Journal of Optometry (2015) 8, 131–139

Journal of Optometry

www.journalofoptometry.org

ORIGINAL ARTICLE

The King–Devick test for sideline concussion screening in collegiate football

Danielle F. Leong[a,*], **Laura J. Balcer**[b], **Steven L. Galetta**[b], **Greg Evans**[c], **Matthew Gimre**[c], **David Watt**[c]

[a] *King–Devick Test, LLC, Oakbrook Terrace, IL, USA*
[b] *Departments of Neurology, Ophthalmology and Population Health New York University School of Medicine, New York, NY, USA*
[c] *Wheaton College Sports Medicine, Wheaton, IL, USA*

Received 4 August 2014; accepted 3 December 2014
Available online 31 January 2015

KEYWORDS
King–Devick;
Sports-related concussion;
Eye movements;
Vision;
Brain injury

Abstract
Purpose: Sports-related concussion has received increasing attention as a result of neurologic sequelae seen among athletes, highlighting the need for a validated, rapid screening tool. The King–Devick (K–D) test requires vision, eye movements, language function and attention in order to perform and has been proposed as a promising tool for assessment of concussion. We investigated the K–D test as a sideline screening tool in a collegiate cohort to determine the effect of concussion.
Methods: Athletes ($n = 127$, mean age 19.6 ± 1.2 years) from the Wheaton College football and men's and women's basketball teams underwent baseline K–D testing at pre-season physicals for the 2012–2013 season. K–D testing was administered immediately on the sidelines for football players with suspected head injury during regular games and changes compared to baseline were determined. Post-season testing was also performed to compare non-concussed athletes' test performance.
Results: Concussed athletes ($n = 11$) displayed sideline K–D scores that were significantly higher (worse) than baseline (36.5 ± 5.6 s vs. 31.3 ± 4.5 s, $p < 0.005$, Wilcoxon signed-rank test). Post-season testing demonstrated improvement of scores and was consistent with known learning effects (35.1 ± 5.2 s vs. 34.4 ± 5.0 s, $p < 0.05$, Wilcoxon signed-rank test). Test-retest reliability was analyzed between baseline and post-season administrations of the K–D test resulting in high levels of test-retest reliability (intraclass correlation coefficient (ICC) = 0.95 [95% Confidence Interval 0.85–1.05]).

Abbreviations: CI, confidence interval; CTE, chronic traumatic encephalopathy; ICC, intraclass correlation coefficient; K–D, King–Devick; PCS, post-concussion syndrome; SAC, standardized assessment of concussion; SCAT2, sport concussion assessment Tool 2; TBI, traumatic brain injury.

* Corresponding author at: Two Mid America Plaza Ste #110, Oakbrook Terrace, IL 60181, USA. Tel.: +1 630 501 0073; fax: +1 630 501 0285.
E-mail address: leong.danielle@gmail.com (D.F. Leong).

http://dx.doi.org/10.1016/j.optom.2014.12.005

Conclusions: The data show worsening of K–D test scores following concussion further supporting utility of the K–D test as an objective, reliable and effective sideline visual screening tool to help identify athletes with concussion.

PALABRAS CLAVE
King–Devick;
Conmoción relacionada con el deporte;
Movimientos oculares;
Visión;
Lesión cerebral

Test de King-Devick para el screening en la banda de la conmoción cerebral en el fútbol universitario

Resumen
Objetivo: Cada vez se presta más atención a las conmociones cerebrales relacionadas con el deporte, como resultado de las secuelas neurológicas que se han visto en los atletas, lo que incrementa la necesidad de encontrar una herramienta validada y rápida de detección diagnóstica. El test de King-Devick (K–D) abarca el análisis de la visión, movimientos oculares, función del lenguaje y atención, habiéndose propuesto como una herramienta prometedora para la evaluación de las conmociones cerebrales. Realizamos una investigación sobre el test K–D, como herramienta para usar en la banda de screening en un grupo universitario, para determinar los efectos de la conmoción cerebral.
Métodos: Los atletas ($n = 127$, edad media $19{,}6 \pm 1{,}2$ años) de los equipos de fútbol y baloncesto masculino y femenino del Wheaton College se sometieron a un test K–D de referencia, durante los exámenes físicos de la temporada 2012-2013. Se realizó el test K–D de manera inmediata en la línea de banda a los jugadores de fútbol con sospecha de lesiones en la cabeza durante los partidos regulares, determinándose los cambios con respecto a los valores de referencia. También se realizaron pruebas al finalizar la temporada, para comparar el resultado de las pruebas en aquellos atletas que no habían sufrido conmoción cerebral.
Resultados: Los atletas con conmoción cerebral ($n = 11$) mostraron unas puntuaciones K–D suplementarias que fueron significativamente superiores (peores) a las basales ($36{,}5 \pm 5{,}6$s frente a $31{,}3 \pm 4{,}5$s, $p < 0{,}005$, test de los rangos con signo de Wilcoxon). La prueba al finalizar la temporada reflejó una mejora de las puntuaciones, siendo consistente con los efectos conocidos del aprendizaje ($35{,}1 \pm 5{,}2$s frente a $34{,}4 \pm 5{,}0$s, $p < 0{,}05$, test de los rangos con signo de Wilcoxon). Se analizó la fiabilidad test-retest entre las realizaciones del test K–D basal y al finalizar la temporada, existiendo unos niveles elevados de fiabilidad test-retest (coeficiente de correlación intra-clase (ICC) = 0,95 [95% Intervalo de confianza 0,85 - 1,05]).
Conclusiones: Los datos reflejan el empeoramiento de las puntuaciones del test K–D tras la conmoción cerebral, lo que refuerza la utilidad de dicha prueba como herramienta adicional y realizable en la banda de screening visual objetiva, fiable y efectiva, para la identificación de los atletas con conmoción cerebral.

Introduction

It is estimated that sports-related concussion afflicts 3.8 million American athletes each year.[1–6] This rate may be an underestimate, as recent studies have revealed that many sport-related concussions go unreported.[5] Concussion is a brain injury caused by an impulsive force transmitted to the head resulting in a complex pathological process manifesting in the rapid onset of short-lived impairment of neurological function.[6,7] During trauma to the head occurring during sports related concussion, linear and rotational accelerations of the brain may occur relative to the skull producing pressure and shear forces upon brain tissue.[8] Shear-induced tissue damage may produce diffuse axonal stretching resulting in changes of neurological function.[8] The short-term sequelae of concussion can include a variety of acute symptoms including headache, irritability, balance and memory dysfunction, impaired eye movement function, confusion, amnesia, nausea, slurred speech, fatigue, sensitivity to light, and sleep disturbances. [6–10] Symptoms may become prolonged in post-concussion syndrome.[6] Recent studies also indicate that long-term sequelae include a 1.5-fold increased risk of depression and a 4.5-fold increased risk of Alzheimer's-like symptoms in patients with concussion history.[11,12] Although no causal relationship has yet been established, recent post-mortem research suggest that repeated head trauma may be associated with the development of chronic traumatic encephalopathy (CTE), a neurodegenerative condition believed to be caused by a series of metabolic, ion, membrane, and cytoskeletal disturbances as a result of neurological trauma.[13–16] These potentially devastating outcomes emphasize the need for practical sideline screening tests to help accurately detect concussions immediately after injury.

The function of eye movements may become impaired following brain trauma.[17–20] Latency and inaccuracy of saccades have been described in traumatic brain injury (TBI) subjects.[19] In detailed saccade studies in post-concussion syndrome (PCS) in which signs and symptoms of concussion remain over a prolonged recovery, PCS subjects were distinguishable from normal controls as they were found to make more directional errors, require a significantly higher number of saccades and showed poor movement timing with longer durations and slower velocities of movement.[20,21] Additionally, dysfunction of the ocular motor system is one of the most widely reported visual problems in individuals with traumatic brain injury.[17,18] Given that the network of visual and eye movement pathways is widely distributed throughout the brain,[22] ocular dysfunction is not uncommon following traumatic brain injury.

The King—Devick (K—D) test is a 2-min, sideline assessment of rapid number naming which requires the athletes to quickly read a series of numbers on three test cards (Fig. 1). The K—D test requires eye movements, language function and attention in order to perform functions which have been shown to reflect suboptimal brain function in concussion,[23–31] Parkinson's,[32] multiple sclerosis,[33] extreme sleep deprivation,[34] and hypoxia.[35,36] The K—D test has been studied as an acute sideline concussion screening tool in several cohorts throughout a variety of contact sports including boxers and mixed martial arts (MMA) fighters, collegiate athletes in contact sports, amateur rugby players, elite professional hockey players and high school level football (Yevseyenkov V, et al. IOVS 2013; 54: ARVO E-abstract 2344) and hockey.[23–30] In these cohorts, worsening of performance on the K—D test from baseline was shown to be an accurate indicator of concussion. The addition of this type of vision based test has also been shown to enhance the detection of athletes with concussion.[29]

The purpose of this investigation was to further determine the effect of concussion on K—D scores compared to pre-season baseline in collegiate level football athletes. Additionally, the effect of physical exercise on K—D scores in the absence of concussion was studied.

Subjects and methods

Study participants

For this study of collegiate athletes, 127 athletes were enrolled at the time of pre-season physical examinations for the 2012—2013 season. Athletes were players from the football team and the men's and women's basketball teams. The Wheaton College Institutional Review Board (IRB) approved all study protocols. Participants underwent pre-season baseline testing with the K—D test. During the playing season, the K—D test and a modified version of the Sport Concussion Assessment Tool 2 (SCAT2) were both utilized in the sideline assessment of athletes suspected of head trauma.

The King—Devick test

The K—D test is based on the time to perform rapid number naming and takes less than 2 min to administer.[23,24] The test involves reading aloud a series of random single-digit numbers from left to right. The K—D test includes one demonstration card and three test cards that vary in format (Fig. 1). Standardized instructions are used and participants are asked to read the numbers from left to right as quickly as they can without making any errors. Time is kept for each test card using a stopwatch and the K—D summary score for the entire test is based on the cumulative time taken to read all 3 test cards. The number of errors made in reading the test cards is also recorded. A baseline score is established by testing a subject twice. The best time (fastest) of the two trials without errors becomes the established baseline K—D test time.[23] When head trauma is suspected, the K—D test is used as a screening tool. The test is administered once using the same instructions and the time and errors are recorded and then compared to the subject's baseline. Worsening of time and/or errors committed on the sideline test have been associated with concussive injury.[23–30] K—D test performance has been previously shown to be unaffected in various noise levels and testing environments.[30] The test-retest reliability for the K—D test has been examined in previous studies and shown to be high with intraclass correlations of 0.97 (95% confidence interval [CI] 0.90, 1.0) between measurements in the absence of concussion in one study[23] and 0.96 (95% CI 0.93, 0.99) in another.[28] The K—D test v1.1.0 physical test was utilized in this study.

Modified sport concussion assessment Tool 2 (SCAT2)

The Sport Concussion Assessment Tool 2 (SCAT2) is a standardized concussion tool that contains an extensive set of subtests, including: Symptoms evaluation, Physical signs, Glasgow Coma score, Balance and Coordination as well as a cognitive subtest, the Standard Assessment of Concussion (SAC).[2] The SAC includes Orientation, Immediate Memory, Concentration and Delayed Recall testing.[2] Due to the time constraints of immediate sideline evaluations, Wheaton College Sports Medicine adopted an abbreviated version of the SCAT2 to be used to assess athletes suspected of concussion. This version included the following standardized SCAT2 subtests: Symptoms evaluation (Likert scale 0 to 6 of severity for 22 standard concussion symptoms), Balance and Coordination testing (Balance Error Scoring System (BESS) and Finger-to-nose task), Orientation, Memory and Concentration testing (using the SAC). SCAT2 results were recorded as a pass or fail based on the presence of any SCAT2 defects in which an athlete displayed any signs of symptoms of concussion (i.e. loss of consciousness, balance incoordination, disorientation or confusion or loss of memory).

Testing procedures

Baseline K—D times for all athletes were established during pre-season physical exams with multiple individuals being testing simultaneously in a noisy training room environment. Subjects were given standardized instructions for the K—D test. Athletes sustaining a suspected head injury were given the K—D test immediately on the sidelines followed by the Modified SCAT2. Judgments with regard to the occurrence of concussion were made as per standard practice by the team

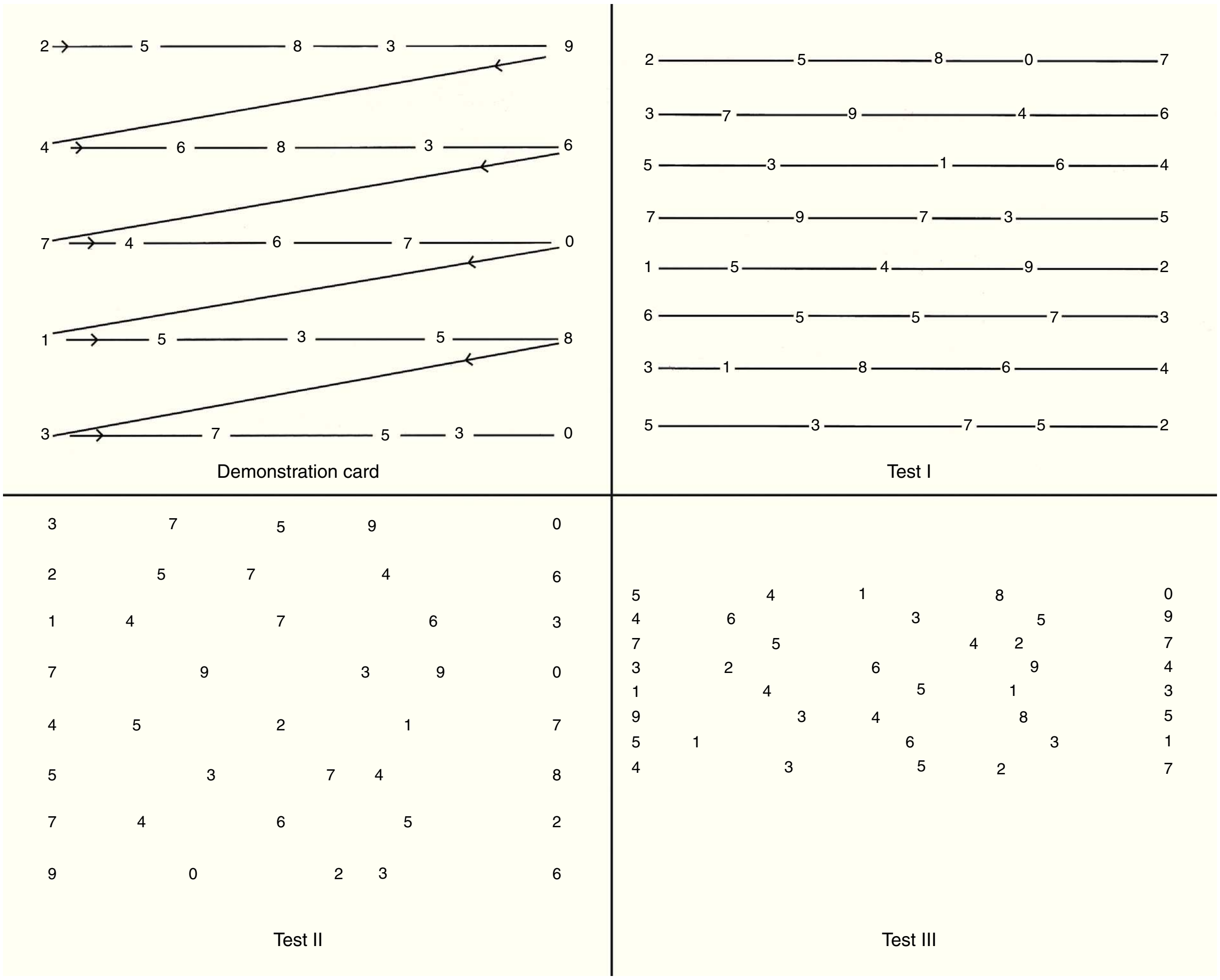

Figure 1 Demonstration and test cards for the King–Devick (K–D) Test: a rapid sideline screening tool for sports-related concussion based on the time to perform rapid number naming. To perform the K–D test, participants are asked to read the numbers from left to right as quickly as they can without making any errors. The tester should start the stopwatch when the subject reads the first number and stop the watch when the last umber has been read. Time required to complete each card are recorded and in seconds using a stopwatch and the K–D time score is based on the cumulative time taken to read all 3 test cards. The number of errors made in reading the test cards is also recorded; misspeaks on numbers are recorded as errors if the subject does not immediately correct the mistake before continuing on to the next number.

physicians and athletic trainers on the sidelines. Post-season testing was also performed on a convenience sample of non-concussed football players to determine how K–D performance changes over the course of a season in the absence of concussion. Additionally, basketball players were tested immediately following an intense 2.5 h sprint work-out to test the effects of physical exercise on K–D performance independent of concussion.

Data analysis

Statistical analyses were performed using STATA 12.0 software. Given the small sample size ($n = 11$) for the athletes with concussion and sideline testing, non-parametric statistical tests were used. Changes in K–D time scores from pre- to post-season were calculated and compared using the Wilcoxon signed-rank test. Similarly, differences in sideline K–D scores were calculated and compared to pre-season baseline scores in athletes with concussion. Wilcoxon signed-rank test was also used to compare K–D time scores pre- and post-exercise for the basketball teams. Test-retest reliability was estimated using the intraclass correlation coefficient (ICC) to examine agreement between pre- and post-season scores among athletes without concussion. Statistical significant was set at $p < 0.05$.

Results

Characteristics and K–D testing data for the study cohort are shown in Table 1. Lower (improved) K–D time scores were observed for the second K–D trial compared to the first during baseline testing of football players (median 36.8 s vs. 39.4 s, $p < 0.001$, Wilcoxon signed-rank). Additionally, post-season testing of non-concussed athletes ($n = 43$) demonstrated improvement of scores likely consistent with learning effects (median 34.5 s vs. 35.9 s, $p < 0.05$, Wilcoxon

Table 1 Characteristics of the collegiate athlete cohort and K–D test scores.

	All athletes ($n = 127$)
Age, mean ± SD	19.6 ± 1.2 years
Male, n (%)	119 (93.7%)
Sport, no (% of cohort)	
Football	102 (80.3%)
Basketball, men's	17 (13.4%)
Basketball, women's	8 (6.3%)
Pre-season K–D *test 1, median (range)*	
(football only, $n = 102$)	39.4 s (28.3–60.5)
Pre-season K–D *test 2, median (range)*	
(football only, $n = 102$)	36.8 s (26.0–54.5) $p < 0.001$ vs. test 1[a]
Baseline K–D *test, median (range)*	
(entire cohort, $n = 127$)	35.9 s (26.0–54.5)
Post-workout K–D *test, median (range)*	
(men's & women's basketball only, $n = 25$)	31.8 s (25.2–43.9) $p < 0.05$ vs. baseline[b]
Post-season K–D *test, median (range)*	
(football, $n = 43$)	34.5 s (25.2–44.6) $p < 0.05$ vs. baseline[c]
ICC (95% CI), K–D baseline vs. post-season	0.95 (0.85–1.05)

Abbreviations: K–D = King–Devick test; ICC = intraclass correlation coefficient, CI = confidence interval.
[a] Comparison of pre-season K–D test 1 vs. 2 in football cohort, Wilcoxon signed-rank test.
[b] Comparison of post-workout K–D test vs. baseline in basketball cohort, Wilcoxon signed-rank test.
[c] Minimal but significant learning effects (post-season K–D score lower [better] than baseline K–D score) were noted overall for the cohort; negative number for change in K–D score indicates improvement.

signed-rank test). The ICC of K–D test time scores between baseline and post-season tests indicated a high degree of test-retest reliability (ICC 0.95 [95% CI 0.85–1.05]).

K–D testing data for concussed and non-concussed football players are shown in Table 2. Sideline K–D scores of concussed athletes ($n = 11$) were significantly longer (worse) than baseline (36.5 ± 5.6 s vs. 31.3 ± 4.5 s, $p < 0.005$, Wilcoxon signed-rank test). All concussed athletes, with the exception of two, failed sideline SCAT2 testing. These two athletes showed worsening on their sideline K–D test (1.1 and 4.9 s worsening from baseline respectively). All athletes who sustained a concussion during the playing season exhibited defects in their sideline K–D tests. All, except one player, demonstrated worsening of their K–D score from baseline (range −0.9 to 15.6 s) with an average change in score of 4.4 s. There were minimal errors with one concussed athlete making 1 error on sideline testing. This athlete did not substantially worsen from baseline with respect to their K–D time score (30.8 s baseline vs. 29.9 s post-concussion with 1 error).

Post-workout data were obtained during a practice in the middle of the season for the men's and women's basketball teams immediately following a 2.5 h workout. No concussions were sustained in these athletes. K–D scores post-workout showed faster (improved) K–D scores (31.8 ± 4.9 vs. 34.5 ± 4.8, $p < 0.05$, Wilcoxon signed-rank test) and a median improvement of 1.0 s on their post-workout K–D test. There was no worsening of K–D scores following physical fatigue in the absence of concussion (Fig. 2).

Discussion

This study provides additional evidence for the use of the K–D test as an effective, objective sideline assessment tool for concussion. Concussed athletes performed slower on their sideline K–D test compared to baseline with an average slowing from baseline of 4.4 s. This finding was similar to previous studies that have also shown worsening of score with concussion.[23–30] Average worsening from baseline has been reported in previous studies to range from 5 to 7 s. The difference between average changes in times when compared to previous studies[23–30] may be reflective of the population tested, prior history of concussion and the conditions the athletes were tested. Prior studies have included boxers and MMA fighters[23] who were observed to have sustained obvious head trauma. The concussive injuries identified in the current study may have been less severe as overt head trauma was not always witnessed. In a previous study[24] both male and female athletes with concussion were included whereas the current study only included male football players. This may also have played a role in the disparity between average worsening among studies as previous work has shown that gender may be a risk factor for injury and may influence injury severity.[2] Future studies are recommended to investigate the possible correlation between the amount of deviation in post-injury sideline time with concussion severity and recovery time incorporating gender differences.

Detecting concussion on the sidelines, and removing an athlete from play, can assist to minimize the deleterious outcomes of concussion. Rapid screening tools that can be practically implemented into the sideline evaluation of athletes are vital to the detection of concussive injuries. The K–D test is portable and easy to implement on the sidelines. As well, the K–D test takes less than 2 min to complete on the sideline and is given as a series of test cards available in either a moisture-proof 6 × 8 inch spiral-bound physical test or as an application on a tablet or computer system. The K–D test is simply based on time to complete a rapid number naming task. It does not require a medical professional to administer[28] and is therefore a realistic tool for high schools and youth sports organizations, the majority of which do not have access to medical personnel.

Table 2 The effects of concussion during the playing season on K–D scores.

	Athletes with concussion during playing season ($n = 11$, tested on sidelines)	Athletes with no concussion during playing season ($n = 91$)
Age, mean ± SD	19.6 ± 1.2 years	19.5 ± 1.2 years
Baseline K–D score, median (range)	31.3 s (26.0–40.0)	37.4 s (26.6–54.5)
Sideline K–D test, median (range)	36.5 s (27.9–44.9) $p < 0.005$ vs. baseline[a]	–
K–D change baseline vs. sideline test, median (range)	4.4 s (−0.9–15.6)[b]	–
K–D change pre- to post-season, median (range)	–	−0.8 s (−7.9–7.0)[c]

Abbreviations: K–D = King–Devick test.
[a] Comparison of sideline K–D test vs. baseline in concussed cohort, Wilcoxon signed-rank test.
[b] Significant worsening from pre-season baseline was noted for sideline K–D scores in athletes with concussion during the season; positive numbers for change in K–D score indicate worsening.
[c] Minimal but significant learning effects (post-season K–D score lower [better] than baseline K–D score) were noted overall for the cohort; negative number for change in K–D score indicates improvement.

The K–D test requires visual processes, eye movements (saccades, convergence and accommodation), attention and language function. These involve integration of functions of the brainstem, cerebellum, and cerebral cortex and have shown to correlate with suboptimal brain function.[37] The SCAT2 was published as part of the summary and agreement statement of those who attended the Third International Concussion in Sport (CIS) Conference in 2008.[38] Based on expert consensus of the measures to assess concussion that were currently available at the time, the SCAT2 was designed to be administered by medical practitioners as a detailed assessment for concussion and produced as a longer sideline concussion tool taking approximately 20 min to complete. However, the SCAT2 does not objectively assess vision or eye movement function. Some have questioned the utility and sensitivity of the SCAT2 in detecting[39] as well as its overall reliability.[40]

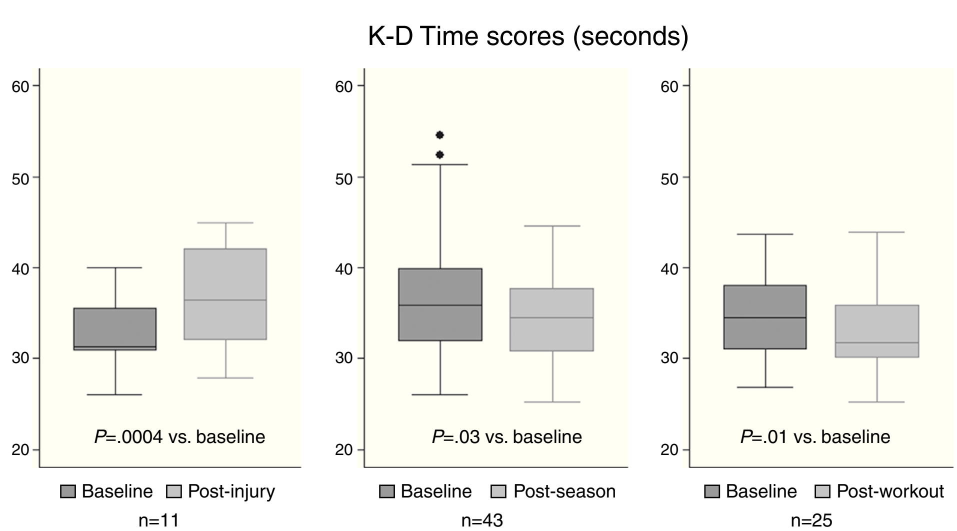

Figure 2 Box plots show the median K–D scores of baseline compared to sideline, post-workout and post-season testing. *Left*: median K–D scores for baseline and sideline testing of athletes with concussion ($n = 11$) during the playing season showing worsening (higher) K–D time scores with concussion. *Middle*: median K–D scores for baseline and post-workout testing of basketball players ($n = 25$) following intense 2.5 h practice demonstrating improved (lower) K–D time scores after exercise. *Right*: median K–D scores for baseline and post-season testing for athletes ($n = 43$) showing slight improvement (lower) K–D time scores likely consistent with learning effects. The line within the box defines the median value. The range of the box corresponds to the interquartile range between the 25th and the 75th percentile. Whiskers extending from the box plot represent the range of observations excluding outliers and the small circles beyond the whiskers represent symbolize outliers. *p* Values are based on Wilcoxon signed-rank tests comparing K–D test scores.

Concussion signs and symptoms may develop and evolve over time, particularly within the first hours following injury.[2,41] This was observed in our study where two concussed athletes showed worsening on their sideline K—D test despite being symptom-free and passing the initial sideline SCAT2 evaluation. Recent work investigating the sensitivity of sideline concussion tests used in collegiate level athletics has shown that key components of the SCAT2, the SAC and BESS, failed to capture all concussions.[29] This is similar to a finding in a previous study of professional ice hockey in which concussed athletes were identified with worsening in K—D test performance even when there had been no changes on components of the SCAT2 testing.[27] In fact, the K—D test has been shown to be complementary to key elements of SCAT2 in detecting concussion;[29] therefore, a multi-faceted method of assessing brain function is critical to making the most informed decision during the acute stage of concussive injury. Since the completion of data collection for this study, the SCAT2 has been updated to the SCAT3[2] for sports participants over the age of 12 years and the Child-SCAT3 with modified questions asked for athletes between the ages of 5 and 12 years old. Future studies are recommended to investigate the additive effect of sideline K—D test and the new SCAT3 for detection of concussion.

This study was similar to previous investigations showing that in the absence of concussion, the K—D test has a learning effect associated with repeated testing.[23—30,36] This is commonly observed in timed performance measures in which there is improvement and corresponding decrease in completion time between subsequent test administrations. Previous investigations of athletes without concussion showed an improvement on average of 2.2—3.1 s[23—25,27,28] between the two baseline test trials. The athletes in this study improved by their baseline trials by an average of 2.6 s. Pre-season and post-season testing showed an improvement of 1.4 s in athletes without concussion, similar to previous studies with pre- and post-season change of 0.72 s improvement in one study[24] and 1.9 s improvement in another.[28] The fatigue trial results of this study (31.8 s vs 34.5 s baseline, $p < 0.05$) confirm previous work that K—D times do not increase after routine exercise and the K—D test is robust to the effects of fatigue. This is similar to prior fatigue studies performed in collegiate basketball athletes (35.0 s vs. 37.9 s baseline, $p < 0.01$)[24], amateur rugby athletes (43.6 s vs. 44.9 s baseline, $p < 0.05$)[25] and a youth hockey study that tested non-concussed athletes before and after games (3.4 s improvement).[30] The learning effect of the K—D test after physical fatigue, frequently experienced by athletes in practice or game situations, and in the absence of concussion gives emphasis to any worsening of scores as a likely indicator that further evaluation for concussion is warranted.

Errors committed in this study were minimal with one concussed athlete making a single error. This is similar to previous studies in which four concussed athletes made one to four errors in addition to worse sideline K—D test times;[24] however, in this study the error was not associated with worsening of time score. Formal eye movements studies[19,20] suggest that these errors likely indicate eye movement inaccuracy as a result of TBI occurring. However, this may also be a reflection of impaired visual processing, concentration, attention or language function. Prior eye movement recorded studies of the K—D test for early detection of hypoxia related cognitive impairment have also shown that errors correlated with hypoxic impairment.[35] It is recommended that future studies undertake to examine the K—D test performance pre- and post-concussion with formal eye movement recordings to further investigate changes as a result of concussion. It is important to note that no errors were made by non-concussed athletes in this study and in prior studies suggesting that worsening of time from baseline or any errors committed deserves further concussion assessment.

Follow-up K—D testing of concussed athletes was not performed on this cohort. Other studies[24,25] have shown improvement and return to baseline. A study reporting on collegiate athletes showed return to baseline within one week following the concussive event,[24] whereas an investigation of rugby athletes[25] showed more variation ranging from one week to beyond 21 days in some athletes in the amount of time elapsed before concussed athletes returned to their established baseline. Interestingly, the time frame to return to baseline appeared to correspond with the severity of injury with the more severe, witnessed concussions taking longer to return to baseline (14 days to more than 21 days) compared to incidentally found concussions. It is recommended that future studies should continue to investigate the utility of the K—D test in concussion management and recovery to determine if there is correlation with clinical improvement.

Concussion may result in a variety of symptoms and may go both unreported by athletes and undetected by trained observers.[25,26,42] Additionally, concussed athletes who continue to play are three times more likely to sustain a second concussion in the same season.[42] The increasing epidemic of sports-related concussion, and the potential link of repetitive brain trauma to long-term neurologic sequelae,[11—16] have emphasized the need for a quick and reliable sideline screening tool to help coaches, parents and athletic trainers accurately detect concussion. The results of this study further validate the K—D test as an accurate, reliable and rapid sideline tool that provides supportive evidence of a concussive event to help objectively identify athletes with concussion and assist with removing from play decisions. It is recommended that future studies should continue to investigate the reliability of the K—D test in detecting concussion across a range of age groups from youth to professional levels, and throughout a variety of contact sports.

Financial support

None.

Conflicts of interest

Dr. Leong is an employee of King—Devick Test, LLC as a Director of Research. Dr. Balcer has served as a consultant for Biogen Idec, Questcor, and Novartis; and has received research support from the NIH/NEI and the National MS Society. Dr. Galetta has served as a consultant for Biogen Idec and Vaccinex. The work performed in this study was not funded by any of the above sources and the remaining authors have no disclosures.

Acknowledgments

The authors are grateful to the Wheaton College Sports Medicine staff for their support in study organization, implementation and testing of athletes.

References

1. Thurman DJ, Branche CM, Sniezek JE. The epidemiology of sports-related traumatic brain injuries in the United States: recent developments. *J Head Trauma Rehabil*. 1998;13: 1–8.
2. McCrory P, Meeuwisse W, Aubry M, et al. Consensus statement on concussion in sport: the 4th international conference on concussion in sport held in Zurich, November 2012. *Br J Sports Med*. 2013;47:250–258.
3. Collins MW, Iverson GL, Lovell MR, McKead DB, Norwig J, Maroon H. On-field predictors of neuropsychological and symptoms deficit following sports-related concussion. *Clin J Sport Med*. 2003;12:222–229.
4. Guskiewicz KM, Weaver NL, Padua DA, Garrett WE JR. Epidemiology of concussion in collegiate and high school football players. *Am J Sports Med*. 2000;28:643–650.
5. Torres DM, Galetta KM, Phillips HW, et al. Sports-related concussion anonymous survey of a collegiate cohort. *Neurol Clin Pract*. 2013;3:279–287.
6. Langlois JA, Rutland-Brown W, Wald M. The epidemiology and impact of traumatic brain Injury a brief overview. *J Head Trauma Rehabil*. 2006;21:375–378.
7. Giza C, Hovda D. The neurometabolic cascade of concussion. *J Athl Train*. 2001;36:228–235.
8. Meaney DF, Smith DH. Biomechanics of concussion. *Clin Sports Med*. 2011;30:19–31.
9. Guskiewicz KM, Broglio SP. Sports-related concussion: on-field and sideline assessment. *Phys Med Rehab Clin N Am*. 2011;22:603–617.
10. Delaney JS, Lacroix VJ, Leclerc S, Johnston KM. Concussions among university football and soccer players. *Clin J Sport Med*. 2002;12:331–338.
11. Gavett BE, Stern RA, Cantu RC, Nowinski CJ, McKee AC. Mild traumatic brain injury: a risk factor for neurodegeneration. *Alzheimers Res Ther*. 2010;2:18.
12. Plassman BL, Havlik RJ, Steffens DC, et al. Documented head injury in early adulthood and risk of Alzheimer's disease and other dementias. *Neurology*. 2000;55:1158–1166.
13. Gavett BE, Stern RA, McKee AC. Chronic traumatic encephalopathy: a potential late effect of sport-related concussive and subconcussive head trauma. *Clin Sports Med*. 2011;30:179–180.
14. Holsinger T, Steffens DC, Phillips C, et al. Head injury in early adulthood and the lifetime risk of depression. *Arch Gen Psychiatry*. 2002;59:17–22.
15. Lehman EJ, Hein MJ, Baron SL, Gersic CM. Neurodegenerative causes of death among retired National Football League players. *Neurology*. 2012;79:1.
16. McKee AC, Cantu RC, Nowinski CJ, et al. Chronic traumatic encephalopathy in athletes: progressive tauopathy after repetitive head injury. *J Neuropathol Exp Neurol*. 2009;68: 709–735.
17. Ciuffreda KJ, Kapoor N, Rutner D, Suchoff IB, Han ME, Craig S. Occurrence of oculomotor dysfunctions in acquired brain injury: a retrospective analysis. *Optometry*. 2007;78: 155–161.
18. Goodrich GL, Flyg HM, Kirby JE, Chang CY, Martinsen GL. Mechanisms of TBI and visual consequences in military and veteran populations. *Optom Vis Sci*. 2013;90:105–112.
19. Heitger MH, Anderson TJ, Jones RD. Saccade sequences as markers for cerebral dysfunction following mild closed head injury. *Prog Brain Res*. 2002;140:433–448.
20. Heitger MH, Jones RD, Macleod AD, Snell DL, Frampton CM, Anderson TJ. Impaired eye movement in post-concussion syndrome indicate suboptimal brain function beyond the influence of depression, malingering or intellectual ability. *Brain*. 2010;133:2850–2870.
21. Heitger MH, Jones RD, Anderson TJ. A new approach to predicting postconcussion syndrome after mild traumatic brain injury based upon eye movement function. *Conf Proc IEEE Eng Med Biol Sci*. 2008;357:0–3.
22. Fellerman DJ, Van Essen DC. Distributed hierarchical processing in the primate cerebral cortex. *Cerebral Cortex*. 1991;1: 1–47.
23. Galetta KM, 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.
24. Galetta KM, Brandes LE, 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;309:34–39.
25. King D, Brughelli M, Hume P, Gissane C. Concussions in amateur rugby union identified with the use of a rapid visual screening tool. *J Neurol Sci*. 2013;326:59–63.
26. King D, Clark T, Gissane C. Use of a rapid visual screening tool for the assessment of concussion in amateur rugby league: a pilot study. *J Neurol Sci*. 2012;320:16–21.
27. Galetta MS, Galetta KM, McCrossin J, et al. Saccades and memory: baseline associations of the King–Devick and SCAT2 SAC tests in professional ice hockey players. *J Neurol Sci*. 2013;328:28–31.
28. Leong DF, Balcer LJ, Galetta SL, Liu Z, Master CL. The King–Devick test as a concussion screening tool administered by sports parents. *J Sports Med Phys Fit*. 2014;54:70–77.
29. Marinides Z, Galetta KM, Andrews CN, et al. Vision testing is additive to the sideline assessment of sports-related concussion. *Neuro Clin Pract*. 2014, http://dx.doi.org/10.1212/CPJ.0000000000000060, published online 9 July.
30. Dhawan P, Starling A, Tapsell L, et al. King–Devick test identifies symptomatic concussion in real-time and asymptomatic concussion over time. *Neurology*. 2014;82. S11.003.
31. Lin TP, Adler CH, Hentz JG, et al. Slowing of number naming speed by King–Devick test in Parkinson's disease. *Parkinsonism Relat Disord*. 2014;20:226–229.
32. Prasad S, Galetta SL. Eye movement abnormalities in multiple sclerosis. *Neurol Clin*. 2010;28:641–655.
33. Davies EC, Henderson S, Balcer LJ, Galetta SL. Residency training: the King–Devick test and sleep deprivation. *Neurology*. 2012;78:e103.
34. Stepanek J, Cevette M, Pradhan G, et al. Early detection of hypoxic cognitive impairment using the King–Devick test. *Aviat Space Environ Med*. 2013;84:1017–1022.
35. Stepanek J, Cevette M, Cocco D, Kuhn F, Studer M, Pradhan G. Assessing eye tracking features in hypoxic and isocapnic hypoxia with King–Devick test. *Aviat Space Environ Med*. 2014;85:700–707.
36. Spradley B, Wiriyanpinit S, Magner A. Baseline concussion testing in different environments: a pilot study. *Sport J*. 2014. Published online March 12. http://thesportjournal.org/article/baseline-concussion-testing-in-different-environments-a-pilot-study/
37. Dziemianowicz MS, Kirschen MP, Pukenas BA, Laudano E, Balcer LJ, Galetta SL. Sports-related concussion testing. *Curr Neurol Neurosci Rep*. 2012;12:547–559.
38. McCrory P, Meeuwisse W, Johnston K, et al. Consensus statement on concussion in sport: the 3rd international conference on concussion in sport held in Zurich, November 2008. *J Athl Train*. 2009;44:434–448.

39. Guskiewicz KM, Register-Mihalik J, McCrory P, et al. Evidence-based approach to revising the SCAT2: introducing the SCAT3. *Br J Sports Med*. 2013;47:289–293.
40. Chan M, Vielleuse JK, Vokaty S, Wener MA, Pearson I, Gagnon I. Test-retest reliability of the sport concussion assessment tool 2 (SCAT2) for uninjured children and young adults. *Br J Sports Med*. 2013;47:e1.
41. Duhaime AC, Beckwith JG, Maerlender AC, et al. Spectrum of acute clinical characteristics of diagnosed concussions in college athletes wearing instrumented helmets. *J Neurosurg*. 2012;117:1092–1099.
42. Meehan WP, Bachur RG. Sport-related concussion. *Pediatrics*. 2009;129:114–123.