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The King-Devick test in an outpatient concussion clinic: Assessing the diagnostic and prognostic value of a vision test in conjunction with exercise testing among acutely concussed adolescents

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ABSTRACT

Objective: This study investigated the diagnostic and prognostic value of the King-Devick (K-D) test in conjunction with treadmill testing in adolescents after sport-related concussion (SRC) in an outpatient concussion management clinic without baseline measures.
Design: Prospective cohort.
Methods: The K-D test was administered pre- and post-exercise on a graded treadmill test to acutely concussed (AC, < 10 days from injury, n = 46, 15.4 ± 2.1 years) participants for 2 clinic visits (1 week apart) and to matched controls (MC, n = 30, 15.8 ± 1.4 years) for 2 visits (1 week apart). Initial K-D test times were compared between MC and AC. Changes in times from pre- to post- exercise during a treadmill test were compared for MC and AC and from Visit 1 to Visit 2. Smooth pursuits and repetitive saccades were compared with initial visit K-D test performance.
Results: Comparison of pre-exercise K-D test times at Visit 1 distinguished MC from AC (46.1 ± 9.2 s vs. 53.7 ± 13.0 s, p = .007). Comparison of pre- and post-exercise K-D test times revealed significant improvements for MC (46.1 ± 9.2 s vs. 43.1 ± 8.5 s, p < .001) and AC who recovered by Visit 2 (Fast Recovery Group [FRG], n = 23, 50.4 ± 10.0 s vs. 47.3 ± 9.8 s, p = .002). No significant difference was seen in pre- and post-exercise K-D test times on Visit 1 for AC who took longer than 2 weeks to recover (Slow Recovery Group [SRG], n = 23, 57.0 ± 15.0 s vs. 56.0 ± 16.3 s, p = .478). At Visit 1, AC had more abnormal smooth pursuits than MC (17% vs. 3%, non-significant, p = .064). AC, however, had significantly more abnormal repetitive saccades than MC (37% vs. 3%, p = .001) and AC with abnormal repetitive saccades took significantly longer to complete the Visit 1 pre-exercise K-D test than AC with normal repetitive saccades (58.6 ± 16.0 s vs 50.8 ± 10.2 s, p = .049).
Conclusion: The study supports utility of the K-D test as part of outpatient concussion assessment. Lack of improvement in K-D test performance after an exercise test may be an indicator of delayed recovery from SRC.

1. Introduction

Sport-Related Concussion (SRC), a subset of mild traumatic brain injury (mTBI), is a growing public health concern [1]. An estimated 1.6–3.8 million SRCs occur annually in the United States [2]. Concussions are caused by blunt mechanical forces to the head, resulting in a pathophysiological process that alters brain function and causes widespread neurological and cognitive deficits [3,4]. The most commonly used sideline assessment tools are the Sports Concussion Assessment Tools (SCAT) [5]. The most recent version, the SCAT-5, includes a symptom checklist, the Standardized Assessment of Concussion (SAC), the modified Balance Error Scoring System (mBESS), the timed tandem gait (TTG), and a brief neurological exam. Recently, there has been increasing evidence for the King-Devick (K-D) test to be used as an additional sideline concussion assessment tool [6]. The Buffalo Concussion Treadmill Test (BCTT) is a graded exercise test used in clinical

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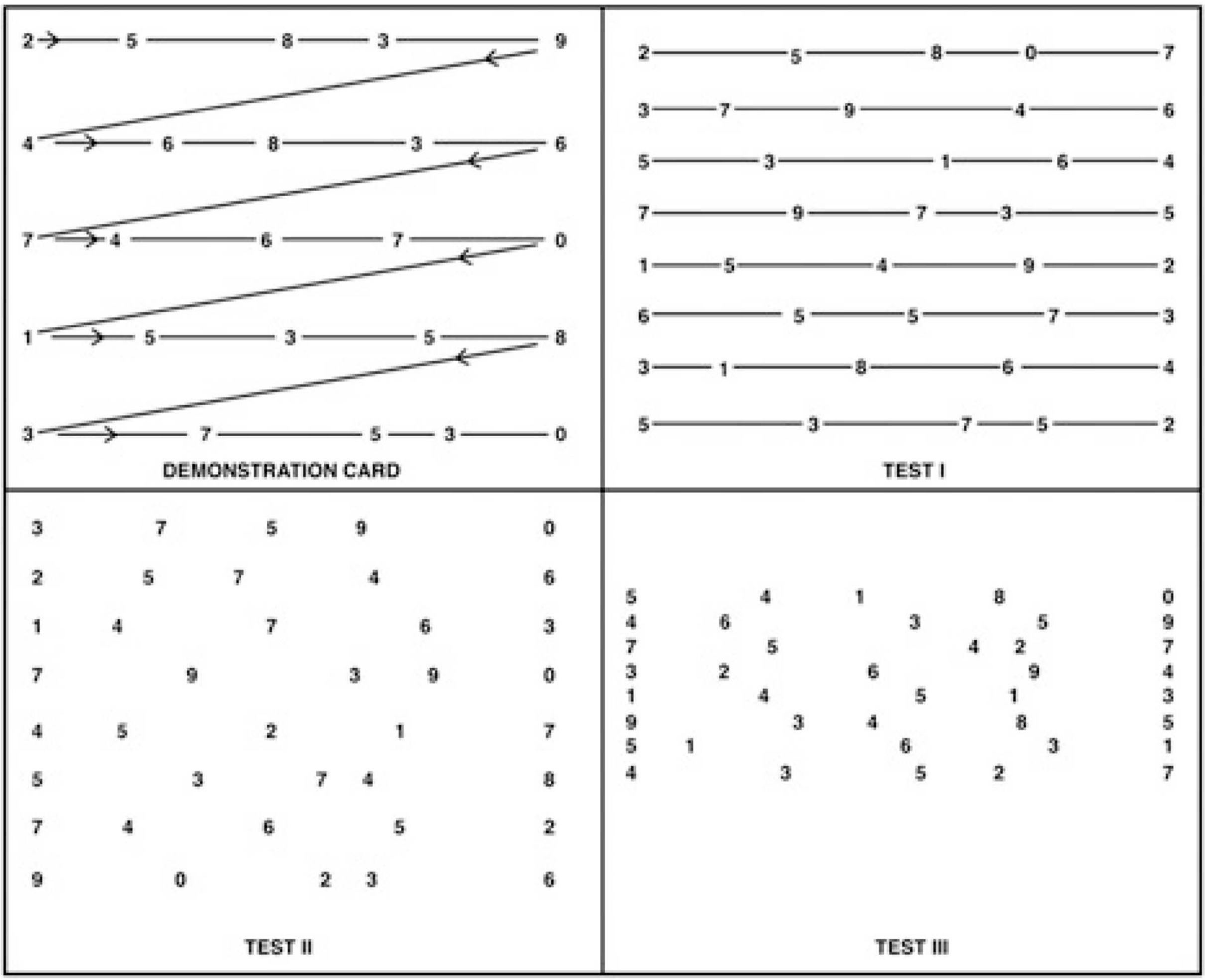

Fig. 1. Demonstration and test cards for the K-D test.

settings to diagnose physiological dysfunction after concussion [7]. The BCTT can quantify clinical severity of concussion and can be used to prescribe safe aerobic exercise treatments for recovery [7].

The K-D test is a rapid number naming task originally developed in 1976 to evaluate school-aged children with reading disabilities [8]. The K-D test evaluates saccadic eye movements, processing speed, and visual tracking [9]. Cortical structures, including the frontal eye fields, supplementary eye fields, dorsolateral prefrontal cortex, parietal eye fields, and brainstem areas are involved in saccade generation [10–13]. The incidence of oculomotor abnormalities after SRC is high and presence of these deficits is associated with prolonged recovery times [14]. Hence, the K-D test is becoming a complement to other sideline concussion assessment tools [15,16] because of ease of use and portability [17]. Furthermore, the test can be effectively administered by non-medically trained parents and coaches [18].

Designed for sideline usage, post-exercise assessment of performance is an important aspect of the K-D test. Mild to moderate exertion has been shown to have immediate improvement on cognitive speed, so a single bout of activity could significantly affect K-D test scores [19]. Leong et al. [20] showed a significant improvement in K-D test scores after a 2.5 h exercise session. Galetta et al. [21] showed a mean 2.8 s ($p = .03$) second improvement on average on the K-D test score in basketball players before and after 2 h of intense activity, Galetta et al. [17] observed a mean improvement of 1.2 s ($p = .0001$) in boxers and MMA fighters before and after a fight, and Dhawan et al. [22] showed a 1.8 s ($p < .05$) improvement on the KD Test before and after a high school hockey game.

Relatively few studies have evaluated the K-D test in an outpatient clinical setting. Subotic et al. [23] assessed the diagnostic value of the K-D test in a cross-sectional comparison among acutely concussed patients, persistent post-concussive syndrome (PPCS) patients, and in healthy controls. PPCS patients took longer than healthy controls to complete the K-D test but participants with PPCS did not differ from acutely concussed patients and no differences were found between acutely concussed patients and controls. The authors concluded that the K-D test has more assessment value immediately following a concussive hit on the sideline and was most useful when athletes had pre-injury baseline scores [23]. Unfortunately, baseline K-D test scores are not available for every athlete. The purpose of this study was to examine the diagnostic and prognostic value of the K-D test without individual baseline scores in a clinic setting and to see the effect of the BCTT on K-D test values. We hypothesize that K-D test performance would be significantly different between acutely concussed and healthy controls on the initial visit, between those who recovered and those who did not, and would be affected by exercise on BCTT.

2. Methods

2.1. Study participants

Participants for this study were obtained from a larger study investigating the role of exercise in concussion recovery (clinicaltrials.gov NCT02710123). Acutely concussed (AC) participants were recruited following a clinical visit at a University Concussion Management Clinic.

A diagnosis of acute concussion was made during the initial clinic visit (Visit 1) by a physician based on history, a concussion symptom checklist, a physical examination, and demonstrated exercise intolerance [24,25]. Inclusion criteria included individuals aged 13–18 years with physician-diagnosed SRC within 10 days of injury. Exclusion criteria were previous exposure to the K-D test, history of learning disorders including ADHD and reading disorders, history of ophthalmic disorders except corrective lens, inability to understand English, and presence of other orthopedic injuries that would affect research interventions. Age-matched controls (MC) were recruited from both in- and out-of-season sports from local adolescent sport teams. Inclusion criteria included participants aged 13–18 years with no history of concussion within the past year. Exclusion criteria were the same as for AC. For analysis, the AC group was further divided according to duration of recovery. The Institutional Review Board (IRB) at the University at Buffalo approved all study protocols. Informed consent and/or age appropriate assent was obtained from each participant.

2.2. Demographic & previous medical history questionnaire

All participants completed a questionnaire regarding their previous concussion history and general health. Demographic information, including student status and athletic involvement, was also obtained.

2.3. King-Devick (K-D) test

The K-D test is an assessment tool involving a series of rapid number naming tasks [17,21,25] that take < 2 min to administer [26]. The participant reads aloud a sequence of single digit numbers from left to right. The paper version of the K-D test was used for this study. The K-D test includes one demonstration card and three visually distinct test cards of increasing difficulty (Fig. 1). Card 3 represents the most difficult card with high levels of visual complexity. Standardized instructions were given to read the single digit numbers from left to right as quickly as possible without errors. The time to complete each individual card and number of errors were recorded. Participants started with the demonstration card (upper left quadrant) to familiarize them with the task. Participants were then asked to read each test card with the same instructions. Number of non-corrected errors, including omissions and misspeaks, was recorded as per the instructions in the K-D test manual [17,27]. The K-D test was completed twice at Visit 1 prior to exercise, with the faster of the two trials being recorded as the baseline time. This was performed pre-exercise on Visit 1 and once at all subsequent time points.

2.4. Eye movement assessment

The physician-performed physical examination included orthostatic vital signs, cranial nerve function, cervical motion, motor coordination, and oculomotor function [28]. For this study, only the eye movement data for smooth pursuits and repetitive saccades were used because they represent eye movements assumed to be tested during the K-D test. For smooth pursuits, the patient was asked to visually track an object moving slowly in the horizontal direction (20°/s) with the head stationary. Target movement was limited to 30° from neutral to avoid eliciting end-gaze nystagmus. Abnormal eye movement included saccadic (or jerking) eye motion, corrective (catch-up or back-up) saccades, or loss of visual fixation. For repetitive saccades, the physician held both index fingers three feet apart at half an arm length's distance from the patient. The patient was instructed to move the eyes from one finger to the other in rapid succession in the horizontal visual plane thirty times. Abnormal responses include delayed initiation of eye movement, slow velocity, or inaccurate movements such as over/undershooting with > 1 re-fixation saccade, or symptom provocation of increased headache or dizziness.

2.5. Buffalo concussion treadmill test (BCTT)

The BCTT is a graded exercise test that can diagnose physiological dysfunction after concussion and has demonstrated prognostic value [7]. The test is a modification of the cardiac Balke protocol. Patients begin with a speed of 3.2–3.6 mph (depending on height) at 0% incline. At the first minute and every minute thereafter, the incline is increased by 1°. Speed remains constant until a maximum incline is reached or the patient cannot continue. Rating of perceived exertion (RPE, Borg scale) [29], symptoms (10-point Visual Analog Scale [VAS]), heart rate (Polar HR monitor, Model #FIT N2965; Kempele, Finland) are recorded every minute. The test is stopped when there is symptom exacerbation (≥ 3-point increase from the pre-treadmill VAS value) or exhaustion (RPE of 18 or more). The test is also stopped if there are any visible signs of distress. The treadmill test has a high degree of interrater reliability (95%) for distinguishing symptom exacerbation [30].

2.6. Study design

The initial research visit (Visit 1) occurred immediately after the first clinic visit where participants completed the demographic and history questionnaire. The K-D test and the Post- Concussion Symptom Scale (PCSS) from the Sport Concussion Assessment Tool (SCAT)-3 were administered once before and once after each BCTT trial [31]. SCAT-3 was the current version at the time the study was conducted. Symptoms, RPE, heart rate, and time spent on the treadmill were recorded. The post-treadmill K-D test was administered immediately following a 2-minute cool-down. AC followed up with the physician and performed the BCTT after one week. Recovery was defined a-priori as a normal level of symptoms, a normal physical examination, and normal exercise tolerance. Medical records were searched to find the date of recovery. Research visits immediately followed clinic visits. At study completion, AC was divided into two groups based on recovery time. The fast recovery group (FRG) included AC participants recovered by the second clinic visit. The slow recovery group (SRG) included AC participants not recovered by the second clinic visit. MC completed 2 trials of the BCTT one week apart. At the initial visit, participants completed the demographic and history questionnaire. Controls were given a physical exam prior to each BCTT trial. The K-D test and the PCSS from the SCAT 3 were administered before and after each BCTT following the same procedures as in the AC group.

2.7. Statistical analysis

ANOVA was used to assess group-wise differences in age, height, weight, days to initial visit, recovery time, and K-D test times (single card and cumulative). Chi-square was used to assess group-wise differences in sex, athletic status, history of concussions, and vision tests. Bonferroni correction was performed on single card K-D test times and a p-value of 0.016 (0.05/3) was considered significant. MC Visit 1 and Visit 2 pre-exercise scores were compared to assess the learning effect. Visit 1 pre-exercise scores were compared between MC and AC to assess diagnostic ability. Pre- and post-exercise score were compared for the effect of exercise on test performance and compared between groups. All data were analyzed using SPSS Version 20 (IBM Corporation USA).

3. Results

3.1. Demographics

Demographic data for MC and AC are shown in Table 1. The mean recovery time for AC was 16.6 ± 12.0 days from date of injury. The mean pre-treadmill PCSS score for MC was 0.69 ± 1.0 and for AC was 30.79 ± 18.1 ($p < .001$). Demographic data for FRG and SRG are shown in Table 2. FRG was slightly older than SRG and had a history of more concussions but this difference was not significant. Mean pre-

Table 1
Demographic and oculomotor information for matched controls (MC) and acutely concussed (AC) participants.

	MC (n = 30)	AC (n = 46)	P-value*
Age (years)	15.8 ± 1.4	15.4 ± 2.1	0.287
Height (centimeters)	172.1 ± 10.5	168.4 ± 10.3	0.131
Weight (kilograms)	65.1 ± 11.1	63.0 ± 12.4	0.466
Sex			0.138
Male	22 (73%)	26 (56.5%)	
Female	8 (27%)	20 (43.5%)	
Athlete	29 (97%)	44(95.7%)	0.770
History of concussion	7 (23%)	20 (43.5%)	0.281
Post-Concussion Symptom Scale (max = 132)	0.69 ± 1.0	30.79 ± 18.1	< **0.001**
Days from injury	–	5.0 ± 2.4	–
Recovery time (days)	–	16.6 ± 12.0	–
Abnormal Smooth Pursuits	1 (3%)	8 (17%)	0.064
Abnormal Repetitive Saccades	1 (3%)	17 (37%)	**0.001**

"Bold" indicates significant p-values.
* P-values ≤ .05 considered significant.

Table 2
Demographic information for fast recovery group (FRG) and slow recovery group (SRG).

	FRG (n = 23)	SRG (n = 23)	P-value*
Age (years)	16.0 ± 1.8	14.8 ± 2.1	0.051
Height (centimeters)	171.6 ± 9.9	165.2 ± 9.9	**0.034**
Weight (kilograms)	66.4 ± 8.7	59.5 ± 14.8	0.064
Sex			1.00
Male	13 (57%)	13 (57%)	
Female	10 (43%)	10 (43%)	
Athlete	22 (96%)	23 (100%)	0.312
History of concussion	7 (30%)	13(57%)	0.137
Post-Concussion Symptom Scale (max = 132)	24.95 ± 13.6	37.20 ± 20.4	**0.027**
Days from injury	4.9 ± 2.6	5.0 ± 2.2	0.853
Recovery time (days)	9.4 ± 3.4	23.8 ± 13.1	< **0.001**
Abnormal Smooth Pursuits	3 (13%)	5 (22%)	0.437
Abnormal Repetitive Saccades	7 (30%)	10 (43%)	0.359

"Bold" indicates significant p-values.
* P-values ≤ .05 considered significant.

exercise PCSS scores were significantly different between FRG and SRG (24.95 ± 13.6 vs. 37.20 ± 20.4, p = .027).

3.2. K-D test performance

The mean K-D test times for MC and AC at Visit 1 are presented in Table 3. The pre- and post-treadmill K-D test times for AC were significantly higher (worse) compared with MC at Visit 1 except for pre-exercise Card 1, which was not significant after Bonferroni correction.

Table 3
Visit 1 K-D test performance, mean time in seconds.

	MC (n = 30)	AC (n = 46)	P-value*
Visit 1 Pre-test			
Card 1	15.1 ± 3.1	17.1 ± 4.3	0.038
Card 2	14.9 ± 2.8	17.6 ± 4.3	**0.002**
Card 3	16.0 ± 3.7	19.0 ± 5.0	**0.007**
Total	46.1 ± 9.2	53.7 ± 13.0	**0.007****
Visit 1 Post-test			
Card 1	14.3 ± 2.7	16.5 ± 5.0	**0.013**
Card 2	14.0 ± 3.2	17.1 ± 4.7	**0.001**
Card 3	14.7 ± 3.0	18.1 ± 4.8	< **0.001**
Total	43.1 ± 8.5	51.6 ± 14.0	**0.001****

"Bold" indicates significant p-values.
* P-values ≤ .016 considered significant.
** P-values ≤ .05 considered significant.

Statistically significant differences in mean total K-D test time were found between the MC and SRG for Visit 1 pretest (46.1 ± 9.2 vs 57.0 ± 15.0, p = .002) and Visit 2 pretest (42.9 ± 9.1 vs 50.0 ± 8.6, p = .006). FRG and SRG times differed significantly only on Card 3 on the Visit 1 pre-exercise test (17.5 ± 3.1 vs 20.6 ± 6.1, p = .039). No statistically significant differences were found between MC and FRG at Visit 1 pretest (46.1 ± 9.2 vs 50.4 ± 10.0, p = .111) and Visit 2 pretest (42.9 ± 9.1 vs 42.9 ± 7.5, p = .996). Comparison of pre- and post-treadmill K-D test times for MC, FRG, and SRG are presented in Table 4. Both MC and FRG showed an improvement in K-D test times after the treadmill test at Visit 1 and Visit 2. MC improved by 3.0 s (p < .001) at Visit 1 and by 2.3 s (p < .001) at Visit 2. FRG improved by 3.1 s (p = .002) at Visit 1 and 1.5 s (p = .016) at Visit 2. SRG, however, did not significantly improve post-treadmill K-D test times at Visit 1 (p = .478) or at Visit 2 (p = .772).

3.3. Vision assessment

Abnormal vision assessment findings from the Visit 1 physical examination are summarized in Tables 1 and 2. AC had significantly higher rates of abnormal repetitive saccades but not smooth pursuits during Visit 1 when compared with MC. There were no significant differences in abnormal smooth pursuits or repetitive saccades when comparing FRG and SRG. Mean K-D test times and vision assessment findings are presented in Table 5. AC participants with abnormal smooth pursuits did not differ in K-D test times on Visit 1, but AC participants with abnormal repetitive saccades had significantly longer times for Card 3 (p = .012) and for total K-D time (p = .049).

4. Discussion

This study showed that acutely concussed adolescents who did not improve their post-treadmill test exercise K-D test times took significantly longer to recover from SRC when compared with adolescents whose post-exercise times improved. The data suggest that lack of improvement in K-D test performance after an exercise test is prognostic for delayed recovery from SRC, which is a clinically useful result. The sensitivity of the K-D test for detecting SRC has been validated in multiple studies across various sports including rugby, mixed martial arts, boxing, football, and hockey, and in multiple age cohorts including youth, high school, and collegiate athletes [15–18,20–21,28,32–37]. Our study confirms that K-D test performance distinguished the concussed cohort from the non-concussed cohort, even without baseline K-D measures. Such an effect has been well demonstrated in adolescent athletes tested on the sideline but if they had a baseline measurement [28,32,33]. Interestingly, when our concussed cohort was subdivided into those who recovered fast (FRG) versus those who did not (SRG), only group SRG was distinguishable from the healthy controls. SRG was slightly younger and had a history of more concussions than FRG, which has been associated with longer recovery and worse K-D test times, but these differences were not significant.

Other researchers have found no difference in K-D performance between acutely concussed patients and healthy controls in the clinic setting [23]. Our results may differ because Subotic et al. [23] studied much older non-athlete participants (concussed and controls had a mean age of 43 and 37 years, respectively) while we studied adolescent athletes after SRC. Additionally, SRC may be a different clinical entity than non-SRC because SRC patients recover faster, have fewer total symptoms, have lower severity scores, and have fewer clinic visits [38]. Thus the diagnostic value of the K-D test in a clinical setting may vary with respect to age and mechanism of injury. Moran et al. [39] found that healthy athletes aged 8–11 had slower KD test times and more errors than individuals aged 12–14 years (p < .001). Weise et al. [40] showed that KD scores improved with age in junior high and high school athletes and that they were highly variable within these age groups. Alsalaheen et al. [41] showed that 16–18 year old athletes

Table 4
Comparison of pre- and post-treadmill K-D test times at Visit 1 and Visit 2.

	Visit 1			Visit 2		
	Pre-test	Post-test	P-value*	Pre-test	Post-test	P-value*
MC						
Card 1	15.1 ± 3.1	14.3 ± 2.7	**0.006**	14.2 ± 3.2	13.2 ± 2.6	< **0.001**
Card 2	14.9 ± 2.8	14.0 ± 3.2	**0.006**	13.9 ± 2.8	13.3 ± 3.2	0.036
Card 3	16.0 ± 3.7	14.7 ± 3.0	< **0.001**	14.7 ± 3.5	14.2 ± 3.6	0.057
Total	46.1 ± 9.2	43.1 ± 8.5	< **0.001****	42.9 ± 9.1	40.6 ± 9.2	< **0.001****
FRG						
Card 1	16.2 ± 3.7	15.2 ± 3.2	**0.015**	13.9 ± 2.5	13.3 ± 2.3	0.058
Card 2	16.7 ± 3.8	15.6 ± 3.3	0.035	14.0 ± 2.5	13.8 ± 2.4	0.569
Card 3	17.5 ± 3.1	16.6 ± 3.8	0.036	15.0 ± 2.9	14.3 ± 2.7	0.026
Total	50.4 ± 10.0	47.3 ± 9.8	**0.002****	42.9 ± 7.5	41.4 ± 6.8	**0.016****
SRG						
Card 1	17.9 ± 4.8	17.9 ± 6.0	0.996	16.2 ± 2.9	16.2 ± 3.7	0.951
Card 2	18.5 ± 4.6	18.5 ± 5.6	0.998	16.4 ± 3.1	16.1 ± 3.9	0.411
Card 3	20.6 ± 6.1	19.6 ± 5.2	0.117	17.5 ± 3.1	17.6 ± 4.1	0.766
Total	57.0 ± 15.0	56.0 ± 16.3	0.478**	50.0 ± 8.6	49.7 ± 11.3	0.772**

"Bold" indicates significant p-values.
* P-values ≤ .016 considered significant.
** P-values ≤ .05 considered significant.

Table 5
Vision assessment and mean K-D test times (in seconds) among AC at Visit 1.

	AC with normal repetitive saccades (n = 29)	AC with abnormal repetitive saccades (n = 17)	P-value
Card 1	16.3 ± 3.3	18.3 ± 5.6	0.147
Card 2	16.8 ± 3.8	18.9 ± 4.8	0.110
Card 3	17.6 ± 3.5	21.4 ± 6.3	**0.012***
Cumulative	50.8 ± 10.2	58.6 ± 16.0	**0.049****
	AC with normal smooth pursuits (n = 38)	AC with abnormal smooth pursuits (n = 8)	
Card 1	16.9 ± 4.6	17.6 ± 3.2	0.715
Card 2	17.4 ± 4.4	18.6 ± 3.9	0.459
Card 3	18.9 ± 5.0	19.4 ± 5.3	0.811
Cumulative	53.3 ± 13.5	55.6 ± 11.3	0.648

"Bold" indicates significant p-values.
* P-values ≤ .016 (0.05/3) considered significant.
** P-values ≤ .05 considered significant.

achieved faster KD times than 13–15 year old athletes whereas Anderson et al. [42] and Benedict et al. [43] showed that KD test scores become worse with age in adults (mean age 40.5 and 36 years, respectively). These studies suggest that KD test scores, eye tracking, and/or visual processing improve with age, peak in the late adolescent and young adult phase, and then decline. On the other hand, McIntyre at al [44]. and Oberlander [45] found no correlation between age and KD test scores. Future studies should explore the role of age and concussion etiology in the diagnostic ability of the K-D test and clinicians should consider this information when administering the K-D test in the outpatient setting.

The lack of a learning effect on K-D test performance after a standardized exercise tolerance test (the BCTT) identified patients that took significantly longer to recover from SRC. This is an interesting and potential useful addition to concussion assessment in the outpatient clinic setting, particularly in those doing exertional testing to manage concussed adolescents. Exercise typically has a beneficial effect on K-D test performance in non-concussed athletes. King et al. [46] reported a significant improvement in KD test time (50 vs. 45 s, $p < .001$) between the first and second test after a 10 min interval in amateur rugby players, consistent with a learning effect. Oberlander et al. [45] found acceptable re-test reliability of the KD test (ICC = 0.81, 95% CI 0.73–0.87) because there was a 4.3 ± 0.5 s ($p < .001$) improvement between first and second test and a 6.9 ± 0.5 s ($p < .001$) improvement between first and third test. Our data show that both MC and FRG improved K-D test performance following the BCTT at the initial visit: MC by 3.0 s ($p < .001$) and FRG by 3.1 s ($p = .002$). SRG, however, did not improve K-D test performance after the Visit 1treadmill test. Similar results were found for Visit 2, with both MC and FRG continuing to improve post-treadmill cumulative K-D test times while SRG did not. Therefore, K-D test performance following the BCTT was able to distinguish AC participants who recovered within a week of their initial visit (mean 9.4 days post-injury) from AC who took longer to recover (mean 23.8 days post-injury). Thus, lack of improvement in K-D test performance after a standardized exercise test within a week of SRC could help clinicians identify adolescent patients at risk for prolonged recovery from SRC, which is important for school and athletic team planning purposes.

The reason for the lack of improvement in K-D test times in those slow to recover is unclear. It is speculated that the SRG group had exacerbation of symptoms following exercise that interfered with reading the K-D test cards. Human experimental data indicate that excessive activity after concussion can increase symptoms and worsen neurocognitive performance [46]. A study of neurocognitive performance following SRC showed that concussion can be associated with a lack of expected practice effect rather than a decline per se, particularly on traditional measures of speed and complex attention [47]. Another possibility for the lack of improvement in post-exercise K-D test times is that SRG experienced a more severe initial injury compared to FRG. Pre-treadmill symptom evaluation at Visit 1 revealed that SRG had significantly more symptoms than FRG, indicating a difference in initial concussion severity.

Lastly, vision involves the relay of information through a number of dispersed brain structures that include cortical and brainstem areas [10–13]. The wide distribution and location of neural networks involved make the pathways susceptible to damage during concussion. The vision assessments used in the present study test two separate pathways that may be injured together or separately. On average, participants with abnormal repetitive saccades took 8 s longer to complete the K-D test than participants with normal repetitive saccades. It was perhaps unsurprising to find an association of abnormal repetitive saccades with longer K-D test times because saccadic testing assesses quick fixation and re-fixation moves between two targets. We did not find a relation between abnormal smooth pursuits and K-D test scores, perhaps because the saccades in a smooth pursuit task are corrective, not defective [48]. These results suggest that the K-D test may also be a useful clinical tool for assessing abnormal repetitive saccades in adolescents.

The current study has several limitations. Although we were as uniform as possible with our instructions, the K-D test may be affected by patient motivation. Researchers were not blinded to AC and MC groups so there is a possibility of bias. All participants were tested using the paper version of the K-D test because the study began before the computer version of the test was released. There are no documented limitations for using the paper version, however, the results of this study may not generalize to the computerized K-D test. This study had a higher percentage of males in the MC cohort compared with the AC cohort but this difference was not statistically significant. Further assessments should include sex-matched controls to eliminate sex as a confounder. The BCTT is a graded treadmill test and involves limited rotational head movement. Some symptoms of concussion, specifically vestibular and oculomotor symptoms, may be triggered by rotational head movement in sport activities that should be considered in the future. Lastly, the study focused on a specific cohort of adolescent athletes suffering from SRC. Therefore, results may not easily generalize to other ages, non-athletes, non-SRC patients, or patients with learning disorders. Clinicians should keep this in mind when administering the K-D test within a clinical setting.

5. Conclusion

Our study shows that a lack of improvement in K-D test performance immediately after a standardized exercise test (the BCTT) performed within a week of SRC was associated with significantly prolonged recovery in adolescent athletes when compared with those who demonstrated the typical post-exercise improvement in performance. This could help some clinicians give their athletic patients important prognostic information that has relevance for school and athletic team planning. We also confirmed that the K-D test is useful in identifying acutely concussed adolescents from healthy controls, even without baseline values. This may add objective data to the clinician's arsenal for helping to determine physiological recovery from SRC.

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Conflict of interest

The authors declare no conflict of interest.

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