doi: 10.4085/1062-6050-0063.21

TITLE PAGE

King-Devick Sensitivity and Specificity to Concussion in Collegiate Athletes

Authors:
Rachel K. Le, MS, ATC*; Justus D. Ortega, PhD†; Sara P. D. Chrisman, MD, MPH‡; Anthony P. Kontos, PhD§; Thomas A. Buckley, EdD, ATC||; Thomas W Kaminski, PhD, ATC, FNATA, FACSM|||; Briana P. Meyer¶; James R Clugston, MD, MS#; Joshua Goldman, MD**; Thomas W. McAllister, MD+++; Michael A. McCrea, PhD, ABPP-CN¶¶; Steve P. Broglio, PhD, ATC##; Julianne D. Schmidt, PhD, ATC*

Affiliations:
* Department of Kinesiology, University of Georgia, Athens, GA
† Department of Kinesiology and Recreation Administration, Humboldt State University, Arcata, CA
‡ Seattle Children’s Research Institute and Department of Pediatrics, University of Washington, Seattle, WA
§ Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, PA
|| Department of Kinesiology and Applied Physiology, University of Delaware, Newark, DE
||| Department of Neurosurgery, Medical College of Wisconsin, Milwaukee, WI
# Department of Community Health and Family Medicine, Department of Neurology, and Division of Sports Health, University Athletic Association, University of Florida, Gainesville, FL
** Department of Family Medicine, University of California Los Angeles, Los Angeles, CA
+++ Department of Psychiatry, Indiana University, Indianapolis, IN
¶¶ Michigan Concussion Center, School of Kinesiology, University of Michigan, Ann Arbor, MI

Corresponding Author:
Rachel K. Le, MS, ATC
330 River Rd., Athens, GA 30602
email: Rachel.Le@uga.edu
Twitter: @Rachel_LeATC

Funding:
This study was made possible, in part, with support from the Grand Alliance Concussion Assessment, Research, and Education Consortium, funded by the National Collegiate Athletic Association and the Department of Defense. The US Army Medical Research Acquisition Activity, 820 Chandler Street, Fort Detrick, MD 21702-5014, USA is the awarding and administering acquisition office. This work was supported by the Office of the Assistant Secretary of Defense for Health Affairs through the Psychological Health and Traumatic Brain Injury Program under Award no. W81XWH-14-2-0151. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the Department of Defense (Defense Health Program funds).
Conflicts of Interest: The authors report no conflicts of interest outside of the above funding source.

Acknowledgments:

The authors thank all research team members and clinical athletic trainers who helped in the data collection for this study. This study was made possible, in part, with support from the Grand Alliance Concussion Assessment, Research, and Education Consortium, funded by the National Collegiate Athletic Association and the Department of Defense. The US Army Medical Research Acquisition Activity, 820 Chandler Street, Fort Detrick, MD 21702-5014, USA is the awarding and administering acquisition office. This work was supported by the Office of the Assistant Secretary of Defense for Health Affairs through the Psychological Health and Traumatic Brain Injury Program under Award no. W81XWH-14-2-0151. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the Department of Defense (Defense Health Program funds).

Readers should keep in mind that the in-production articles posted in this section may undergo changes in the content and presentation before they appear in forthcoming issues. We recommend regular visits to the site to ensure access to the most current version of the article. Please contact the JAT office (jat@slu.edu) with any questions.
**King-Devick Sensitivity and Specificity to Concussion in Collegiate Athletes**

**Context:** The King-Devick (K-D) is used to identify oculomotor impairment following concussion. However, the diagnostic accuracy of the K-D over time has not been evaluated.

**Objective:** (a) Examine the sensitivity and specificity of the K-D test at 0-6 hours of injury, 24-48 hours, asymptomatic, return-to-play, and 6-months following concussion and (b) compare outcomes for differentiating athletes with a concussion from non-concussed across confounding factors (sex, age, contact level, school year, learning disorder, ADHD, concussion history, migraine history, administration mode).

**Design:** Retrospective, cross-sectional design.

**Setting:** Multisite institutions within the Concussion Assessment, Research, and Education (CARE) Consortium.

**Patients or Other Participants:** 1239 total collegiate athletes without a concussion (age=20.31±1.18, male=52.2%) were compared to 320 athletes with a concussion (age=19.80±1.41, male=51.3%).

**Main Outcome Measure(s):** We calculated K-D time difference (sec) by subtracting baseline from the most recent time. Receiver operator characteristics (ROC) and area under the curve (AUC) analyses were used to determine the diagnostic accuracy across timepoints. We identified cutoff scores and corresponding specificity at 80% and 70% sensitivity levels. We repeated ROC with AUC outcomes by confounding factors.

**Results:** King-Devick predicted positive results at 0-6 hours (AUC=0.724, p<0.001), 24-48 hours (AUC=0.701, p<0.001), return-to-play (AUC=0.640, P<0.001), and 6-months (AUC=0.615, P<0.001), but not at asymptomatic (AUC=0.513, P=0.497). The 0-6 and 24-48-
hour timepoints yielded an 80% sensitivity cutoff score of -2.6 and -3.2 seconds (faster) respectively, but 46% and 41% specificity. The K-D test had significantly better AUC when administered on an iPad (AUC=0.800, 95%CI:0.747,0.854) compared to the spiral card system (AUC=0.646, 95%CI:0.600,0.692; p<0.001).

Conclusions: The K-D test has the greatest diagnostic accuracy at 0-6 and 24-48 hours of concussion, but declines across subsequent post-injury timepoints. AUCs did not significantly differentiate between groups for confounding factors. Our negative cutoff scores indicate that practice effects contribute to improved performance, requiring athletes to outperform their baseline.

Word Count: 300 out of 300

Key Words: Diagnostic accuracy, Oculomotor Performance, Mild Traumatic Brain Injury, Baseline Testing, Post-injury Assessments

Key Points: (1) The K-D test contributes acceptable diagnostic value at the 0-6 and 24-48 hour post-concussion timepoints, but is not adequate at the asymptomatic timepoint and is only fair at RTP and 6-month timepoints. (2) The K-D should also be used with caution over repeated administrations as there is significant practice effect.
Concussion assessment and diagnosis is comprised of a multifaceted approach using several tests to understand the entire clinical presentation of the injury.\textsuperscript{1-3} Several assessments are used at baseline and post-concussion to evaluate potential impairments. Concussion evaluation often includes assessing symptoms, neurocognition, balance, and vestibular and ocular performance.\textsuperscript{3,4} Sideline assessments are essential for informing the clinician who is making the diagnosis but must be conducted quickly and must be sensitive to acute impairment. These assessments are often used to facilitate return to play decisions among sports medicine and allied healthcare providers.\textsuperscript{5-8} The Sports Concussion Assessment Tool – 5\textsuperscript{th} edition, which was developed as a sideline screening tool, includes a patient reported symptom scale, cognitive screening, brief neurological screening, and balance; however, this test does not assess vision or eye movements.\textsuperscript{1,9} There has been an increasing use of eye movement and tracking assessments, such as the King-Devick (K-D) test, to identify oculomotor abnormalities following brain injury.\textsuperscript{1,10-13}

When administering the K-D test, health care providers ask athletes to read aloud a demonstration card and three test cards with rows of random single-digit numbers as quickly as possible with no errors. Saccadic movements may evoke post-concussion impairment in visual and eye movement pathways which are widely distributed throughout the brain.\textsuperscript{9} Increased latency and decreased accuracy of eye movements are common following a concussion.\textsuperscript{6}

Despite being widely used, little is known about the diagnostic accuracy of the K-D test. In a meta-analysis,\textsuperscript{9} researchers concluded that the K-D test had high sensitivity (86\%) and specificity (90\%) when using a cutoff where post-concussion completion time is longer than baseline completion time. There is little information and scarce publication on the diagnostic accuracy of the K-D test from autonomous, external investigators who do not have any financial
interests with the test. We also lack evidence exploring the sensitivity and specificity of the K-D
across multiple post-injury time points in collegiate athletes, as many studies have analyzed
repeated baseline performance only.\textsuperscript{11, 14} Further research is warranted to explore collegiate
athletes with concussion across multiple post-injury time points.

There is no consensus regarding a clinically informative cutoff time difference relative to
baseline time for the K-D when screening for a concussion. Recent research suggests that
congestion should be suspected when post-concussion completion time is longer than baseline
completion time.\textsuperscript{2, 6, 15} Using this proposed cutoff warrant caution because healthy adolescent and
collegiate athletes present with pronounced practice effect experiencing improvement or faster
times with repeated administrations.\textsuperscript{15-19} Breedlove et al., 2019 also found 27\% of healthy
participants had slowed or increased time when completing two baselines approximately one
year apart which warrants research investigating specificity.\textsuperscript{18}

Age, sex, and reading skill level affect King-Devick scores at baseline,\textsuperscript{6, 11, 13, 14} however,
no previous studies have determined whether K-D sensitivity and specificity differ across
confounding factors. There is limited data analyzing how athlete’s concussion and migraine
history, neurological (ADHD), learning disorder (e.g. dyslexia), vestibular disorders (vertigo), or
administration mode influence K-D sensitivity and specificity post-concussion. Understanding
how confounding factors of demographic and medical history influences post-concussion K-D
test performance is necessary in order to inform clinical decision making.

Therefore, the purpose of the first aim is to examine the sensitivity and specificity of the
K-D test at 0-6 hours post-injury (initial), 24-48 hours, at beginning of return to play protocol
(asymptomatic), at unrestricted return to play, and at 6 months following concussion. The 48-
hour time point was established as our earliest time point due to a small number of athletes with
a concussion evaluated earlier or <6 hours (n=51; 15.9%). The purpose of the second aim was to
explore the effect of confounding demographic (sex, age, contact level, year in school, learning
disorder, attention deficit hyperactivity disorder/attention deficit disorder, concussion history,
migraine history, and administration mode) on the sensitivity and specificity of the K-D test for
concussion.

METHODS

This study was part of the NCAA-Department of Defense Concussion Assessment,
Research and Education Consortium, an ongoing comprehensive study utilized in examining the
effects of concussion in collegiate athletes and US military service academy members. All sites
use a common definition and criteria for concussion. The King-Devick test was used at 6 of the
30 CARE Consortium sites as a Level B measure, which is considered as an emerging
assessment and added at the discretion of performance site.

Athletes were considered healthy for our control group if they had more than one baseline
and had no concussion documented in the CARE Consortium, only. K-D baseline assessments
were administered one year apart. Athletes were included in our concussed group if they
sustained a concussion and completed K-D longitudinal post-injury assessments. Athletes with a
concussion were determined by each institutions’ sports medicine team with guidance from the
current consensus guidelines and excluded from the control group. In cases where confounding
factor variables were missing, athletes were excluded from corresponding analyses. The United
States Army Medical Research and Materiel Command Human Research Protection Office, the
XXX Institutional Review Board, and each CARE Consortium sites’ Institutional Review Board
received approval. All athletes provided written informed consent prior to participation.

King-Devick
The K-D test consists of a rapid number-naming task that takes < 2 minutes to complete and is available on 2 different platforms (iPad or paper). Athletes completed three test cards of rapid number naming reading from left to right. For baseline assessments, athletes are to complete two trials that are error-free to obtain a baseline score. The athlete’s baseline is the faster of the two trials. Following concussion, the test was re-administered, however trials are not repeated in cases of error. Total time is defined as the time in seconds it takes to complete the entire test.\(^5\)

**Sensitivity & Specificity**

For concussed participants, we subtracted their baseline time from their postinjury time (postconcussion timepoint - baseline). This was done at each postinjury timepoint. The first timepoint was 0-6 hours post-injury. The second timepoint was 24-48 hours within injury. The next timepoint was asymptomatic. This was defined as the participants beginning the return to play protocol. The last timepoint or unrestricted return to play timepoint was defined as participants completing all stages in the gradual return to play protocol, and the last timepoint was defined as 6 months following injury. For non-concussed participants, we subtracted their first baseline K-D test time from their second baseline K-D test time (baseline2 – baseline1). Since additional repeat assessments were not available in the control group, the difference in baseline times was used for the control group relative to the concussed group’s performance across the 4 timepoints. The mean time between the first and second baseline for the non-concussed, control group was 398 ± 1.8 days. For the concussed group, the mean time between the 0-6 hours timepoint and 24-48-hour timepoint was 1±1.8 days, 24-48 hours and asymptomatic was 12±4.3 days, and 5±4.4 days between asymptomatic and unrestricted return to
play. Additionally, for those with a concussion, the mean time between baseline and 0-6 hours post-injury was 286±68.2 days.

**Influence of Confounding Factors**

For the second aim, we extracted the following targeted self-reported demographic and medical history factors from baseline clinical report forms: sex (female, male), sport contact level (contact, limited contact, non-contact), academic year (freshman, sophomore, junior, senior), learning disorder (no, yes), attention deficit hyperactivity disorder/attention deficit disorder (no, yes), migraine history (no, yes), concussion history (0, 1, 2, 3+), and administration mode (iPad, Spiral Bound Cards).

**Statistical Analyses**

To address our first aim, we used receiver operator characteristics (ROC) curves and area under the curve (AUC) analyses to determine the diagnostic accuracy of the King-Devick test across the four post-concussion timepoints with the Wilson/Brown method using GraphPad Prism (Version 8.1.2). For significant AUC analyses, we identified cutoff scores and corresponding specificity at both the 80% and 70% sensitivity levels but have also included continuous levels of varying sensitivity and specificity values in supplement file.

To address our second aim, we repeated ROC curves with AUC outcomes from the 24-48 hours timepoint segmented by sex (female, male), sport contact level (contact, limited contact, non-contact), academic year (freshman, sophomore, junior, senior), learning disorder (no, yes), attention deficit hyperactivity disorder/attention deficit disorder (no, yes), migraine history (no, yes), concussion history (0, 1, 2, 3+), and administration mode (iPad, Spiral Bound Cards). We used the 24-48 hour timepoint because there was a gain of n=38 compared to 0-6 hours post-injury. To determine whether characteristics differed across confounding factor segments, we
compared the 95% confidence intervals around each AUC outcome. AUC outcomes with scores of <.50 were considered poor, .51-.69 as fair, .70-.80 as acceptable, .80-.90 as excellent, and .90+ as outstanding.\textsuperscript{23} Values >0.55 were considered significant. We evaluated AUC confidence interval overlap and calculated \( z \) and \( p \) values using the following formula: \( Z = \frac{\text{abs}(\text{AUC}_1 - \text{AUC}_2)}{\sqrt{\text{SE}_{\text{AUC}_1}^2 + \text{SE}_{\text{AUC}_2}^2}} \). We also conducted a multivariate logistic regression using these same confounding factors to predict false negatives in the concussed group and a separate multivariate logistic regression to predict false positives in the control group. To classify false negatives and false positives, we used the 80% sensitivity cutoff from the 24-48 hours timepoint.

**RESULTS**

An initial sample of 1,719 athletes were examined for eligibility, with 1,579 subjects meeting inclusion criteria. Of these 1,579 athletes, 1,239 were in the healthy control group and 320 in the concussion group (Table 1).

King-Devick difference scores predicted concussion diagnosis status at 0-6 hours (AUC=0.724, \( p<0.001 \)), 24-48 hours (AUC=0.701, \( p<0.001 \)), return to play (AUC=0.640, \( P<0.001 \)), and 6-month time points (AUC=0.615, \( P<0.001 \)), but not at the asymptomatic time point (AUC=0.513, \( P=0.497 \)). Figure 1 shows the ROC curves and outcomes across the five postinjury timepoints. Supplemental data files with ROC raw data including sensitivity, specificity, likelihood ratios, and 95% confidence intervals with corresponding K-D cutoffs can be found online [INSERT LINK TO SUPPLEMENTAL FILES HERE]. The 0-6 and 24-48 hour timepoints had “acceptable” discrimination for sensitivity and specificity, but other significant timepoints were considered “fair.” A cutoff score of -2.6s (performing 2.6 seconds faster than baseline) yields 80% sensitivity to athletes with a concussion at 0-6 hours timepoint. However, this results in a specificity of 46%. A cutoff score of -3.2s (performing 3.2 seconds faster than...
baseline) yields 80% sensitivity to athletes with a concussion at 24-48 hour timepoint. However, this results in a specificity of 41%. A cutoff score of -1.5 seconds (performing 1.5 second faster than baseline) yields a 70% sensitivity, with a specificity of 57%. Asymptomatic ROC curves were not significant, thus cutoff scores are not proposed.

A cutoff score of -0.8 seconds (performing 0.8 seconds faster than baseline) at the return to play timepoint yields 80% sensitivity, but a specificity of 37%. A cutoff score of -1.9 seconds (performing 1.9 second faster than baseline) yields a 70% sensitivity yields, but a specificity of 47%.

At the 6-month timepoint, a cutoff score of -0.4 seconds (performing 0.4 seconds faster than baseline) yields 80% sensitivity, but a specificity of 34%. A cutoff score of -1.6 seconds (performing 1.6 second faster than baseline) yields 70% sensitivity with a specificity of 44%.

Concussed individuals at the 6-month timepoint tend to perform better compared to their baseline.

**Influence of Confounding Factors**

Most confounding factors did not find differ significantly in AUC ($P$ range:0.06 to 0.94), with the exception of administration mode where the iPad administration mode (AUC=0.800, 95%CI:0.747,0.854) had greater AUC compared to the spiral card system (AUC=0.646, 95%CI:0.600,0.692) (Figure 2g). We also observed a trend for learning disability outcomes ($P$=0.067), such that the King-Devick test score differences tended towards having better AUC for those with a learning disability (AUC=0.819, 95%CI:0.715,0.924) relative to those without a learning disability (AUC=0.716, 95%CI:0.680,0.752) (Figure 2d). Similarly, confounding factors did not influence the odds of false negatives ($P$=0.654) in the concussed group. However, KD
administration mode did influence the odds of false positives in the control group ($P=0.002$), such that iPad administration reduced the odds of false positives (OR:0.59, 95%CI:0.45,0.76).

**DISCUSSION**

**Overall Diagnostic Accuracy**

Our ROC curves at the 0-6 and 24-48 hour timepoints show an interesting and somewhat counterintuitive pattern whereby a sensitivity is lower with slower post-injury KD times and specificity is higher. This then flips (Figure 1d&e) at the return to play and 6 month timepoints and follows a pattern where sensitivity is higher with a slower post-injury K-D time and specificity is higher, which better matches the clinical interpretation. Clinicians should be aware that this pattern does not follow conventional clinical patterns, despite an AUC that suggests overall moderate diagnostic accuracy.

Based on our results, the King-Devick test contributes acceptable diagnostic accuracy 0-6 hours and 24-48 hours of concussion. This is concurrent with the designer’s recommendation of being used as a remove from play test. However, it is not sufficient to be a standalone test, which supports using a multifactorial approach. Additionally, as expected, the K-D had poor to no diagnostic accuracy at the asymptomatic time point. It is highlighted that the diagnostic accuracy moved to fair levels at unrestricted return to play and 6 months following concussion which is indicative of the K-D test correctly predicting concussion diagnosis and magnitude of practice effects. At these timepoints, the athletes with a concussion have cleared previous timepoints to return to sport. This has been associated with modest improvements in K-D performance due to participating in physical activity and improvement of cognitive performance. Practice effects greatly influence repeat K-D performance and clinical interpretation across repeated administrations. Our results may show that a practice effect (leading to faster completion of K-D test) has a stronger influence on post-injury K-D test scores than concussion
effect (which in theory is associated with slower completion of K-D test). Athletes with a concussion will take the test 4 times in 6 months whereas the healthy athletes will take the K-D test only two times in one year. Clinicians should expect a considerable improvement in completion time (i.e. faster) with subsequent K-D test administrations. A faster K-D time is a product of a practice effect and there should be caution when interpreting the outcomes across timepoints for concussed individuals. In addition, our data reveal recommended cutoff scores at each timepoint to improve the clinical interpretation of the K-D test over concussion recovery.

**Recommended Cutoff Scores**

To achieve 80% sensitivity, clinicians should expect a 1.0-2.6 seconds faster time within 0-6 hours, 1.0-3.2 faster at 24-48 hours post-injury, and 1.0-2.1 seconds faster time at return to play. Similar to our study, Dhawan et al. found a cutoff time of 2 seconds faster than baseline had high sensitivity (90%) and specificity (91%) in adolescent athletes, which is notably higher than our observed levels of specificity. However, this study had a smaller sample size with only 20 participants diagnosed with a concussion and 121 participants without a concussion. Sensitivity is calculated by the number of true positives divided by the total number of individuals with a concussion. However, this could artificially inflate the sensitivity value with a smaller sample size for those with a concussion. Other previous studies have shown 0.7-2.5 second improvements in K-D times in healthy athletes between two baseline measurements. Breedlove et al. found the K-D test to be reliable between trials and years. Retesting with a one-year interval revealed a small improvement of 2 seconds among intercollegiate athletes. However, 27% of athletes showed a slower performance from year 1 to year 2. Overall, these prior studies with our results confirm that athletes should perform considerably faster relative to
their baseline time with subsequent K-D testing. Repeated tests will cause practice effects and improvement of scores regardless of injury.\textsuperscript{18}

\textbf{Confounding Factors}

Confounding factors largely did not influence K-D test diagnostic accuracy post-concussion. The K-D test AUC for those with a learning disorder was slightly higher (AUC=0.747) relative to those without a learning disorder (AUC=0.691), although the confidence intervals overlap (Figure 2d). Originally, the K-D test was developed in 1976 to study eye movement in conjunction with reading ability to screen children for learning disorders such as dyslexia.\textsuperscript{27} Our results suggest that learning disability does not largely influence the diagnostic accuracy of the K-D test when referenced to a pre-injury baseline. Future studies should examine whether learning disabilities influence diagnostic accuracy in the absence of a baseline and in a larger sample, as ours including just 15 athletes with concussion that had a diagnosed learning disability.

King-Devick test time and errors decreased (improved performance) as age increases among high school, collegiate, and professional athletes.\textsuperscript{14} However, we found no difference in performance by academic year (freshmen to seniors). Additional research has suggested that sex influences K-D test performance where males tend to score worse or slower.\textsuperscript{14} However, our results indicated no differences were found across sex. We also did not find significant differences in AUC among those with ADHD. We found that concussion history is not an influential factor on K-D performance which has yet to be studied.

Administration mode did influence AUC outcomes. We found that the iPad version outperformed the card system. There has been a shift from the card system to the iPad version as the card system is no longer commercially available.\textsuperscript{28} Previous research has also found the iPad
version to be recommended over the cards because it has higher test-retest reliability and improved testing standards to minimize errors from administrators.\textsuperscript{28, 29} Institutions should use the iPad versions or they risk inappropriately diagnosing someone with concussion when they do not have one.

Lastly, physical activity may also be a confounding factor contributing to our results at the return to play and 6-month timepoints, but possibly different for asymptomatic or beginning return to play protocol. Physical activity such as aerobic fitness is supported by evidence to improve cognitive performance following a bout of exercise.\textsuperscript{30} The 48-hour time point likely occurs prior to the athlete being asymptomatic and thus it is presumed they are not participating in physical activity. Our results show the diagnostic accuracy decreases to poor levels at the asymptomatic timepoint then improves to fair levels at unrestricted return to play. Physical inactivity may hinder cognitive performance which is reflected in our results.

**Limitations**

Though our study included a large multi-site sample of control and concussed athletes, there are limitations. These findings are limited to those who were participating at these sites only. In addition, we used the difference in baseline times for the control group across the 4 timepoints since repeat testing was not available for the control group. Sample sizes for the subanalyses were much smaller which is a limitation of this study. Future research should consider using the K-D test in healthy-matched individuals across the same timepoints to their concussed counterparts.

In conclusion, we examined a large sample of collegiate athletes from multiple sites to determine the diagnostic accuracy of a test commonly used to evaluate concussions. Based on our findings, the K-D test contributes acceptable diagnostic value at the 48-hour post-concussion
time point, but is not adequate at the asymptomatic timepoint and is only fair at RTP.

Confounding demographic and medical history factors were not significant across the same
timepoints. These findings suggest that the K-D should not be used as a standalone assessment at
any time point. Instead the K-D should be included as one part of a comprehensive assessment
battery.
REFERENCES

1. Dessy A, Yuk F, Maniya A, al. e. Review of assessment scales for diagnosing and monitoring sports-related concussion. Cureus. 2017;9(12):e1922.

2. Broglio SP, Katz BP, Zhao S, et al. Test-retest reliability and interpretation of common concussion assessment tools: findings from the NCAA-DoD Care Consortium. Sports Med. 2018;48(5):1255-1268. doi:10.1007/s40279-017-0813-0

3. Putukian M. Clinical evaluation of the concussed athlete: a view from the sideline. J Athl Train. 2017;52(3):236-244.

4. Borich M, Cheung K, Jones P, et al. Concussion: current concept in diagnosis and management. J Neurol Phys Ther. 2013;37(3):133-139.

5. Galetta K, Brandes L, Maki K, et al. The King-Devick test and sports-related concussion: study of a rapid visual screening tool in a collegiate cohort. J Neurol Sci. 2011;309(1-2):34-39.

6. King D, Gissane C, Hume P, Flaws M. The King-Devick test was useful in management of concussion in amateur rugby union and rugby league in New Zealand. J Neurol Sci. 2015;351(1-2):58-64.

7. Seidman D, Burlingame J, Yousif L, et al. Evaluation of the King-Devick test as a concussion screening tool in high school football players. J Neurol Sci. 2015;356(1-2):97-101.

8. Galetta K, Morganroth J, Moehringer N, et al. Adding vision to concussion testing: a prospective study of sideline testing in youth and collegiate athletes. J Neuroophthalmol. 2015;35(3):235-241.

9. Galetta K, Mengling L, Leong D, Ventura R, Galetta S, Balcer L. The King-Devick test of rapid number naming for concussion detection: meta-analysis and systematic review of the literature. Concussion. 2015;1(2):1-17.

10. Russell-Giller S, Toto D, Heitzman M, Naematullah M, Shumko J. Correlating the King-Devick test with vestibular/ocular motor screening in adolescent patients with concussion: a pilot study. Sports Health. 2018;10(4):334-339.

11. Chrisman SPD, Harmon KG, Schmidt JD, et al. Impact of factors that affect reading skill level on king–devick baseline performance time. Ann Biomed Eng. 2019;47(10):2122-2127.

12. Marinides Z, Galetta K, Andrews C, et al. Vision testing is additive to the sidelines assessment of sports-related concussion. Neurol Clinic Pract. 2015;5(1):24-34.

13. Lempke L, Schmidt J, Lynall R. Athletic trainers' concussion-assessment and management practices: an update. J Athl Train. 2020;55(1):17-26.

14. Moran R, Covassin T. Risk factors associated with baseline King-Devick performance. J Neurol Sci. 2017;383(1):101-104.
15. Leong D, Balcer L, Galetta S, Evans G, Gimre M, Watt D. The King-Devick test for sideline concussion screening in collegiate football. *J Optometry*. 2015;8(2):131-139.

16. Oberlander T, Olson B, Weidauer L. Test-retest reliability of the King-Devick test in an adolescent population. *J Athl Train*. 2017;52:439-445.

17. Galetta K, Barrett J, Allen M, et al. The King-Devick test as a determinant of head trauma and concussion in boxers and MMA fighters. *Neurology*. 2011;76:1456-1462.

18. Breedlove K, Ortega J, Kaminski T, et al. King-Devick test reliability in National Collegiate Athletic Association Athletes: A National Collegiate Athletic Association-Department of Defense Concussion Assessment, Research and Education Report. *J Athl Train*. 2019;

19. Buckley T, Breedlove K, Oldham J, et al. Year to year reliability of the King-Devick test in collegiate student-athletes: An NCAA/DoD Grand Alliance report. *Neurology*. 2017;88(16S):P5.220.

20. Broglio S, McCrea M, McAllister T, et al. A national study on the effects of concussion in collegiate and US Military Service Academy Members: The NCAA-DoD concussion assessment, research and education (CARE) consortium structure and methods. *Sports Med*. 2017;47(7):1437-1451.

21. McCrory P, Meeuwisse W, Dvořák J, et al. Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med*. Jun 2017;51(11):838-847. doi:10.1136/bjsports-2017-097699

22. Rice SG. Medical conditions affecting sports participation. *Pediatrics*. Apr 2008;121(4):841-8. doi:10.1542/peds.2008-0080

23. DW H, L L. Applied Logistic Regression. Second ed. John Wiley & Sons; 2000:160-164:chap 5.

24. Herring M, O'Connor P, Dishman R. The effect of exercise training on anxiety symptoms among patients. *Arch Intern Med*. 2010;170(4):321-331.

25. Dhawan P, Leong D, Tapsell L, et al. King-Devick test identifies real-time concussion and symptomatic concussion in youth athletes. *Neurol Clin Pract*. 2017;7:464-473.

26. Leong D, Balcer L, Galetta S, Liu Z, Master C. The King-Devick test as a concussion screening tool administered by sports parents. *J Sports Med Phys Fitness*. 2014;54(1):70-77.

27. Weise K, Swanson M, Penix K, Hale M, Ferguson D. King-Devick and pre-season visual function in adolescent athletes. *Optom Vis Sci*. 2017;94(1):89-95.

28. The King-Devick Test: Frequently Asked Questions.

29. Raynowska J, Hasanaj L, Zhang I, al. e. Agreement of the spiral-bound and computerized tablet versions of the King-Devick Test of rapid number naming for sports related concussion. *Ann J Sports Med Res*. 2015;2(9):1051-1057.
Chang YK, Etnier JL. Exploring the dose-response relationship between resistance exercise intensity and cognitive function. *J Sport Exerc Psychol.* 2009;31(5):640-56.
Table 1. Demographic Information of Concussed and Controlled Groups.

|                          | Concussed (n=320) | Control (n=1,239) | X²   | p value |
|--------------------------|-------------------|-------------------|------|---------|
| Sex                      |                   |                   |      |         |
| Female                   | 158 (49.4%)       | 593 (47.9%)       | 0.233| 0.692   |
| Male                     | 162 (50.6%)       | 646 (52.1%)       |      |         |
| Sport Contact Level⁵     |                   |                   |      |         |
| Contact                  | 221 (69.0%)       | 516 (41.6%)       | 77.321| <.001   |
| Limited Contact          | 68 (21.2%)        | 460 (37.1%)       |      |         |
| Non-Contact              | 31 (9.6%)         | 263 (21.2%)       |      |         |
| Academic Year⁶           |                   |                   |      |         |
| Freshman                 | 81 (25.3%)        | 45 (3.6%)         | 171.134| <.001   |
| Sophomore                | 84 (26.2%)        | 386 (31.2%)       |      |         |
| Junior                   | 76 (23.8%)        | 368 (29.7%)       |      |         |
| Senior                   | 79 (24.7%)        | 440 (35.5%)       |      |         |
| Learning Disorder        |                   |                   |      |         |
| No                       | 299 (93.4%)       | 1185              | 6.359| 0.042   |
| Yes                      | 21 (6.6%)         | 54 (4.3%)         |      |         |
| Attention Hyperactivity  |                   |                   |      |         |
| Deficit Disorder/Attention Deficit Disorder | | | | |
| No                       | 293 (91.5%)       | 1123              | 3.726| 0.155   |
| Yes                      | 27 (8.5%)         | 116 (9.4%)        |      |         |
| Migraine Disorder        |                   |                   |      |         |
| No                       | 298 (93.1%)       | 1175              | 6.911| 0.032   |
| Yes                      | 22 (6.9%)         | 64 (5.2%)         |      |         |
| Concussion History       |                   |                   |      |         |
| 0                        | 120 (37.5%)       | 958 (77.3%)       | 218.856| <.001   |
| 1                        | 144 (45.0%)       | 215 (17.4%)       |      |         |
| 2                        | 43 (13.4%)        | 34 (2.7%)         |      |         |
| 3+                       | 13 (4.1%)         | 12 (1.0%)         |      |         |
| Administration Mode      | iPad              | Spiral Bound Cards| | | |
|                          | 111 (34.7%)       | 343 (27.6%)       | 6.044| 0.014   |
|                          | 209 (65.3%)       | 896 (72.3%)       |      |         |

|                          | Mean±SD | Mean±SD | F    | p value |
|--------------------------|---------|---------|------|---------|
| Age                      | 19.80±1.41| 20.31±1.18| 50.36| <.0001  |
| Baseline K-D Time (s)    | 40.05±9.31| 40.98±7.23| 8.49 | 0.004   |
| Baseline 2 K-D Time (s)  | NA      | 38.93±7.14| NA   | NA      |
| Post-Concussion K-D Times (s) | 47±15.3 | 44.96±16.29| NA   | NA      |
|                          |         | 44.2±48.76| NA   | NA      |
|                          |         | 39.47±5.26| NA   | NA      |
|                          |         | 36.08±5.02| NA   | NA      |

⁵Sport Contact Level: Contact: Athletes purposely hit or collide with each other or inanimate objects; Limited Contact: Contact with others or inanimate objects is infrequent or inadvertent; Noncontact: Contact is rare and unexpected.

⁶Academic year for concussed individuals refers to the year they sustained their concussion. For control individuals, it is the year they completed their first K-D Baseline assessment.
Figure 1. Receiver operating characteristic curves and area under the curve across post-concussion timepoints. The horizontal dotted line at y=80 indicates is included to indicate the 100%-specificity at a sensitivity of 80%.
Figure 2a-h. Receiver operating characteristic curves at the within 48 hours timepoint segmented by sex (a), sport contact level (b), academic year (c), learning disorder (d), attention hyperactivity deficit disorder/attention deficit disorder (e), migraine history (f), concussion history (g), and (h) administration mode (*P<0.05). The horizontal dotted line at y=80 indicates is included to indicate the 100% specificity at a sensitivity of 80%.

*AUC significantly differs (p<0.001)*