocol of signs and symptoms, balance, and cognitive assessment with these three ocular tests. Through use of these ocular tools certain symptoms commonly missed in concussed athletes previously may be potentially identified.

Recommendations for Future Research

In the future, the use of a prospective pre- post-test control design would be most beneficial in the investigation of these tools. By collecting participants' baseline data, any differences in individual performance would be accounted for. Furthermore, other ocular-motor tests should be investigated for their diagnostic accuracy as this domain of a concussion assessment is still lacking in most health-care professionals protocol. Based on the results of the present study, these tools may aid in detecting and monitoring an athletes' concussion.

CHAPTER 2

REVIEW OF LITERATURE

Sport Concussion

Epidemiology

Concussions are a growing problem in sports; currently it is estimated annual incidence rate is 1.6 to 3.8 million (Langlios, Rutland-Brown, & Wald, 2006). This number has risen in emergency rooms, and high school and college sports (Hootman, Dick, & Agel, 2007; Lincoln, Caswell, & Dunn, 2011; Selassie et. al., 2013) possibly due to an actual increase in the incidence of concussion, or possibly due to the increased education, awareness, and diagnosis of the injury. Not taken into account in this estimate of yearly occurring concussions are the undiagnosed concussions that occur. A recent study (Meehan, Mannix, & O'brien, 2013) found that of 486 patients, 30.5% reported having previously suffered a head impact that resulted in concussion symptoms indicating a large portion of these injuries remain undiagnosed even with our current education efforts.

A surveillance study over 16 years using the National Collegiate Athletic Association (NCAA) injury data found that out of 15 collegiate sports, football had the highest number of reported concussions. Fifty five percent of all concussions recorded throughout this surveillance study occurred in football; incurring an injury rate of .37 per 1,000 athlete-exposures (Hootman et al., 2007). Soccer had the third highest exposure rate with women’s soccer having an injury rate of .41 per 1,000 while men’s soccer had .28 per 1,000 athlete exposures (Hootman et al., 2007). Overall, women’s ice hockey had the highest injury rate of .91 per 1000 exposures, yet the data for this particular sport was only collected for four years unlike the other sports in this NCAA study.

Concussion rate trends in high school have been found to be of similar nature with football leading the incidence rates. A recent study (Lincoln et al., 2011) examining injury data from 25 public high schools showed an overall concussion rate of .24 per 1000 exposures. Football had the highest incidence rate of .60, girl’s soccer with .25, and boy’s lacrosse with a rate of .30 per 1000 exposures. Compared to all other injury data collected, concussion accounted for 74.9% of injuries incurred by male athletes, and 25.1% for female athletes in this high school population. Beyond sport, position also influences the incidence of this injury. Within football, quarterbacks, wide receivers, running backs and defensive backs have three times greater risk of concussion than lineman

(Pellman et al., 2004). Similarly, the number of head impacts an athlete experiences has been found to be position dependent (Crisco et al., 2010). Defensive lineman have been found to sustain the greatest number of head impacts as compared to offensive linemen and the other involved skill players in football.

Through a traumatic brain injury surveillance system in 65 hospitals, and 67 emergency departments, data were collected pertaining to sport-related traumatic brain injuries (TBI’s) (Selassie et al., 2013). Through this study, injury information was collected on 16,642 admitted patients. Of these sport-related TBI’s, 93.2% presented as mild cases, as defined by diagnosis codes collected. For these mild sports-related brain injuries, the most common mechanism of injury was through direct contact collision in either football or rugby (38.1%), followed by falling during play (20.3%), and off-road motorized vehicle injuries (16.1%).

Recovery

Normally, 80-90% of athletes will have resolution of their concussion symptoms within one week of their injury (Makdiss et al., 2010; McCrea, Barr, & Guskiewicz, 2013). However, although these acute symptoms usually resolve, several negative long-term effects have also been identified. Professional football players with a history of concussions have been shown to develop cognitive impairments later in life (Broglio et al., 2012; De Beaumont et al., 2009) along with earlier onset of dementia-related syndromes such as Alzheimer's disease (Guskiewicz, 2005). Likewise, there is also a correlation between a history of concussion and recurrent concussions and clinical depression (Guskiewicz, 2007; Vanderploeg et al., 2007). Athletes with a previous history of concussion are more likely to suffer from concussions in the future, while also requiring a longer recovery time after a concussion occurs (Guskiewicz et al., 2003). One study (Vanderploeg et al., 2007) used questionnaires to examine the long-term difference between those who have suffered a mild traumatic brain injury and their controls. The investigators found that those who had previously suffered a mild traumatic brain injury had poorer psychosocial outcomes including being more likely to have self reported disability, underemployment, low income, and marital problems.

Researchers have found that acute symptom severity is independent of impact magnitude and that individuals react differently to the same forces (Guskiewicz, 2007). These individual reactions may be related to certain risk factors such as age, gender, history of concussion, or genetics. Because of this, a thorough history, to identify these factors, is imperative to a concussion evaluation. Age is one of the modifying factors that may influence the evaluation and management of concussion. Younger developing athletes may be predisposed to longer recovery in addition to being more likely to suffer a concussion accompanied by a catastrophic injury (Field, Collins, & Lovell, 2003; Moser, Schatz, & Jordan, 2005; Zuckerman, Odom, & Lee, 2012). This may be related to the anatomical differences in developing brains and continuing cognitive maturation seen in younger age groups (Guskiewicz et al., 2011).

Gender may also be another modifying factor for the risk of concussion or females have been shown to have a higher reported incidence of concussion (Covassin, Swanik, & Sachs, 2003; Gessel, Fields, & Collins, 2007; Lincoln et al., 2011; Marar, McIlvain, & Fields, 2012), and report more symptoms, more severity in their symptoms, and have more prolonged recoveries when compared to males (Colvin et al., 2009; Covassin et al., 2003). Possible reasons to account for these differences between genders include decreased head-neck mass of females which may lead to greater acceleration of the head after a head impact and thus leading to a more severe injury (Tierney et al, 2005).

Hormone differences and even innate differences in blow flow within the brain between genders may also attribute to this modifying factor (Esposito et al., 1996).

Having a history of concussion increases the risk of suffering another concussion (Colvin, Mulllen, & Lovell, 2009; Guskiewicz et al., 2003; Guskiewicz et al., 2007; Hollis, Stevenson, & McIntosh, 2009; Schulz, Marshall, & Mueller, 2004). Yet a significant relationship between history of concussion and protracted recovery has yet to be determined because conflicting research exists (Lau, Lovell, & Collins, 2009; Slobounov, Slobounov, & Sebastianelli, 2007). No difference in recovery time in those with a prior concussion compared to controls has been found (Lau et al., 2009). Contrarily, another study (Slobounov et al., 2007) found significant correlations between prolonged recover and a history of at least two concussions.

A history or preexisting migraines may also be a risk factor for concussion (Kinart, Cuppett, & Berg, 2002) for a correlation between the two has been identified (Gordon et al., 2006). Evidence has yet to be found for an association between this risk factor and a prolonged recovery from concussion. Similarly, depression, which may also coincide with abnormal pathophysiology prior to injury, may be a risk factor for concussion (Chamelian et al., 2006; Chen et al., 2008; Mooney et al., 2005; Vanderploeg et al., 2007).

Lastly, an athlete's genotype may also be a modifying factor for concussion. Associations between concussion and polymorphisms in APOE e4, APOE G-219T promoter, and tau exon 6, have been seen but these results are limited by their methodology and small sample sizes (Terrell, Bostick, & Abramson 2008; Tierney et al., 2010). Contrarily, no association has also been seen between APOE e4 and concussion (Kristman et al., 2008), but this study also had several limitations including a very small sample size. Very few studies have shown an association between genotype and incidence or severity of concussion, but this may be a factor in the sequela of concussion as differences in genotype may directly affect the pathophysiology and outcome of this injury.

Pathomechanics

A concussion can be defined as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces (Herring, et al., 2011). The brain is protected by meninges, cerebrospinal fluid, and the skull; however injury to brain tissue can still occur even without a skull fracture due to transmitted biomechanical forces. Mechanisms through which a concussion can occur include a direct blow to the head, indirect blow to the head, which causes inertial loading on the head, or through intense changes in pressure (e.g. blast exposure). Through such insults both acceleration and deceleration forces occur either linearly or rotationally causing loading of these forces to the brain. The direction of acceleration, either linearly or rotationally, has been seen to be sport dependent, but likely present during most events (Ohhashi, Tani, & Murakami, 2002; Viano, Casson, & Pellman, 2005). In boxing, punches resulting in concussion have been found to have rotational acceleration (Ohhashi et al., 2002), while in football a concussion is more likely to occur from linear acceleration (Viano et al., 2005). This may be due to the nature of the sports, and where force is usually directed, for rotational forces have been shown to have worse outcome in brain injury (Gaetz, 2004; Ommaya et al., 1974)

Concussions can result from a wide range of head impact magnitudes, and resulting head accelerations. Forces ranging from 60 to 168g have been shown to result in concussions (Guskiewicz, 2007), yet no correlation between head impact magnitudes and concussion severity has been found (Broglio et al., 2011). Repetitive forces (e.g., soccer heading) may also lead to a concussion (Tysvaer & Lochen, 1991). No threshold of impact magnitude, which may cause a concussion, has been identified. Tissue of the brain deforms in response to shear forces, which can be produced through rotational acceleration. No gross pathology, such as hemorrhaging, is associated with a concussion. These biomechanical forces cause injury to neurons at the cellular level in the brain.

Diffuse brain injury, as seen in mild brain injuries such as concussion, is caused by the stretching and tearing of brain tissue and diffuse axonal injury. These injured cells become susceptible to ion fluctuations across the neuron resulting in an ionic imbalance. This causes propagation of action potentials to fail and damage to the cytoskeleton and microtubule components of these cells to occur. As the amount of strain increases, and the axon is stretched further, the ionic imbalances intensify and if too much strain is incurred, some of the influx can become irreversible. Also occurring after an initial impact is cell death, which can lead to disruption of the blood brain barrier integrity. This, in addition to ionic fluxes, leads to an inflammatory reaction. Glial cells become activated and proteins involved with the inflammatory cascade become up-regulated (Nimer, Lindnlom, & Strom 2013).

Pathophysiology

A concussion begins at the cellular level. During a mechanical insult, neurons become stressed and stretched causing a neurometabolic cascade (Giza & Hovda, 2001). Immediately upon being concussed, channel regulation systems within neurons become damaged causing a flux of ions. An influx of calcium and sodium occurs along with a release of potassium. This ionic disequilibrium causes a release of excitatory neurotransmitters causing depolarization. In order to restore a balance in ions, active sodium/potassium pumps work at intense levels, which require an increase of adenosine triphosphate (ATP). With an increased need for glucose for ATP, the brain increases its metabolism. Coinciding with this process, as a result of injury, is a decrease in cerebral blood flow. Energy demand no longer meets energy production because of this decline in blood flow, creating an energy crisis and rendering the brain weak and vulnerable. Following these events, the brain depresses its metabolism. Several different events may then occur such as increased lactate production, mitochondrial dysfunction, impaired neural connectivity, axonal injury, and even cell death (Giza & Hovda, 2001).

In addition to a metabolic cascade, an inflammatory cascade also occurs in the brain after physical insult. The acute inflammatory cascade first involves recruitment of neutrophils to injured areas as the first form of defense in innate immunity. Through the process of chemotaxis, which is aided by cytokines, neutrophils become localized to the injured area. Neutrophil degranulation and tissue destruction occur while inhibition of TNF-α and neutrophils diapedesis happens. Then these cells act through phagocytosis and degranulation to repair the injured area. Furthermore, neutrophils can express and release cytokines and other signaling molecules leading to further amplification of the inflammatory process (Wang et al., 2000). Additionally, microglia and astrocytes are capable of directly releasing pro-inflammatory cytokines for local repair (Galic et al., 2012; Singh et al., 2011). After 24-48 hours, when acute inflammation begins to cease, monocytes and T cells replace neutrophils. By reducing the amount of neutrophils, any tissue damage that may be caused from prolonged accumulation proteases and reactive oxygen species that are released by neutrophils will be prevented.

The newly recruited monocytes can then differentiate into macrophages, which phagocytize debris while also contributing to the recruitment of lymphocytes. Coinciding with this process is astrogliosis and angiogenesis, which helps the recovery process by aiding tissue remodeling and recovery from the initial stimuli.

Assessment

Diagnosing a concussion can be difficult because of its complex symptomatology. Many different parts of the brain can be affected through a concussion, requiring assessment of several different brain functions for a thorough evaluation of a head injury. In order to increase sensitivity of diagnosis, use of a battery of tests, including such tools as signs and symptoms scaling, balance, and neurocognitive testing has been recommended by researchers (Broglio et al., 2007; Lau et al., 2011; McCrory et al., 2013). Because many sports related concussions go unreported (Meehan et al., 2013), possibly because of an athletes desire to continue playing, it is important to focus upon the objective measures of concussion. This includes neurocognitive testing, balance testing, and possibly ocular testing. Reporting of signs and symptoms by an athlete is an important facet to a full evaluation, but is subjective, and may be censored by an athlete.

Standard imaging procedures such as an standard structural MRI or CT scan are useless as acute diagnostic tools with this injury for no gross injury to brain tissue occurs (McCrory et al., 2013). However, functional MRI’s (fMRI) have shown correlations between activation patterns in certain areas of the brain and symptom severity in subacute concussion (Chen, Johnston, & Frey, 2004; Chen, Johnston, & Petrides, 2008; Gosselin, Saluja, & Chen, 2010). Through using blood oxygen level dependent fMRI, less activation in certain brain areas have been seen in concussed individuals when given working memory tasks (Chen et al., 2004) indicating these areas have been compromised. Furthermore, injured athletes have been tracked with this imaging technique, and improvements have been seen in their functioning throughout their rehabilitation (Chen et al., 2004; Chen et al., 2008).

Furthermore, through this imaging technique, changes in brain functioning have been identified in concussed individuals who display no behavioral symptoms (Gosselin et al., 2010). These results indicate that cognitive symptoms may persist beyond resolution of all other symptoms, indicating again the need for a multi-assessment approach for the evaluation and tracking of a concussion. Should an athlete return to play prior to resolution of symptoms, they pose the risk of suffering second impact syndrome, diffuse cerebral swelling, recurrent or more severe concussion and possibly an even longer duration of protracted symptoms (Harmon et al., 2013).

Fortunately, cognitive deficits can be identified through serial neurocognitive testing (e.g., ImPACT, Headminder CRI), which has become a common assessment tool in a concussion evaluation. This form of computerized testing examines several different domains of cognitive functioning including attention span, working memory, reaction time, and non-verbal problem solving. After entering demographic data, athletes are taken through different mental tasks set up like games, which then produce several scores, correlating to their level of cognitive functioning. Interpretation of these scores requires specific training, but can illuminate specific deficits an athlete possesses, while also being able to track their progress in a rehabilitation program. This type of testing has proved to be useful in a battery of assessments, but its sensitivity to concussion, as a stand-alone tool, is very low (Broglio, et al., 2007; McCrea et al., 2005). Therefore, this test should always be used in conjunction with other assessment tools such as a signs and symptoms checklist.

Collecting symptom information is an important aspect to a concussion evaluation. When a concussion occurs, there are several identifying signs and symptoms that can be immediately observed including confusion, amnesia, loss of consciousness, headache, dizziness, nausea, poor concentration, and/or poor balance (Herring et al., 2011). Headache is the most common symptom reported with a concussion with dizziness the being next most common (Makdissi, Darby, & Maruff, 2010). Headaches and the feeling of fatigue, lethargy or fogginess have been shown to last the longest of all reported symptoms (Makdiss et al., 2010). This information can be easily collected through symptom checklists or scales, and can be assessed for duration and severity. Self-reporting of these symptoms causes this aspect of an evaluation to be subjective. Furthermore, because some of these symptoms are similar to symptoms of dehydration (Patel et al., 2007), or feelings associated with heavy physical activity (Williams et al., 1994), these scales and checklists yield low specificity to concussion. In addition, athletes may underreport symptoms in efforts to conceal their injury and continue playing (McCrea et al., 2004).

The Sport Concussion Assessment Tool 3 (SCAT3), which includes a symptom scale, is a tool that was developed for medical professionals to evaluate a head injury through several different assessments at once. In addition to signs and symptoms, this tool includes a Glasgow Coma Scale, cognitive and memory assessment, neck exam, and balance and coordination exams. This tool only takes five minutes and can easily be incorporated into a sideline concussion assessment. In addition to its convenience, it’s helpful in that it guides a healthcare practitioner through several screening exams that can aid in the assessment of a head injury. The standardized assessment of concussion (SAC), which compromises only the mental-status screening aspect of the SCAT3, has been shown to be highly sensitive (80%) and specific (91%) to concussion (McCrea et al., 2005). This sensitivity rises even more when the SAC is combined with other assessment tools, such as a balance test (McCrea et al., 2005).

Balance testing is an objective way to assess postural control deficits, which can be produced by a concussion (Guskiewicz et al., 1997; Guskiewicz et al., 2001; McCrea et al., 2003; Peterson et al., 2003). Problems with balance may arise due to the failure of integration of information from both the vestibular and ocular systems involved with this task (Guskiewicz et al., 1997; Guskiewicz et al., 2001; Peterson et al., 2003). The balance error scoring system (BESS) has been shown to be sensitive in the assessment of concussion (McCrea et al., 2003; McCrea et al., 2005), and is commonly incorporated into this injury evaluation. In order to assess postural control deficits, the SCAT3 uses a modified version of this tool, as it is easy and convenient to perform on the sideline. The full version of this tool consists of three different poses, each held for 20 sec, on two different surfaces (stable and unstable). The number of errors, or times the athlete falls out of their stance is added up to form the total score.

Baseline testing of these concussion assessment tools is recommended (Broglio et al., 2014) as it can aid diagnosis of this injury. By testing an athlete while they are healthy, prior to an injury, baseline data can be gathered to further understanding of how they would normally test in ideal conditions. Then, post injury, these scores can be compared to assess if deficits are present, and to track their progress through a rehabilitation program. Baseline testing helps to personalize an evaluation by identifying deficits specific to the individual, not in comparison to a normative value generalized to a population. Within many athletics programs, baseline testing has been incorporated into standard protocols.

A less commonly incorporated assessment battery is that of an ocular motor exam. An ocular assessment for head injuries has traditionally included only smooth pursuits (i.e., H-test) and testing of the pupillary reflex to examine cranial nerves. Only in the presence of severe traumatic brain injury or intracranial bleeding will the pupillary reflex test be positive. Even though ocular tests are not commonly incorporated into a concussion assessment, it is estimated that up to 65% of concussion patients present with ocular motor dysfunction (Capo-Aponte et al., 2012). Consequently, more robust ocular motor screenings are starting to become incorporated into a concussion assessment battery. Different aspects of vestibular and ocular functioning such as smooth pursuits, saccades, convergence, vestibular ocular reflex, and visual motion sensitivity have proven useful in assessing a concussion and identifying athletes in need of special treatment (Collins et al., 2014).

Vision

Vision is considered the primary sense because of the numerous structures of our brain that contribute to this function. Out of the 52 cortical areas, 32 are believed to be involved with vision (Tovee, 1996). Beyond the cerebral cortex, other deeper structures are involved with this complex functioning. From the retina in the eyes, visual information is carried to the lateral geniculate nucleus (LGN) and then to different cortical areas. Depending upon the type of stimulus (e.g., color, shape, motion) different pathways within the brain are used to communicate this information.

The first point in any visual pathway is the retina. Specific neurons are located on the inner surface of this structure. Two main nerve clusters, or ganglion cells exist in this structure; M class and P class cells (M and P cells). The P cells respond to wavelength and high spatial frequencies and slow sustained responses. The P cells have much smaller dendritic trees and cell bodies and therefore receive little information from rods and cones. The M cells have larger dendritic trees and cell bodies and are therefore sensitive to low spatial frequencies and have faster conduction velocities. All of the ganglion cells located here converge to form the optic nerve, which projects posteriorly from the eye. The right and left optic nerves then join forming the optic chiasm. The optic nerves have a partial decussation causing each hemisphere to receive information from the contralateral visual hemifield (e.g. the left visual hemispace projects to the right side of the brain). Posterior to the optic chiasm, the nerves are now labeled as the optic tracts. These tracts project posteriorly towards the cortex to the LGN (Snowden & Thompson, 2006).

The LGN is a collection of neural cell bodies with six different layers. Layers one and two have larger cell bodies and are named magnocellular or M layers. These layers receive input from M cells while the Parvocellular or P layers receive input from the P cells. These layers of the LGN are similar in functional characteristics to their correlating ganglionic cells. The axons projecting from the LGN to the cortex are called optic radiations or the geniculo-calcarine tract.

The optic radiations continue to the primary visual cortex, or V1, which is a cortical area located within the occipital lobe. Structurally, this area consists of six functionally different layers. Several pathways between layers and communicating neurons exist here, all dealing with different information (e.g. orientation, perception of motion, binocular disparity and color). From V1 most information is then sent to the second major visual area in the cortex or V2. Visual areas 3, 4, 5, and 6 also receive information from V1 and the other visual areas. These areas all help to integrate the visual information that has arrived there (Tovee, 1996).

Vision in Brain Injury

Brain injury, caused by acceleration and deceleration forces, may cause damage to neurons through stretching and shearing of axons. Because of the diffuse nature of this type of injury, many different brain areas and their associated functions may be affected in a negative manner. One such function which has been shown to be compromised in severe TBI (Ciuffreda et al., 2007; L.J Miller et al., 1999), and mild TBI (Hellerstein et al., 1995) is vision.

Damage to afferent or efferent structures involved in vision, such as the optic nerves, cranial nerves that control eye movements, or areas of the brain involved with cortical processing can all affect vision. Different areas of the brain are involved with both the afferent and efferent visual pathways. The afferent visual pathway consists of the structures from the retina to the visual centers in the brain. From the retina, the optic nerve travels to the optic chiasm. From there, signals travel through the optic tract to lateral geniculate nuclei, to optic radiations and then to the occipital lobe (Snowden et al., 2006). Cranial nerves III (oculomotor), IV (trochlear), and VI (abducens) are involved with the efferent pathways of vision, and if damaged they may produce diplopia, or double vision. Beyond damage to the classic visual system structures, damage to the vestibular system including the brain stem, cortex and cerebellum can cause nystagmus, blurred vision or diplopia.

Dysfunction within the ocular motor system can produce vision discomfort and loss of functions that enable one to read (Ciuffreda et al., 2006; Kapoor et al., 2004). These symptoms from such an injury may prolong or hinder the rehabilitative process, especially cognitive therapy (Grosswasser et al., 1990; Reding et al., 1988). Most brain injury rehabilitation involves the visual system. For instance, cognitive rehabilitation necessitates the use of many visual functions for reading and processing, while vestibular rehabilitation involves interaction between vergence and accommodative systems. If the appropriate vision diagnosis is not made, these deficits may negatively affect the rehabilitative process, and possibly even become exacerbated. Because of this, it is important to recognize deficits in the visual system so as to enhance the direction of rehabilitation and overall quality of life for those recovering from a concussion. Optimal management of individuals with concussion requires that clinicians be aware of the expected visual dysfunctions that can be found in these athletes as well as their potential effects on the overall rehabilitation process.

Investigation into the occurrence of visual dysfunctions and symptoms associated with mTBI found that those diagnosed with a mTBI showed normal eye health measurements (e.g. normal visual fields, pupil responses, intraocular pressure) while presenting with ocular motor deficits (Capo-Aponte et al., 2012). This suggests these clinical characteristics are poor indicators of overall visual function status of those with mTBI. Further evaluation of ocular functions which have been shown to be negatively affected in mild TBI such as NPC, pursuits, and stereopsis (Hellerstein et al., 1995), could provide sensitive and objective assessment markers of ongoing brain function impairment.

Convergence

The vision related ocular motor system includes the vergence, and accommodative systems (Ciuffreda & Tannen, 1995). Accommodation describes the process by which the eye maintains focus on an object, by changing the shape of the lens through the contraction of the ciliary body. Vergence refers to the simultaneous movement of both eyes in opposite directions to obtain or maintain binocular vision. More specifically, convergence is when the eyes rotate towards each other while divergence is when they rotate away from each other.

Convergence specifically involves adduction of the eyes to focus the eye upon the object of interest. The medial rectus muscles, which are controlled by cranial nerves III (oculomotor), control this movement. When these extraocular muscles function out of balance, diplopia, or double vision occurs. The near point of convergence (NPC) measures the closest point to which one can maintain convergence while focusing on an object, before diplopia or deviation of an eye occurs. Convergence insufficiency is an eye muscle coordination problem where there is dysfunction in coordination of rotation of the eyes inward. The cause of this is unknown, but it could result from damage to the involved eye muscles, cranial nerves, or ocular motor pathways within the brain contributing to this function. Ultimately, it can result in blurred vision, diplopia, problems reading, headache, and eyestrain. Measurement of a receded NPC aids in diagnosis of this binocular vision disorder.

Convergence insufficiency, defined by a receded NPC by Cohen et al., was found to be significantly more common in patients with severe TBI then healthy individuals (Cohen et al., 1989). More recently, this measurement has been used to assess more mild forms of TBI as defined by less than 30 min. loss of consciousness, greater than or equal to a score of 13 on the Glasgow Coma Scale, and less than 24 hr. posttraumatic amnesia. When comparing the visual profile of mild TBI patients to controls, NPC has been found to be significantly more receded (Capo-Aponte et al., 2012; Hellerstein et al., 1995; Szymanowicz et al., 2012).

Capo-Aponte et al. (2012) investigated the occurrence of visual dysfunctions and associated symptoms in active duty warfighters who experienced blast-related mTBI. Those who suffered a blast-related mTBI were evaluated between 15 to 45 days after their injury occurred for basic eye health in addition to a detailed ocular motor assessment, which included the measurement of NPC. In addition to this group, 20 age-matched (31.2 $\pm$ 7.36 yrs.) control subjects were tested on all measures. Upon comparison, NPC (9.95 $\pm$ 7.43 vs. 2.9 $\pm$ 2.43 cm), pursuit, and saccadic eye movements were all significantly more defective in the mTBI group. Overall, the most prevalent visual dysfunctions found within their mTBI group were vergence, version, accommodation, and reading deficits. Furthermore, these patients presented with significantly more symptoms such as blurred vision, diplopia, headaches, and reading problems which could all be related to disturbances in convergence (Capo-Aponte et al. 2012; Hellerstein et al., 1995), indicating some symptoms that are observed as a result of a concussion may be vision related in origin.

Similar studies (Hellerstein et al., 1995; Szymanowicz et al., 2012) have found comparable results when assessing NPC in mTBI patients. Hellerstein et al., found significantly receded measures in NPC (1.501 vs. 0.188; units not recorded) between mTBI patients and age matched control subjects. Likewise, Szymanowicz et al. reported significantly receded NPC measurements in mTBI patients compared to age matched controls (13.98 ± 2.06 vs. 7.03 ± 0.33 cm). However, both studies recruited participants from optometric centers where patients were referred for visual symptoms related to their injuries. This may imply their deficits are more pronounced than most patients, and these findings may not be generalizable to all mTBI patients, such as concussed athletes.

Most recently, Mucha et al. (2014) investigated the use of an entire vestibular/ocular motor screening (VOMS) assessment battery in the use of sport related concussion (Mucha et al., 2014). NPC was one of the tools incorporated into this assessment battery and was found to produce significantly different measurements in concussed athletes compared to healthy controls (5.9 ± 7.7 vs. 1.9 ± 3.2 cm). In total, sixty-two patients (13.9 ± 2.5 yrs), who were referred to their medical center, were examined using this assessment battery. A cutoff measurement of ≥ 5 cm, based off of previous studies, was used to investigate diagnostic accuracy within this study. Sensitivity was only reported for the entire assessment battery, which was found to be 84%. Their findings also produced an area under the curve of 0.65 for NPC, and a positive likelihood ratio of 5.8 for this test indicating good accuracy and a 38% increase in probability of correctly identify a concussion through the use of this test (Mucha et al., 2014).

Ocular Tracking

The King-Devick Test (KDT) was originally developed to assess impaired ocular motor functions and its relation to learning disabilities (Oride et al., 1986). This simple ocular test involves the reading of a pattern of numbers on separate cue cards as quickly as possible. The skill of reading is a complex task, which requires the integration of vergence, version, and accommodative functions as well as attention and cognitive functions. In particular, versional oculomotility includes fixations, saccades, and pursuits (Ciuffreda et al., 1995). The premotor components involved in these ocular motor pathways include the frontal and supplemental eye fields, parietal area, right prefrontal cortex and right posterior parietal cortex for fixation. Saccades utilize the rostral mesencephalon, and paramedian pontine reticular formation while smooth pursuit, which is a voluntary slow shift in gaze, involves the medial vestibular nuclei and prepositus hypoglossi. Both saccades and pursuits then use associated integrated areas, parietal area, basal ganglia, superior colliculus, and cerebellum along with the pathways involving the oculomotor nerve (Ciuffreda & Tannen, 1995).

Damage to any of these areas within the brain could impair basic ocular motor functions. In particular, saccades, which could contribute to lower scoring on the KDT, have been found to be indicative of compromised brain function (Heitger et al., 2009). This test has been found to be highly reliable (Galetta, Barrett, et al., 2011), and has been investigated in the sports setting as a sideline concussion assessment tool. Furthermore, scores of this test have been shown to worsen after concussion (Brandes et al., 2011; Brughelli et al., 2013; Galleta, Barrett, et al., 2011), showing it may be sensitive to the injury.

The first investigation into the use of the KDT within the sports setting (Galetta, Barrett et al., 2011) indicated a worsening of scores in athletes who has suffered head trauma. Seven boxers and mixed martial arts athletes were observed for head trauma, which was defined simply, and generally, as "overt blows to the head." After matches, all athletes were given the KDT and significant differences ($p < .001$) in scores were found between those who suffered head trauma and those who did not (59.1 ± 7.4 vs. 41 ± 6.7 sec). Overall, the authors reported a worsening of five seconds or more was only seen in those who had experienced head trauma.

Further investigations have found KDT scores to worsen in collegiate athletes following an acute concussion by a median increase of 5.9 seconds (Galetta, Brandes, et al., 2011). Similarly, in a group of amateur rugby league players, an average increase of 7.4 seconds was found in testing for three players who had experienced concussion (King et al., 2012). Fatigue, as measured by a sport practice, has been shown to have no negative effect on scoring of this test (Galetta, Brandes, et al., 2011; King et al., 2013). Scores from King-Devick testing, over the course of patient's recovery, have shown improvements and resolution. These improvements have also been associated with deficits and improvements in ImPACT testing (Tjarks et al., 2013).

Overall, the KDT has shown potential as a concussion assessment tool within sports. With a high degree of test-retest reliability (Galetta, Barrett, et al., 2011), and worsening and graduated improvement of scores within previously concussed athletes (Galetta, Brandes, et al., 2011; King et al., 2012; Tjarks et al., 2013), this evaluation tool could even be used as a recovery assessment tool when tracking an athletes return to baseline during rehabilitation. However, all of the previous research within the literature has involved very small sample sizes of concussed athletes ($n \leq 10$) where the concussion may or may not have been witnessed by a health care professional. Furthermore, within these studies a concussion has typically not been well-defined. Many times it is not reported as to which tools were used to compare KDT scores to, or how an athlete was identified as having a concussion.

Stereopsis

Binocular perception, or stereopsis, is the combination of visual fields from each eye. The different images seen by each eye are joined to form one fused image enabling a perception of depth. Monocular cue such a relative size, arial perspective, and lighting and shading help to provide insight into relative distance and depth, but stereopsis provides depth discrimination through binocular cues. This visual characteristic is an innate ability that does not require previous experience in the environment and allows the viewer to perceive object size, surface orientation, and depth within the environment (Snowden et al., 2006).

Two different neural systems exist for interpretation of perception of depth. For interpretation of objects at the fixation point in central vision, information is processed by the retinas and then projects to the contralateral occipital lobe via the geniculocalcarine tract. Adjacent regions of the parietal cortex then interpret this information. For interpretation of objects in front of, or past the fixation point, different regions of the retina are involved where monocular information is eventually sent to separate hemispheres. Binocular integration then occurs by transmission of the information across the corpus callosum from the parietal and occipital regions. Ultimately, through these different pathways binocular information is processed within the visual areas of the cortex, and depth is perceived (Howard & Rogers 1995).

Abnormal binocular vision occurs when a scene is viewed with both eyes yet depth is not perceived. This disorder can be due to a lack of coordination between extraocular muscles, or as a result of damage to areas of the brain involved with neural processing of this information. Stereopsis can be measured through a random-dot stereogram, which uses a series of imprinted shapes on a card printed in a way that when viewed with special lenses they appear to be raised from the card, similar to a hologram. Each shape, or figure is composed of thousands of identical dots randomly arranged. One half of the stereogram is copied to the other half, except a small section of them are moved horizontally. The resulting gap is then filled in with more dots. This small shift causes retinal disparity and will therefore appear to have a different depth (Snowden et al., 2006).

Miller et al.(1999) investigated the incidence of astereopsis following traumatic brain injury. Subjects (n = 93) suffered traumatic brain injuries (age 33.05 $\pm$ 13.69 yrs), and were admitted to an emergency department for their injury. Diagnosis was characterized by a Glascow Coma Scale (GCS) of 13 to 15 and length of posttraumatic amnesia (PTA). A control group of 30 patients, who were admitted for orthopedic injuries not involving the head and with healthy neurological status, were used for comparison. Computed tomography scans were also reviewed to determine if there were any associations between symptoms and location of structural abnormalities due to injury. In addition, cognitive functioning was assessed in a portion of the patients using the Wechsler Adult Intelligence Scale-Revised. Stereoacuity was evaluated using a six item raised circle test of graded difficulty, with each item being worth a point for scoring. Six is the highest score achievable and indicates better performance. The TBI group scored significantly lower (3.85 ± 2.2) than the control group (5.33 ± 1.09). There was a correlation between the degree of impairment and severity as determined by GCS scoring and length of PTA. Clinically significant impairment of stereoacuity was determined to be a scoring lower than two SDs below the mean of the control group. Of the TBI group, 41% fit this criterion. Patients with parietal lesions, as evidenced by the CT scans, had significantly reduced stereopsis ($t(88)=2.86$, $p =.005$) compared to other TBI patients with no intracranial abnormalities. Other areas of damage were not significantly associated with impairment in stereopsis, and may be attributed to diffuse injury. Lastly, associations between reduced stereoacuity and decreased visuospatial ability and reduced visual and verbal memory efficiency were identified.

Two similar studies (Hellerstein et al., 1995; Szymanowicz et al., 2012) examined stereoacuity within a population of patients suffering from mild TBI. Hellerstein et al. found highly significantly ($p = .007$) reduced stereoacuity within the TBI group (64.67 ar sec) compared to healthy matched controls (40.00 arc sec). Likewise, Szymanowicz et al., found significant ($p = .01$) differences in stereoacuity between the TBI (38.8 $\pm$ 3.8 arc sec) and healthy matched control group (20.5 $\pm$ 0.5 arc sec). The authors noted their control group scores may not be as accurate as possible because they used the randot stereoacuity test. This test does not assess below 20 arc sec, meaning those with who scored 20 arc sec might actually exhibit better, or less than 20 arc sec, stereopsis. Furthermore, both of these studies recruited brain injury patients from optometric centers, where they were referred because of their visual symptoms due to their head injuries. Therefore, this population may not be generalizable to a typical sample of mild TBI patients; however, it still provides insight into visual deficits, which can be produced through a brain injury.

In the future, these NPC, stereoacuity, and the KDT could potentially become incorporated into a concussion assessment battery. These tests may aid in the identification of visual dysfunctions, which can be experienced by athletes with this injury. Furthermore, by contributing to a more comprehensive examination, they could help to ensure a more appropriate course of rehabilitation. However, more investigation is needed to determine the diagnostic accuracy of these tests for concussion.

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Appendix A

Tables of Literature Review

Appendix A-1. Near Point of Convergence Literature Review

Reference	**Population**	**Definition of Concussion**	**TBI Group (M ± SD) cm**	**Control Group (M ± SD) cm**
Scheiman 2003	Eye Institute Patients with Convergence Insufficiency Patients N =38 Controls N=175 Average Age = 20.2	No Concussion	9±6.74	2.49±1.74
Shippman 1983	Eye Institute Patients with Convergence Insufficiency Patients N = 75 Average Age = 29.5 Controls N = 46 Average Age = 38	No Concussion	Average = 7.9cm	Average = 5cm
Szymanowicz 2012	Recruited from an optometric center Etiology: All non sports related (MVA, falls, etc.) mTBI N = 21 for mTBI group Age (45.7 ± 3.1yr) N = 10 Age (36.7 ± 5.4 yr)		13.98 ± 2.06	7.03 ± 0.33
Capo-Aponte 2012	Military – Blast induced mTBI w/in 45 days N = 20 for mTBI group Age (45.7 ± 3.1yr) N = 20 Age (36.7 ± 5.4 yr)		99.45 ± 74.28	29.00 ± 24.26

Miller 1999	Recruited from ER Etiology: (MVA, falls, etc.) N= 93 for TBI group Age (33.05 ±13.69 yr) N = 30 for Control group Age (37.63 ± 17.56yr)		3.85 ± 2.2	5.33 ± 1.09
Vernau 2015	Ice Hockey Athletes Average age = 12.5 N concussion = 7 N baseline = 78		Only 1 athlete ≥ 6cm	Average = 4.2 (range 1.5-10.5)
Master 2016	Concussion Clinic Average age = 14.5 65% sports related concussion 45% seen >3 mo post injury 26% seen between 1-3mo post injury 29% seen within 1 month post injury	MOI & Signs and Symptoms Consensus Statement on Concussion in Sport		
Pearce 2015	Athletes Age = (14.31 ± 2.77 yr) N concussion = 78 Seen within 30 days	MOI S&Sx	Abnormal = >5cm N= 33 (42.3%) Average = 12.64±8.97	Normal = >5cm N= 45 (57.7%) Average = 1.53±1.53cm

Appendix A-2. King Devick Test Review of Literature

Reference	Population	Definition of Concussion	Concussion Group (M ± SD) Seconds	Control Group Or Baseline Scores (M ± SD) Seconds
Leong 2015	Collegiate Football Age (19.6 ± 1.2yr) Concussion N = 11	SCAT2 Pass or Fail MOI & Standard Practice of Physician and/or ATC	36.5 ± 5.6	31.3±4.5
King 2015	Junior Rugby League Age (10.4±0.9yr) Concussion N = 7 Baseline N = 19	S&Sx MOI	74.4 ± 8.8	67.7 ± 24.26
Seidman 2015	High School Football Age (15.4±1.3 yr) Concussion N= 9	Standard Team Protocol based on Concussion in Sport Group 1st Position Statement & ImPACT	Median = 66.2	Median = 47.2
Galetta 2015	Youth & Collegiate Athletes Youth Age = (11±3yr) Collegiate Age = (20±1) N = 12 for Concussion Group N = 332 for Baseline Group	Judgment of ATC's and volunteer parents for MOI & also S&Sx	Scored worsened by an average of 5.2 seconds	54.3 ± 21.6 for all 60.6±22.3 = Youth 38.4±6.3 = Collegiate
Silverberg 2014	Emergency Department Age= (36.6±12.2yr) N=26 27% sport related	World Health Organizations criteria for mTBI	58.86±16.21	52.7±11.95 no sig. difference p=.110

Vartiainen 2014	Professional Ice Hockey Age = (23.8yrs) N = 185			40.0±6.1
King 2012	Amateur Rugby Age = (22.4±4.1yrs) N Concussion = 3 N Baseline = 50	MOI S&Sx SCAT2	5.0-7.1s worsening	Median 53.0
Galetta 2011	College Athletes Age = (20.3±1.4yrs) N Concussion = 9 N Baseline = 219	MOI S&Sx Standard Practice	5.9s worsening	Median = 38.6s
Vernau 2015	Ice Hockey Athletes Average age = 12.5 N Baseline = 103 N concussion = 11	Consensus Statement on Concussion in Sport	8 scored faster than baseline, 2 scored 1 sec slower than their baseline	Average = 55.9

Appendix A-3. Stereoacuity Review of Literature

Reference	Population	Measure	TBI Group (M ± SD)	Control Group (M ± SD)
Szymanowicz 2012	Recruited from an optometric center Etiology: All non sports related (MVA, falls, etc.) mTBI N = 21 for mTBI group Age (45.7 ± 3.1yr) N = 10 Age (36.7 ± 5.4 yr)	Stereoacuity (sec arc)	38.8 ± 3.8	20.5 ± 0.5
Miller 1999	Recruited from ER Etiology: (MVA, falls, etc.) N= 93 for TBI group Age (33.05 ±13.69 yr) N = 30 for Control group Age (37.63 ± 17.56yr)	Stereoacuity Scored 0-6 (6 being the highest score)	3.85 ± 2.2	5.33 ± 1.09

Appendix B

Handout for Data Collectors

Ocular Tests Procedures

Near Point of Convergence Assessment

The near point of convergence (NPC) measures the closest point to which one can maintain convergence while focusing on an object, before diplopia or deviation of an eye occurs.

Procedure for Measurement:

- Seat the participant so that they are sitting upright and maintaining proper head position.
- Rest the accommodative ruler on the participant's upper lip
- Instruct the subject to stare at any letter on the target card (except for the large E).
- Explain that you will move this card slowly towards them, and they should continue to stare at the letter that they have picked out. Once that letter becomes DOUBLE, not just blurry or fuzzy, they should signal for you to stop either with their hand or by saying the word STOP.
- Begin to move the target at a rate of approximately 1-2cm/s. Once the participant signals for you to stop OR you sees abnormal tracking of the eyes, stop the movement of the target
- Record the distance on the ruler where the target.
- Repeat this test for two trials, and record the near point of convergence in cm for both trials.

Stereoacuity Test

Binocular perception, or stereopsis, is the combination of visual fields from each eye. The different images seen by each eye are joined to form one fused image enabling a perception of depth.

Test Procedures:

For this test we will be using page two, section B, of the booklet where the participant will identify the circle in each block that is popping out towards them.

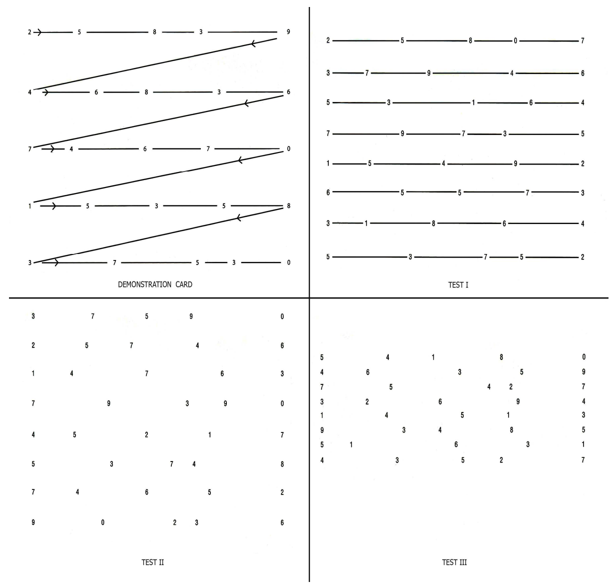
- This test must be performed in a well-lit area.
- Polarized sunglasses must be placed on the participant

- If the subject wears prescription glasses, these polarized glasses are to be worn over their glasses.

- Hold the test booklet approximately 16 inches (40cm) from the test subject.
- For part B, ask the subject to identify the circle (left, center, or right) that appears to be floating, or different from the others in each block.
- Start with box #1 and repeat this for all of the boxes progressing forward.
- When one is missed, retest the preceding box to ensure this previous level of stereoacuity can be achieved.
    - Record the level of stereopsis for the circle in the last box chosen correctly (answer sheet is on the back of the booklet).

King-Devick Test

This simple ocular test involves the reading of a pattern of numbers on separate cue cards as quickly as possible. The skill of reading is a complex task, which requires the integration of vergence, version, and accommodative functions as well as attention and cognitive functions.



Test Procedures:

For Baseline Testing:

- Complete the KDR procedure twice during baseline testing.
- The baseline time is the fastest TOTAL TIME of TWO trials without errors.
- The baseline test should be completed without errors. If an error is made, stop the test, emphasize to the subject that they should read as quickly as they can with NO errors and restart at the beginning of test card 1.

For Concussion Screening:

- Test the subject ONCE with the number of test cards used in baseline testing.
- Record the TOTAL TIME and the total number of ERRORS on the score sheet.
- As recommended by the King-Devick Company, if the subject has a total time that is slower than their baseline time, or has any errors, or has any other indications of concussion, the subject should be removed form play and further evaluated.

KDT Procedure

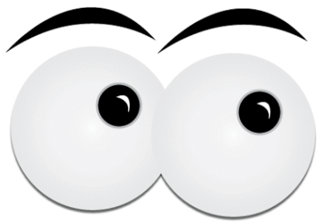
- The subject should hold the test card at a normal reading distance.
- If the subject uses glasses or contact lenses for reading, they should be worn for testing and noted on the score sheet.
- Explain to the subject: “You will be reading a series of numbers aloud as quickly as you can without making any mistakes.

- Have the subject flip to the demonstration card and explain this to them. "This is the demonstration card. The arrows connecting the numbers on this card show the direction to read the numbers. You will start at the top and read from left to right. When you reach the last number on the end of a row, you will move down to the next line and read from left to right just ass the arrows demonstrate on this card.
- After completion of the demonstration cards, move to the test cards and explain "There are three test cards that increase in difficulty. I will be timing how quickly you can read aloud the numbers on each card and keeping track of any errors that you make. You cannot use your hand or finger on the test card to help you follow the number pattern. I will start the time when you read the first number and I will stop when you finish saying the last number at the bottom right-hand corner. Then we will continue onto the next cards. Again, you are to read the numbers as quickly as you can without making any errors. Do you have any questions?"
- Record the TOTAL TIME for the reading of all cards

Appendix C

Recruitment Flyer

Do You Have Normal Vision?
Are you an Athlete?



If YES – Please Participate in a
RESEARCH STUDY!

Study Purpose: To further examine simple vision tests that could be used in a concussion assessment

Can Participate	Active Athlete	Normal Vision (Glasses/Contacts ok)
Can't Participate	Abnormal Vision	Uncorrectable Vision
Testing Process	Paperwork at Beginning of Season	If you suffer a concussion during the season, you will complete 3 simple vision tests afterwards

If interested, please contact
Jacqueline Phillips, MS, ATC
Jacqueline.phillips@temple.edu

Appendix D

Informed Consent & HIPPA Forms

Title of research study: ***Sport Concussion Evaluation and Recovery***

Investigator and Department: Ryan Tierney, PhD, ATC; Jacqueline Phillips, MS, ATC, Department of Kinesiology; Evgeny Kyrnetskiy, PhD, School of Pharmacy, Temple University.

Why you are being invited to take part in a research study

We invite you to take part in a research study because you are a current member of an university club or intercollegiate athletic team.

Who can I talk to?

If you have questions, concerns, or complaints, or think the research has hurt you, contact the research team at Ryan Tierney, PhD, ATC 259 Pearson Hall, Temple University rtierney@temple.edu, 215 204-4001;

This research has been reviewed and approved by an Institutional Review Board. You may talk to them at (215) 707-3390 or e-mail them at: irb@temple.edu for any of the following:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You have questions about your rights as a research subject.
- You want to get information or provide input about this research.

Why are we doing this research?

We are trying to learn more about how to assess concussion injury more effectively and what factors influence concussion injury and recovery from concussion.

How long will the research last?

We expect that this research will last approximately 1 year.

What happens if I say yes, I want to be in this research?

During preseason you will sign consent forms. You will also be asked if you have ever had a concussion before, and/or if you have ever had an eye problem before. In addition to your normal concussion baseline testing you will perform three simple eye tests. These eye tests are thought to help identify concussion injury and will take approximately five minutes total to complete. During the season, if you suffer a concussion, your athletic trainer will include these eye tests to evaluate your injury. Your concussion evaluation information and a saliva sample for genotyping will be collected. There is no difference in treatment based on your decision to participate. There is also a possibility that you will be asked to perform concussion assessment tests and saliva sampling because you match (e.g., same team) someone that has sustained a concussion. Genetic samples will be collected via a saliva sample that will take approximately 30 sec to collect. These samples will be stored securely at Temple University until study completion and tested by Temple investigators only for genes thought to be involved in concussion injury.

What are my responsibilities if I take part in this research?

There will be no change in your daily activities if you take part in this research.

What happens if I say no, I do not want to be in this research?
You may decide not to take part in the research and it will not be held against you. It will in no way affect your relationship with the study personnel.

What happens if I say yes, but I change my mind later?
If you agree to take part in the research, you can stop at any time, and it will not be held against you. Again, it will in no way affect your relationship with the study personnel. If you stop being in the research, already collected data may not be removed from the study database.

Is there any way being in this study could be bad for me?
This research involves sampling of DNA and the risk of loss of confidentiality cannot be completely guaranteed. To reduce the loss of confidentiality, DNA samples will be stored in a secure location, with no participant name attached (each participant will have a unique code number), and accessed only by research team members. The protocol in place has been used previously, with no breach of confidentiality (Tierney et al., 2009).
What happens to the information we collect?
Efforts will be made to limit your personal information, including research study and medical records, to people who have a need to review this information. We cannot promise complete secrecy. For example, though the study team has put in safeguards to protect your information, there is always a potential risk of loss of confidentiality.

Organizations that may inspect and copy your information include the IRB, and Temple University,. Federal law provides additional protections of your personal information. These are described in an attached Authorization to use and disclose personal health information which you will need to sign to be in this research study.

Can I be removed from the research without my permission?
If you stop playing on your sports team during the season, we will remove you from the research.

Stipend/Reimbursement
You will not be compensated for participating in this research.

Your signature below indicates that:
- Someone has explained this research study to you.
- You freely volunteer to be in this research study.
- You can choose not to take part in this research study and it will not affect your care.
- You can agree to take part in this study now and later change your mind. Your decision to leave the study will not affect your care.
- You have been offered the opportunity to ask questions and all your questions have been answered.

Signature Block for Capable Adult
Your signature documents your permission to take part in this research.

_________________________________ __________________
Signature of subject Date

Printed name of subject

Signature of person obtaining consent

Printed name of person obtaining consent

Date

Authorization to use and disclose personal health information for research at Temple University, Temple University Health System Affiliates, and Temple University Clinical Faculty Practice Plan

Information that will be collected from you and disclosed

During the course of this research study, which is described by title in the attached consent form and study-specific document, **certain** personal health information **will be collected and disclosed to** recipients **identified in this document. It is important for you to know that your personal health information may identify you by name, address, telephone number, photograph, social security number, health plan number, and date of birth, dates relating to various tests and procedures, or other personally identifiable information. This information may be obtained from your medical records, physical examinations and procedures: (a) to determine if you are eligible to participate in the research study or (b) created as a result of your participation in the research study.**

How your information will be used and to whom it will be disclosed

By signing this authorization form, you give Temple University, Temple University Health System affiliates, and Temple University Clinical Faculty Practice Plan, Temple University Institutional Review Board, and the investigator(s) named in the attached study-specific document, permission to use your personal health information and to disclose this information to the following recipients (as applicable): sponsor; sponsor's agents; governmental entities overseeing research in the United States and abroad, which may include in the United States, the Food and Drug Administration and the Department of Health and Human Services. It is important for you to know that the recipients, and their agents or representatives, will take all reasonable efforts to maintain your personal health information in confidence, and to use appropriate safeguards to prevent further use or disclosure by those not authorized to use or disclose your personal health information. However, once your health information is disclosed to the recipients, then your personal health information may no longer be protected by federal privacy laws and regulations and there is a potential for re-disclosure of this information. However, the laws of the Commonwealth of Pennsylvania or your state of residence may provide further privacy protection.

How you can access your information

You should know that you have the right to see and receive a copy of your personal health information that was collected from you during the research study for as long as this information is maintained by Temple University and the principal investigator. However, while the research study is in progress, you will not be able to access your personal health information in order to preserve the integrity of the research. You will be able to access this information when the study is completed. There may be associated charges for copying these materials.

How to revoke your authorization

You should also know that you can revoke your authorization to disclose your personal health information at any time by sending a written notice to the principal investigator and Temple University at the address listed in the attached study-specific document. Should you decide to revoke your authorization, Temple University and the principal investigator will stop collecting your study-related health information. In addition, Temple University and the principal investigator will stop using and disclosing your personal health information, except to the extent such information was collected prior to your revocation. For instance, Temple University, principal investigator, recipients, and their agents or

representatives may use the information obtained before you revoked your authorization in order to preserve the scientific integrity of the research study.

Important notices

You will receive a signed copy of this authorization to acknowledge your approval for Temple University and the principal investigator to the release your personal health information. If you do not sign this authorization or if you revoke this authorization, the principal investigator and Temple University may decide not to permit you to participate in or to continue to participate in the research study identified in the attached study-specific document.

STUDY-SPECIFIC DOCUMENT

1. RESEARCH STUDY: Sport Concussion Evaluation and Recovery

2. PRINCIPAL INVESTIGATOR: Ryan Tierney, PhD, ATC 259 Pearson Hall, 048-00. Department of Kinesiology Temple University Philadelphia, PA 19122

3. EXPIRATION DATE: This Authorization does not expire.

4. OTHER INFORMATION: Personal and concussion event history. Concussion evaluation information from tests used to assess brain injury such as neurocognitive and balance testing. Saliva sample to assess genes associated with concussion injury.

____
Signature of Patient Date

____
Printed Name of Patient

____
Signature of Person Collecting Authorization Date

____
Printed Name of Person Collecting Authorization

Appendix E

Data Collection Form for Control Subjects

Ocular Concussion Study – Health History & Data Collection Form – Control/Baseline Subjects

Contact for help: Jacqueline.phillips@temple.edu

Please answer the following questions to the best of your ability:

1. Sex: M ___ F____ 2. Age ____

3. Ethnicity/Race Please check all that apply.
____ African American ____ Asian/Pacific Islander ____ Caucasian/White
____Hispanic/Latino ____ Middle Eastern ____ Native American
____ Other

4. Circle all athletic teams in which you are currently a member:
College/University Club

5. What sport(s) and position(s) do you play?

6. How many years have you played your sport(s)? Be sure to answer for each sport you play.

7. Do you have vision which needs to be corrected through contact lenses/glasses? **YES NO**

8. If you answered yes to the above question, do your normally wear your contact lenses/glasses during practice/games? **YES NO**

9. Do you have a history of eye problems (beyond needing contact lenses/glasses)? **YES NO**
9a. If yes, please describe:

10. Has a doctor or certified athletic trainer ever told you that you had a concussion? **YES NO**
10a. If you had a concussion, please complete the boxes below.

Concussion	What year did you have the concussion?	How long did it take you to recover and return to play?
1		
2		
3		
4		
5		

11. Please circle any of the events that have occurred to you in the past week:**Head to head hit** **Head hit the ground/object/limb** **indirect insult to head**

If you circled any of the above events, please describe what happened:

Please check off if you are <u>CURRENTLY</u> feeling any of the following on a scale of 1-6 (1 being very little and 6 being a lot). If you are not feeling any of these things, leave the row blank:

Signs & Symptoms	**1**	**2**	**3**	**4**	**5**	**6**
Headache						
Nausea/vomiting						
Dizziness						
Blurred Vision						
Balance Problems						
Sensitivity to Light						
Sensitivity to Noise						
Fatigued						
Difficulty Concentrating						
Difficulty Remembering						
Confusion						
Drowsiness						
Feeling slowed down						
Feeling “in a fog”						
“Don’t feel right”						
Trouble falling asleep						
More emotional						
Irritability						
Sadness						
Nervous/Anxious						
Neck Pain						

Baseline Measurements:

Convergence	Measurement (cm)
Trial 1	
Trial 2	

Stereoacuity	Please circle the score of the last circle correctly identified		
400°	200°	160°	100°
63°	50°	40°	32°
25°	20°	16°	12.5°

BESS Test:	Firm Surface	Foam Surface
Double Leg Stance		
Single Leg Stance		
Tandem Stance		
Surface Total		
	BESS TOTAL:	

KDT	1st Trial	2nd Trial
Errors		
Time Total		

Appendix F

Data Collection Form for Concussion Subjects

Ocular Concussion Study – Health History Form – Concussion Subjects
Contact for help: Jacqueline.phillips@temple.edu

Please answer the following questions to the best of your ability:

1. Sex: M ___ F____ 2. Age ____

4. Circle all athletic teams in which you are currently a member: **College/University** **Club**

5. What sport(s) and position(s) do you play?

6. How many years have you played your sport(s)? Be sure to answer for each sport you play.

7. Do you have vision which needs to be corrected through contact lenses/glasses? **YES** **NO**

8. If you answered yes to the above question, do your normally wear your contact lenses/glasses during practice/games? **YES** **NO**

9. Do you have a history of eye problems (beyond needing contact lenses/glasses)? **YES** **NO**
   9a. If yes, please describe:

10. Has a doctor or certified athletic trainer ever told you that you had a concussion?**YES** **NO**
    10a. If you had a concussion, please complete the boxes below.

Concussion	What year did you have the concussion?	How long did it take you to recover and return to play?
1		
2		
3		
4		
5		

Ocular Concussion Study – Data Collection Form – Concussion Subjects
Contact for help: Jacqueline.phillips@temple.edu

Date of Injury: _________ **Date of Evaluation:** ______

Time of Injury: _________

MOI: Please circle the mechanism of injury below:

Head to head hit   Head to ground/object/limb to head   Indirect insult

Please check off if you are CURRENTLY feeling any of the following on a scale of 1-6 (1 being very little and 6 being a lot). If you are not feeling any of these things, leave the row blank:

Signs & Symptoms	**1**	**2**	**3**	**4**	**5**	**6**
Headache						
Nausea/vomiting						
Dizziness						
Blurred Vision						
Balance Problems						
Sensitivity to Light						
Sensitivity to Noise						
Fatigued						
Difficulty Concentrating						
Difficulty Remembering						
Confusion						
Drowsiness						
Feeling slowed down						
Feeling “in a fog”						
“Don’t feel right”						
Trouble falling asleep						
More emotional						
Irritability						
Sadness						
Nervous/Anxious						
Neck Pain						

Concussion Measurements:

Convergence	Measurement (cm)
Trial 1	
Trial 2	

Stereoacuity	Please circle the score of the last circle correctly identified		
400°	200°	160°	100°
63°	50°	40°	32°
25°	20°	16°	12.5°

KDT	Time (sec)	Errors
1st Card		
2nd Card		
3rd Card		
Total		

BESS Test:	Firm Surface	Foam Surface
Double Leg Stance		
Single Leg Stance		
Tandem Stance		
Surface Total		
	BESS TOTAL:	

Appendix G

Statistical Tables

APPENDIX G-1. T-Test Summary for Log Transformed NPC Scores Between Groups

Effect	*t*	dF	F	*p*
Recovery	-4.538	46	1.301	0.260

APPENDIX G-2. T-Test Summary for KDT Scores Between Groups

Effect	*t*	dF	F	*p*
Recovery	-2.063	49	3.229	0.078

APPENDIX G-3. Independent Samples Mann-Whitney U Test for Stereoacuity scores Between Groups

Null Hypothesis	*p*	*Decision*
The distribution of stereoacuity scores is the same across groups	.019	Reject the null hypothesis

APPENDIX G-4. Clinical Outcomes for NPC

	Diagnosed Concussion	
NPC	Positive	Negative
Positive	TP (12)	FP (6)
Negative	FN (7)	TN (23)

Note. TP (True Positive), FP (False Positive), FN (False Negative, TN (True Negative); Sensitivity is equal to TP/(TP + FN); Specificity is equal to TN/ (FP + TN)

APPENDIX G-5. Clinical Outcomes for KDT

KDT	Diagnosed Concussion Positive	Negative
Positive	TP (9)	FP (4)
Negative	FN (10)	TN (28)

Note. TP (True Positive), FP (False Positive), FN (False Negative, TN (True Negative); Sensitivity is equal to TP/(TP + FN); Specificity is equal to TN/ (FP + TN)

APPENDIX G-6. Clinical Outcomes for Stereoacuity

	Diagnosed Concussion	
Stereoacuity	Positive	Negative
Positive	TP (5)	FP (3)
Negative	FN (12)	TN (25)

Note. TP (True Positive), FP (False Positive), FN (False Negative, TN (True Negative); Sensitivity is equal to TP/(TP + FN); Specificity is equal to TN/ (FP + TN)

APPENDIX G-7. Coordinates of the ROC Curve for NPC

Positive if Greater Than or Equal to	Sensitivity	1-Specificity
.0000	1.000	1.000
1.5000	1.000	.966
2.2500	1.000	.931
2.7500	1.000	.862
3.1250	.947	.759
3.3750	.947	.724
3.7500	.947	.690
4.1250	.947	.586
4.3750	.947	.552
4.7500	.842	.483
5.1250	.789	.276
5.5000	.789	.241
5.8750	.737	.241
6.2500	.684	.241
6.6250	.684	.207
6.8750	.632	.207
7.1250	.632	.172
7.3750	.579	.172
7.6250	.579	.103
8.1250	.579	.069
8.7500	.474	.069
9.5000	.368	.000
10.2500	.316	.000
10.7500	.263	.000
16.2500	.211	.000
22.7500	.158	.000
25.0000	.105	.000
26.7500	.053	.000
28.5000	.000	.000

APPENDIX G-8. Coordinates of the ROC Curve for KDT

Positive if Greater Than or Equal to	Sensitivity	1-Specificity
32.4600	1.000	1.000
33.4950	1.000	.969
33.7650	1.000	.938
35.0000	.947	.938
36.4700	.947	.906
36.9700	.947	.875
37.3000	.947	.844
37.9100	.947	.813
38.6100	.895	.813
39.1250	.895	.750
39.4500	.895	.719
39.7300	.842	.719
40.3800	.842	.688
41.1050	.842	.656
41.3200	.789	.656
41.5900	.737	.656
41.9500	.737	.625
42.5000	.737	.594
42.9700	.684	.594
43.3700	.632	.594
43.8050	.632	.563
43.9350	.632	.531
44.4800	.579	.531
45.5000	.579	.500
46.5300	.579	.438
47.5300	.579	.406
48.5000	.579	.344
49.0750	.579	.313
49.5000	.579	.281
50.4200	.526	.281
51.1000	.526	.250
51.2400	.474	.250
51.5850	.474	.219
51.9500	.474	.188
52.0450	.474	.156
52.5950	.474	.125
53.1650	.474	.094
53.2400	.421	.094
53.8900	.368	.094
55.3100	.316	.094
57.4350	.316	.063
58.9350	.263	.063

APPENDIX G-8(Continued). Coordinates of the Curve for KDT

Positive if Greater Than or Equal to	Sensitivity	1-Specificity
59.3600	.211	.063
59.8150	.211	.031
60.3500	.158	.031
60.8500	.105	.031
62.5200	.105	.000
64.2100	.053	.000
65.3800	.000	.000

APPENDIX G-9. Coordinates of the ROC Curve for Stereoacuity

Positive if Greater Than or Equal to	Sensitivity	1-Specificity
11.500	1.000	1.000
14.250	1.000	.821
18.000	1.000	.679
22.500	1.000	.607
28.500	.647	.464
36.000	.588	.393
45.000	.294	.107
56.500	.176	.000
64.000	.000	.000

Appendix H

Raw Data

Appendix G-1. Raw Data from all Participants

Participant	Control Or Concussion	Site	Sex	Age	Sport by Impact	Hx of Concussion	Total Symptoms
1	1	1	1	21	1	2	2
2	1	1	1	18	1	2	0
3	1	1	1	19	1	1	2
4	1	1	1	19	1	2	7
5	1	1	1	18	1	2	0
6	1	1	1	19	1	2	0
7	1	1	1	18	1	2	2
8	1	1	2	19	1	2	0
10	1	1	1	20	1	2	19
11	1	1	2	18	1	2	0
12	1	1	1	18	1	2	0
13	1	1	1	18	1	1	0
14	1	1	2	18	2	2	0
15	1	1	1	18	1	1	1
16	1	1	1	20	1	1	0
17	1	1	2	20	1	1	0
18	1	1	2	20	1	2	0
19	1	1	1	19	1	2	0
20	1	1	2	21	1	1	0
21	1	1	1	18	1	2	0
22	1	1	1	20	1	1	0
23	1	1	2	21	1	2	4
24	1	1	2	21	1	2	1

Appendix G-1. (continued)

Participant	Control Or Concussion	Site	Sex	Age	Sport by Impact	Hx of Concussion	Total Symptoms
25	1	1	2	18	1	2	9
26	1	1	2	20	1	2	0
27	1	1	2		1	1	0
28	1	1	1	19	1	1	2
29	1	1	1	18	1	1	0
30	1	1	1	18	1	2	5
31	1	1	1	18	1	2	1
32	1	1	2	17	1	2	0
33	2	1	1	18	1	2	31
34	2	1	1	21	1	2	15
35	2	2	2	20	2	2	42
36	2	4	1	18	2	1	0
37	2	4	1	23	2	1	0
38	2	4	1	20	1	2	58
39	2	4	1		1	1	9
40	2	4	1	22	1	2	6
41	2	4	2	20	1	1	5
42	2	2	2	21	2	1	0
43	1	2	2	20	2	2	0
44	2	3	2	21	2	1	69
45	2	2	2	19	2	1	16
46	2	1	2	18	2	1	0

Appendix G-1. (continued)

Participant	Control Or Concussion	Site	Sex	Age	Sport by Impact	Hx of Concussion	Total Symptoms
47	2	1	1	20	1	1	11
48	2	1	2	21	2	1	11
49	2	1	2	21	2	1	29
50	2	1	1	20	1	2	38
51	2	1	1	22	2	1	7
52	2	4	1	23	2	1	0

Note. Control or Conussion, 1 = control, 2 = concussion; Site 1 = Temple University Club Sports, 2 = Temple Varsity Sports, 3 = Drexel University, 4 = Temple University VETS Lab; Sex 1 = Male, 2 = Female; Sport by Impact 1 = low impact, 2 = high impact; History of concussion 1 = Yes, 2 = No

Appendix G-1. (continued)

Participant	NPC Trial 1	NPC Trial 2	NPC Average	KDT	Stereoacuity	BESS	Days To Evaluation
1	3	0	3	46	25	23	
2	18	20	19	39	50	39	
3	6	4.5	5.25	61	12.5	28	
4	3	4	3.5	39	16	25	
5	17	18	17.5	46		12	
6	4	5	4.5	36	40	9	
7	5	5	5	48	40	13	
8	2	3	2.5	37	25	28	
10	6	12	9	52	16	41	
11	3	3	3	39.81	32	17	
12	2	4	3	49	12.5	22	
13	3	3.5	3.25	33.53	40	11	
14	2	2	2	33.46	100	13	
15	4.5	5.5	5	40.95	12.5	13	
16	6.5	8.5	7.5	49.15	32	13	
17	3.5	4.5	4	53.1	40	21	
18	5	5	5	59.63	40	7	
19	9	9	9	48	40	9	
20	5	4	4.5	51.27	50	7	
21	6	7	6.5	41.8	100	8	
22	4	6	5	42.1	40	11	
23	2.5	2.5	2.5	47.06	20	17	
24		1	1	43.91	16	11	

Appendix G-1. (continued)

Participant	NPC Trial 1	NPC Trial 2	NPC Average	KDT	Stereoacuity	BESS	Days To Evaluation
25	7.5	8	7.75	56.09	12.5	12	
26	4	4.5	4.25	36.94	20	11	
27	5	5	5	51.9	50	22	
28	5	5	5	52.09	12.5	11	
29	6	9	7.5	39.25	40	12	
30	5	3	4	43.7	16	16	
31	4	4	4	37.6	25	8	
32	18	21	19.5	50.99	25	15	
33	26	29	27.5	53.25	40	16	1
34	22	30	26	49.85	25	4	2
35	19	24	21.5	58.78	50	41	2
36	6	6	6	38.22		17	5
37	9	9	9	39.65		3	
38	7	6.5	6.75	41.26	40	14	7
39	4	5	4.5	64.04	50	11	
40	8	9	8.5	51.21	25	9	6
41	5.5	6	5.75	43.96	40	11	7
42	9	8	8.5	41.38	32	27	3
43	6	8	7	45	100		
44	9	9	9	60	63	4	1
45	7.5	7	7.25	34	25	9	1
46	22	26	24	60.7	63	38	13

Appendix G-1. (continued)

Participant	NPC Trial 1	NPC Trial 2	NPC Average	KDT	Stereoacuity	BESS	Days To Evaluation
47	9	12	10.5	54.53	25	17	3
48	5	5	5	64.38	25	3	2
49	10	10	10	59.09	63	20	1
50	5	4	4.5	42.9	40	19	0
51	3	3	3	53.23	40	21	
52	9	13	11	43.04	25	3	8