Sideline Assessment Tools for the Evaluation of Concussion in Athletes: A Review

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Sports-related concussions, which have become more prevalent in the past decade, are an extremely common phenomenon in organized athletics and create a substantial economic burden on the health care system. Furthermore, they can have devastating impacts on the athletic careers and long-term health of athletes. However, concussion evaluation remains a controversy with respect to diagnosis, management, and return-to-play guidelines for sports-related concussions. This is especially true of the immediate evaluation of sports-related concussion on the sidelines, where decisions must be made quickly and effectively with limited diagnostic resources. Considerable effort has been directed toward developing reliable and valid sidelines assessment modalities for concussion evaluation with a goal of accurately determining whether an athlete requires rapid removal from or is able to return to competition. This paper discusses the role of the concussion specialist on the sidelines during athletic competition and examines the current tools and resources available for the sidelines assessment of concussion. Additionally, new technologies, including electronic applications for Smartphones and tablets, as well as future directions in sidelines assessment of concussion are examined.

KEY WORDS: Concussion, Sideline assessment, Return-to-play, Mobile applications

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According to the Centers for Disease Control and Prevention, at least 1.7 million people sustain a traumatic brain injury (TBI) annually in the United States, creating an economic burden estimated to be greater than $60 billion. Concussions, or mild TBI, account for 75% of all TBIs.[1] Sports-related concussions remain a major contributor to this statistic, resulting in acute consequences and an increased risk of late sequelae, including major depression and long-term neurological and cognitive impairment later in life. In modern sports medicine, sports-related concussion has emerged as a major area of concern, and an emphasis has been placed on increasing awareness, prevention, and early detection. The incidence of sports-related concussion has increased over the past decade, and the actual incidence is likely higher than documented due to the tendency of athletes to underreport their symptoms.[2,3]

ABBREVIATIONS: BESS, Balance Error Scoring System; **CTE,** chronic traumatic encephalopathy; **ETA,** Eye-Trac Advance; **GCS,** Glasgow Coma Scale; **ImPACT,** Immediate Post-Concussion and Cognitive Testing; **K-D,** King-Devick; **PCSS,** Post-Concussion Symptom Scale; **SAC,** Standardized Assessment of Concussion; **SCAT,** Sports Concussion Assessment Tool; **SOT,** Sensory Organization Test; **TBI,** traumatic brain injury

Concussion evaluation remains a controversy with respect to diagnosis, management, and return-to-play guidelines for sports-related concussions. This is especially true of the immediate evaluation of downed athletes on the sideline, including assessment for concussion as well as evaluation for cervical spine injury, which has been added to the recently created Sports Concussion Assessment Tool (SCAT)-3 test. Trained concussion specialists must be proficient in the immediate evaluation and management of head trauma and cervical spine injury, and important decisions must be made quickly and effectively with limited diagnostic resources. Considerable effort has been directed toward developing reliable and valid sidelines assessment modalities for concussion evaluation with a goal of accurately determining whether an athlete requires rapid removal from or is able to return to competition.

The current standard of care mandates that once an athlete is diagnosed with a concussion on the sidelines, he or she is immediately removed from play and monitored with serial neurological assessments. The athlete is then subjected to

a more in-depth battery of tests in a delayed fashion (eg, 24-72 hours after the injury).[2,4] In many sports leagues, athletes are required to complete this same battery of tests before engaging in competition to have a baseline for comparison. These concussion evaluation tools, with few exceptions, can then be used to track an athlete's recovery and aid in determining when an athlete may safely return to competition. Current evidence suggests that athletes who prematurely return to play after a concussion are at an increased risk of additional concussions as a result of impaired vestibular function and mental processing.[2,4-6] Further, athletes who sustain repeated concussions experience more prolonged symptoms and may be at an increased risk of psychiatric illnesses, dementia, and chronic traumatic encephalopathy (CTE).[2,6-10] Originally observed in boxers and termed dementia pugilistica, CTE is a neurodegenerative condition that is associated with repetitive head trauma leading to irreversible behavioral, cognitive, and motor impairment. Current evidence suggests that even mild repetitive head trauma associated with a wide range of sports, many of which are less violent than boxing, is sufficient to cause neurodegenerative changes and symptoms similar to those seen in CTE.[11-14] The rare but often fatal second impact syndrome must also be considered when evaluating athletes who sustain multiple concussions. This syndrome, described by Cantu[15] in 1998, occurs when an athlete sustains a second concussion before resolution of the symptoms from the initial concussion, leading to severe cerebral edema, often resulting in severe disability or death. This review summarizes the current most widely used sideline assessment tools for concussion evaluation and tools that are being developed for future evaluation.

ROLE OF THE CONCUSSION SPECIALIST ON THE SIDELINES

Concussion evaluation and management require a multidisciplinary team of medical professionals including physicians, physical therapists, and athletic trainers.[16] Each of these specialists possesses a skill set unique to his or her field of practice that contributes to concussion evaluation and management in an equally important fashion. Physicians who serve the role of trained concussion specialists are representative of a diverse group of medical training backgrounds including neurosurgeons, sports medicine physicians, neurologists, and physical medicine and rehabilitation physicians, to name a few. From a neurosurgical perspective, the neurosurgeon is specifically trained in the diagnosis and management of trauma to the central nervous system and can provide valuable expertise in concussion management. Major injuries involving the central nervous system, such as spinal cord injury and intracranial hematomas, are rare neurological emergencies that can occur in athletic competition and require the attention of neurosurgeons who possess the highly specialized set of skills unique to the nervous system. Early diagnosis followed by early intervention is the mainstay in the management of such serious neurological conditions.

Fortunately, few sports-related injuries to the central nervous system are life-threatening, and routine evaluation with standard imaging techniques such as computed tomography (CT) and magnetic resonance imaging (MRI) is generally not recommended unless concern is raised on serial neurological examination.[2,16-18] Concussion is a common injury across all sports, although it is especially prevalent in contact sports. Paramount to the management of sports-related concussions is early diagnosis, which is facilitated by the on-field presence of at least 1 medical professional skilled in concussion management. The sidelines assessment of concussion in amateur sports is most frequently performed by an athletic trainer. Diagnosis and management of concussion remain challenging because there is significant disagreement and uncertainty regarding the definitive diagnosis of concussions and which guidelines should be used to make return-to-play decisions.[2,16-19] Imaging modalities (ie, CT, MRI) are not readily available on the sidelines, and conventional neuroimaging is typically normal. Thus, the diagnosis of a concussion is made clinically. A multitude of clinical tests are available as adjuncts to the physical exam to assess cognitive and neurological function to objectively diagnose a concussion. These tests also serve as objective measures of recovery after concussion and provide the treating physician with objective data when considering allowing an athlete to return to play.

On the sidelines, in the locker room, and in the office during the postconcussion period, trained sideline concussion specialists are often charged with making difficult decisions regarding when or whether it is appropriate for an individual to return to play. There are potential long-reaching ramifications regarding return-to-play decisions because of the multiple complex social, emotional, and economic aspects of concussions on both individual and global levels. Demand remains high for accurate and specific diagnostic tools. False-positive and false-negative concussion test results in competitive athletics can both have devastating consequences.

Essentially, the primary role of the concussion specialist on the sidelines is to perform appropriate and immediate assessment and triage of potentially concussed athletes. To accomplish this, the concussion specialist relies on 4 key principles that form the foundation of all modern-era concussion evaluations used by organized athletics, from the professional ranks to youth and recreational leagues. These 4 principles are symptom/history evaluation, balance assessment, cognitive/memory evaluation, and the neurological examination. These principles are illustrated in the evaluations described in the following.

CURRENT PRACTICES FOR SIDELINES ASSESSMENT OF CONCUSSION

According to the 4th International Conference on Concussion in Sport in Zurich (2012), concussion signs and symptoms can be divided into 3 categories.[17] Somatic signs/symptoms are more objective neurological findings often associated with certain anatomic neurological structures. These include tinnitus, numbness, motor weakness, nausea/vomiting, imbalance, visual disturbances, headaches, sleep disturbance, etc. Cognitive signs/symptoms are less

focal and more global and include memory impairment, feelings of "fogginess," and poor concentration. Neuropsychiatric signs/symptoms affect the athlete's personality and include irritability, depressed mood, anxiety, and excessive fatigue.[19] Many concussion evaluations available to sidelines concussion specialists involve testing for these signs/symptoms. It is critical that concussion assessment takes place immediately on the sidelines after injury to screen athletes with suspected concussions. However, further testing in a more controlled, quiet locker room setting after sidelines assessment is also necessary to make an accurate diagnosis. Certain signs/symptoms may present earlier than others, and the full spectrum of concussion symptoms may present in a delayed fashion over days after the injury. Thus, the absence of various concussion symptoms in the immediate postconcussive period does not necessarily exclude a diagnosis of concussion, which illustrates the importance of the sideline specialist on the sidelines, in the locker room, and in the office.

POST-CONCUSSION SYMPTOM SCALE

The Post-Concussion Symptom Scale (PCSS) exists in several variations and has been integrated into many standard comprehensive assessment tools. It is a questionnaire comprising 21 items. However, the Immediate Post-Concussion and Cognitive Testing (ImPACT) form of the PCSS contains 22 items and has become widely used.[20,21] Each item represents a common sign or symptom associated with concussions and requires the patient to rate the severity of each symptom on a 7-point Likert scale from 0 to 6 (0 being asymptomatic and 6 being severely symptomatic).[21,22] Sample items include fatigue, sadness, difficulty with concentration, and headache. The patient is also required to document the amount of time elapsed between the injury and the examination so that the same questionnaire might be used to track the progress of recovery. Given that concussion symptoms are different in every patient and that no symptom is pathognomonic of concussion, symptoms-based tests have pitfalls. The PCSS questionnaire contains many items that may be present at baseline and/or associated with mental disorders and other comorbidities. As with any clinic test for concussions, the PCSS is most accurate when a baseline test is completed before the injury. The Concussion Symptom Inventory is similar to the PCSS in that it assesses the same symptoms using a 7-point Likert scale. However, it is further revised and includes only 12 questions. It is administered immediately after the injury and again at 1, 3, and 5 days post-injury. It also provides a free-text item to document additional symptoms not assessed by the standard questionnaire.[23]

The Pittsburgh Steelers football organization of the National Football League (NFL) developed its own postconcussion scale in the late 1980s and early 1990s that has become a cornerstone of its algorithm for evaluating and managing players who sustain concussions. It was the first scale to use the 7-point Likert scale, and it has been adopted by many professional teams across all sports and is prominent in high-school and college athletics as well.[21,22,24] The Pittsburgh Steelers PCSS is a streamlined version of the standard PCSS containing 17 items. In addition to the 7-point Likert scale, the test classifies symptoms ranging in severity from asymptomatic to severe. Should a player demonstrate signs/symptoms of a concussion, he is subjected to the PCSS and his score is documented. He then repeats the test several days later to assess for resolution of symptoms. If symptoms fail to resolve, further testing is warranted.

MADDOCKS QUESTIONS

Maddocks Questions, which form a key component of the SCAT test and are used by the International Olympic Committee and the NFL Sideline Concussion Assessment Tool (among others), are a well-established means of assessing short-term memory and cognitive function after concussion in athletes on the sidelines.[25,26] A major reason for the success of Maddocks Questions is that they are based on the athletic event in progress and universal in that they can be easily tailored to any type of athletic event. They consist of 5 questions: (1) Where are we? (2) What quarter is it right now? (3) Who scored last in the game/practice? (4) Who did we play in the last game? (5) Did we win the last game?

The athlete receives 1 point for each correct answer and no points for an incorrect or incoherent answer for a maximum of 5 total points. Although simple, the Maddocks Questions provide the examiner with important data regarding short- and intermediate-term memory, which can be significantly affected by concussion.

STANDARDIZED ASSESSMENT OF CONCUSSION

The Standardized Assessment of Concussion (SAC) is a comprehensive concussion assessment tool incorporated into the SCAT-3 test, and most of the formal concussion assessment protocols used it organized sports. The SAC is a useful tool for clinicians on the sidelines because it evaluates the immediate effects of concussion on cognition and tracks resolution of these symptoms in the immediate postconcussive period.[27] It is very similar to the Mini Mental Status Examination and consists of 3 parts: orientation, immediate memory. and concentration. Orientation (5 points) is tested by asking the athlete 5 simple questions, similar to Maddocks Questions: (1) What month is it? (2) What is the date today? (3) What is the day of the week? (4) What year is it? (5) What time is it right now?

Again, similar to Maddocks Questions, the athlete receives 1 point for each correct answer and no points for an incorrect answer for a maximum of 5 total points. Immediate memory (20 points) is tested by reading a list of 5 words (eg, elbow, apple, carpet, saddle, bubble) and having the athlete repeat that list of words in any order. This is repeated 2 more times for a total of 3 trials. One point is awarded for each item recalled during each trial for a maximum of 15 total points. The athlete is then asked to recall the same 5 items in a delayed fashion after the remainder of the sidelines assessment is completed. Again, 1 point is awarded for each item

recalled, for a maximum of 5 total points. For concentration assessment (5 points), the examiner reads a string of 3 numbers and requires the athlete to repeat them in the reverse order. If the athlete answers correctly, the examiner then reads a string of 4 numbers, then 5e numbers to a maximum of 6 numbers. If the athlete answers incorrectly, a second string of numbers (same length) is read. Two consecutive incorrect answers prompt cessation of concentration testing. One point is awarded for each sequence correct out of 4 for a maximum of 4 total points. Then, the examiner asks the athlete to list the months of the year in reverse order, beginning with December. One point is awarded for a correct sequence. The maximum SAC score is 30 points.

As with many sidelines concussion assessment tools, the SAC is part of the initial concussion evaluation; however, alone, it is not sufficient as a comprehensive concussion evaluation. No set algorithm exists to categorize concussion severity or make return-to-play recommendations based on the SAC score alone. Several studies exist in the literature demonstrating a significant postinjury decrease in SAC scores compared with baseline.[28,29] Barr and McCrea[30] further demonstrated that injured athletes in the immediate postconcussive period experienced an average decrease in their SAC score by 4 points compared with baseline, whereas uninjured control athletes experienced an average increase in their SAC scores by 1 point. Using multiple regression analysis, they found that a 1-point decrease in the baseline SAC score carries a 94% sensitivity and 76% specificity for diagnosing a concussion. Other studies, however, have revealed weaknesses in the psychometric properties of the SAC test on the grounds that the majority of the items are too simple and lack acceptable discrimination. This creates a ceiling effect that limits the ability of the test to accurately evaluate an athlete's true cognitive ability at baseline. These findings suggest that although the SAC test can be useful as a postinjury test, it may be inaccurate as a baseline test, which may compromise the validity of the test itself.[31,32]

BALANCE ERROR SCORING SYSTEM

While intact cognition is essential to athletic performance, balance and postural stability play an equally important role and are also commonly affected by concussion and TBI. The human ability to maintain balance is the result of a complex integrated neural network involving cortical, subcortical and brain stem structures as well as the spinal cord and peripheral nerves. The Balance Error Scoring System (BESS), designed by Guskiewicz[32] at the University of North Carolina in 2001, was developed to assess an athlete's balance after concussion. Many athletic organizations as well as the SCAT-3 test have developed a modified version of the BESS test suitable for sidelines use. Proper BESS testing requires a watch/stopwatch with second-hand capabilities. The BESS test requires the athlete to perform trials of 3 stances lasting 20 seconds each with the eyes closed: the double-leg stance (both feet together), the single-leg stance (nondominant foot), and the tandem stance (nondominant foot behind the dominant foot). A maximum of 10 errors can be made for each trial. If the athlete is unable to perform the trial for at least 5 seconds, all 10 points are deducted for that trial. The types of errors are as follows: (1) hands lifted off the iliac crests; (2) eye opening; (3) step, stumble, and fall; (4) hip greater than 30° of abduction; (5) lifting forefoot/heel; (6) out of testing position for more than 5 seconds.

The number of errors made during each trial determines the BESS score. The maximum score is 30, 10 points for each trial with a point deducted for each error. Similar to the SAC test, the BESS test alone is not sufficient for the comprehensive evaluation of concussion or for making decisions regarding return-to-play. Although no diagnosis or management algorithm exists based on BESS testing alone, previous studies demonstrated that concussed athletes make an average of 17 errors compared with 10 errors for noninjured control athletes.[33] The BESS is most useful as a sidelines assessment tool in the immediate postconcussive period. It has proved to be a very effective means of evaluating athletes for sports-related concussions. In the time course of events during the recovery process, balance typically returns within 3 days post-injury, rendering the BESS test less helpful in tracking an athlete's subacute to long-term recovery.[32]

SPORTS CONCUSSION ASSESSMENT TOOL

The SCAT, now in its third version, is used by a number of professional and international athletic organizations, including the Federation of International Football Associations and the International Olympic Committee, as the standard for concussion assessment in athletes. It incorporates streamlined versions of the assessments mentioned previously into a compact, efficient, and comprehensive concussion evaluation tool. After the 3rd International Conference on Concussion in Sport in 2008, the SCAT-2 became one of the most widely used concussion assessment tools in both professional and amateur athletics. The SCAT-2 test contains comprehensive cognitive and physical evaluations including symptom assessment, the Glasgow Coma Scale (GCS) score (commonly used in the evaluation of trauma patients), Maddocks Questions, the SAC, the BESS, and coordination testing. Further, SCAT-2 provides the athlete with educational information regarding signs/symptoms, return-to-play guidelines, and concussion advice.[34] An abbreviated pocket version of the test also exists for more rapid assessment. The maximum score on the SCAT-2 test is 100 total points. For best results, athletes should complete a preseason baseline SCAT-2 examination for comparison. The NFL SCAT is a modified version of the SCAT-2 test.

Despite being widely used, however, there have been concerns regarding the sensitivity and specificity of the SCAT-2 test. To date, no large-scale studies have been conducted to assess the validity of the test as a concussion assessment tool.[35] As a result, the SCAT-3 test was released in 2013 after the 4th International Conference on Concussion in Sport (Zurich).[17] There are several updates included in the SCAT-3 test to address concerns regarding the sensitivity of the SCAT-2 test. The SCAT-3 test, included as an addendum to a previous article in this series,

contains a pretest section that highlights the indications for seeking emergency care. It states that any athlete with any signs/symptoms of concussion after any blow to the head should be immediately removed from competition and referred to a concussion specialist. The formal assessment begins with information regarding the events surrounding the injury such as loss of consciousness, observed incoordination, confusion, appearance, and visible evidence of face/head trauma. Additionally, the testing order has been rearranged on the SCAT-3 test such that injury severity assessment begins with the GCS score and orientation questions followed by symptom assessment (SCAT-2 begins with symptom assessment followed by GCS scoring and orientation questions). SCAT-3 incorporates an examination of the neck/cervical spine, not previously included in SCAT testing. The SCAT-3 test is recommended for athletes 13 years and older, whereas a newly designed Child SCAT-3 test is recommended for athletes 12 years and younger.[17]

The SCAT-2 is also available as an application for Smartphones and tablets for increased portability and efficiency. However, the SCAT-2 application is in the process of being converted to the SCAT-3 application, which has not yet been released.

FUTURE DIRECTIONS FOR SIDELINES ASSESSMENT OF CONCUSSION

Eye-Trac Advance

Due to the growing concern over concussions and TBI in the military and in athletes, the Department of Defense began funding

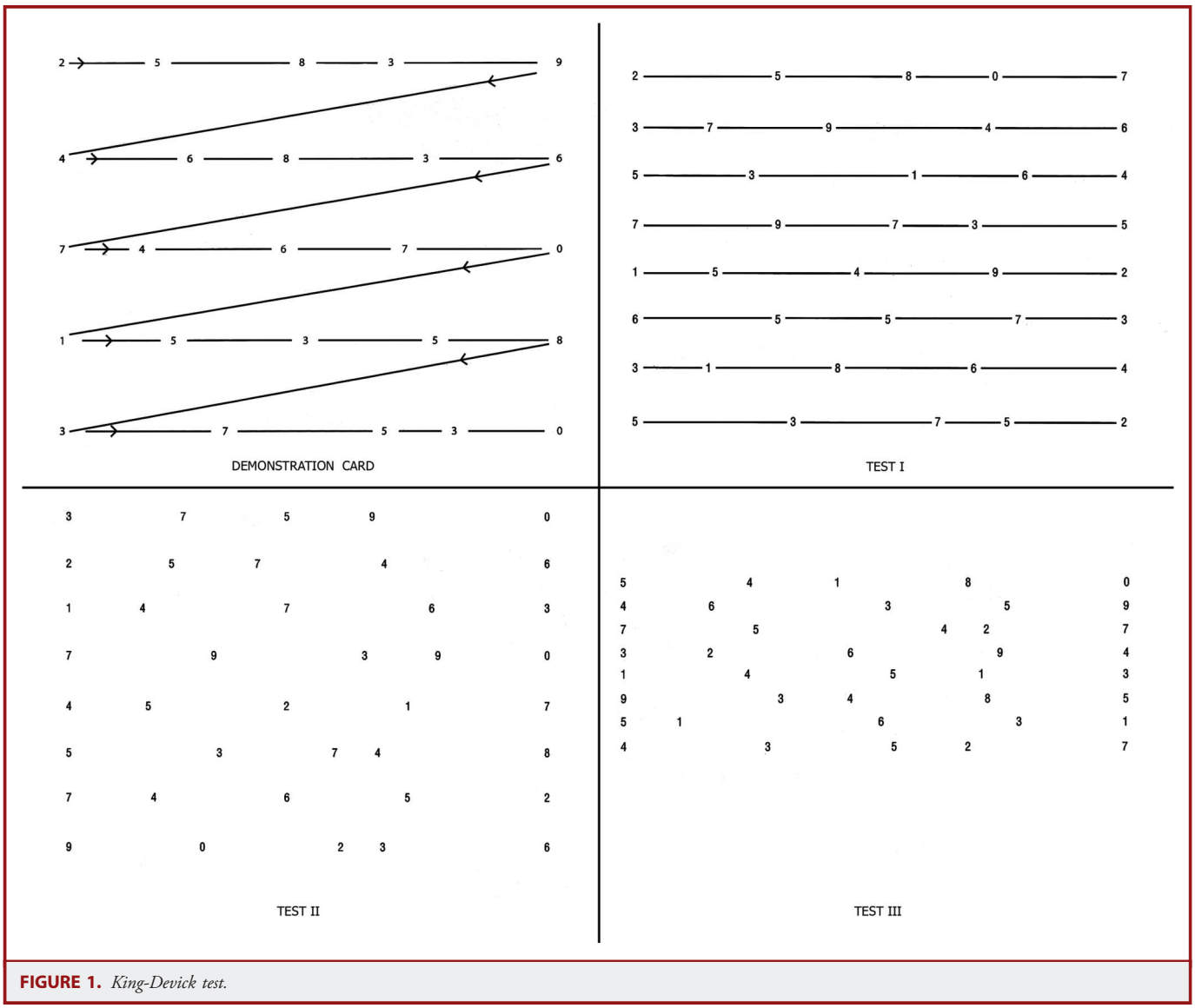

FIGURE 1. *King-Devick test.*

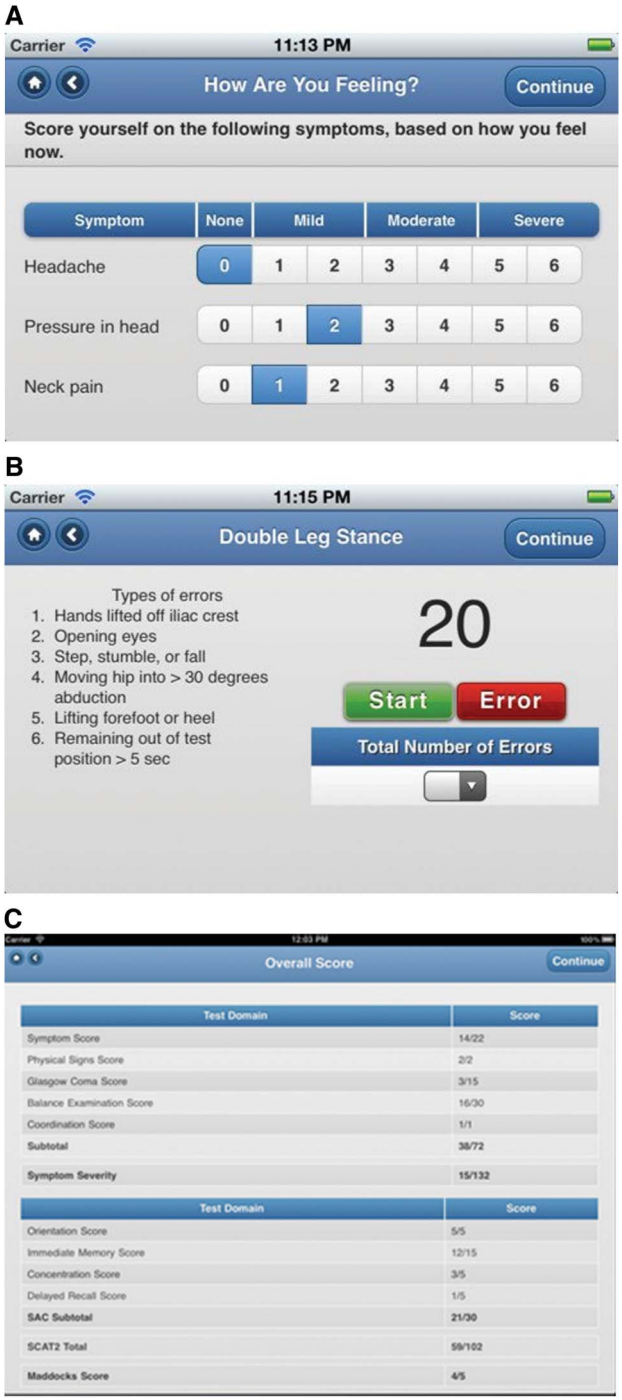

FIGURE 2. **A**, *Sports Concussion Assessment Tool (SCAT)-2 symptom assessment.* **B**, *SCAT-2 balance assessment.* **C**, *SCAT-2 overall score.*

EYE-TRAC Advance (ETA), a study designed to investigate eye-tracking and how it relates to attention and reaction time. Accurate eye-tracking functions as a surrogate for attention and reaction ability. Impaired attention and concentration are 2 common symptoms associated with concussions. The goals of the study are twofold. First, by recruiting members of the military as well as civilians and athletes, ETA seeks to establish a database of normal eye-tracking ability. Second, it examines eye-tracking as a surrogate for neurocognitive impairment, combined with brain MRI, after concussion. Although not available as a sidelines test itself, ETA is relevant to discuss here because it investigates the role of eye-tracking in concussion evaluation. Depending on the results of the study, it could provide useful information regarding the validity of eye-tracking in concussion. Other tests that evaluate eye movement, attention, and concentration, such as the King-Devick (KD) test mentioned in the following, are available in more portable forms suitable for sidelines use.

K-D Test

As a result of increased awareness of the potential short- and long-term devastating effects of concussions on the lives of athletes, athletic teams, organizations, and medical professionals have been charged with developing more efficient and accurate objective diagnostic tools. Although many of the assessment tools described here have been modified to be more practical for sidelines use, they can still be relatively time-consuming. Additionally, although comprehensive, many of the testing items are subjective in nature. The K-D test, which can be administered in less than 1 or 2 minutes, is a rapid number naming test consisting of a demonstration card and 3 successive tests, as demonstrated in Figure 1.[17,36]

The athlete is required to read the numbers on each card from left to right as rapidly as possible without making any errors. As the athlete executes each test, saccadic eye movements are assessed along with language and concentration. The ability to execute this task requires the coordination of multiple cortical and subcortical pathways of the brain (especially the dorsolateral prefrontal cortex) and brainstem, which are often impaired after concussion. Rather than assessing for subjective symptoms, the K-D test is unique in that it provides an objective evaluation of a specific neurological function.

The K-D test has been used to evaluate a wide range of conditions ranging from visual disorders and learning disabilities in children to fatigued medical residents on call. However, over the past few years, the K-D test has been investigated as a potential rapid objective sidelines assessment tool for concussion in multiple athletic cohorts including boxers, mixed martial arts fighters, college athletes, rugby players, and professional hockey players in the NHL.[36-38] Multiple studies have demonstrated that the K-D test scores in concussed athletes decrease compared with their preconcussion baselines.[36-38] In the absence of concussion, however, K-D test scores generally improve over time due to learning effects as a result of repetitive testing. This remains the case for fatigued athletes who are subjected to the K-D test

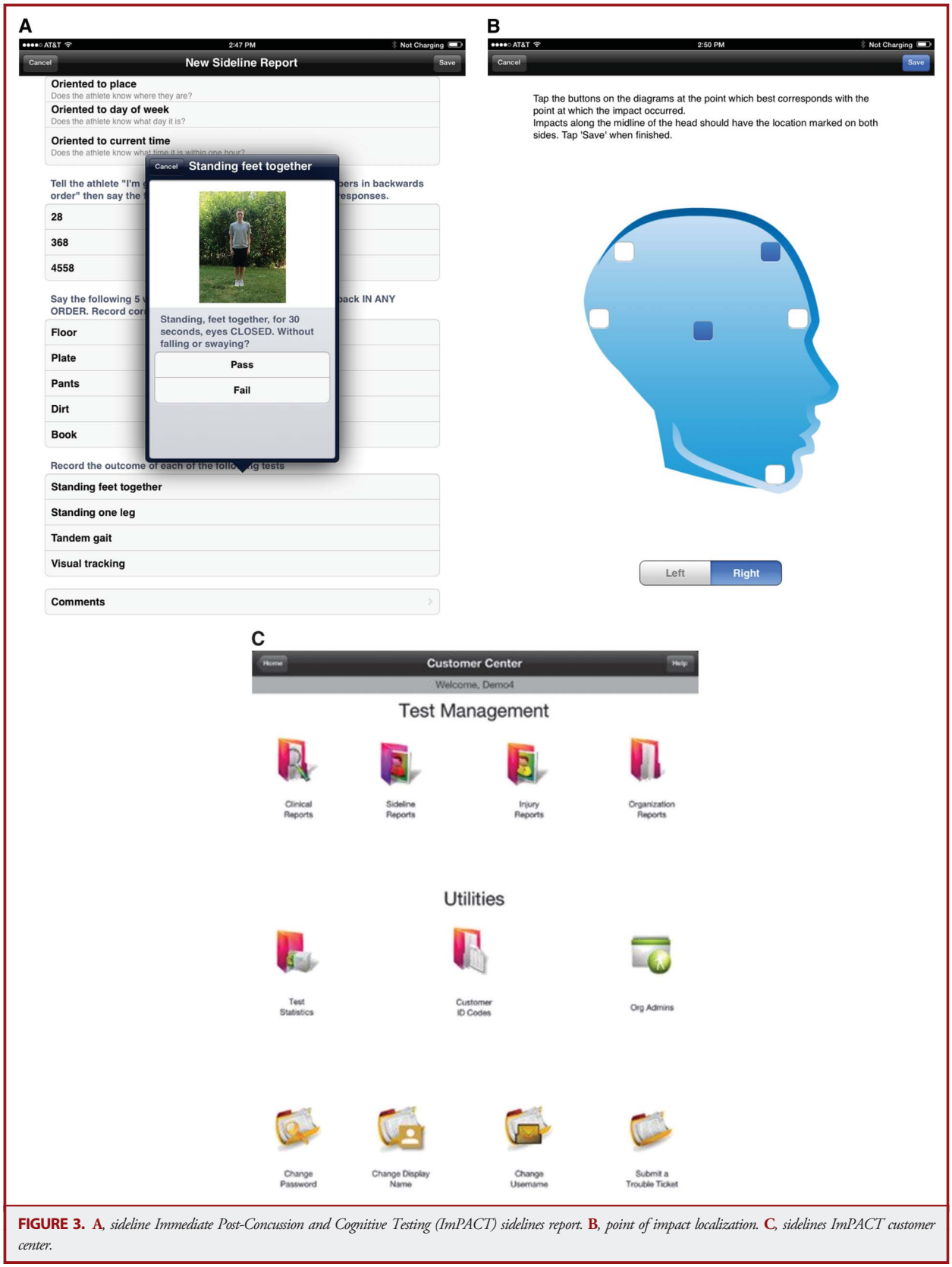

FIGURE 3. A, *sideline Immediate Post-Concussion and Cognitive Testing (ImPACT) sidelines report.* B, *point of impact localization.* C, *sidelines ImPACT customer center.*

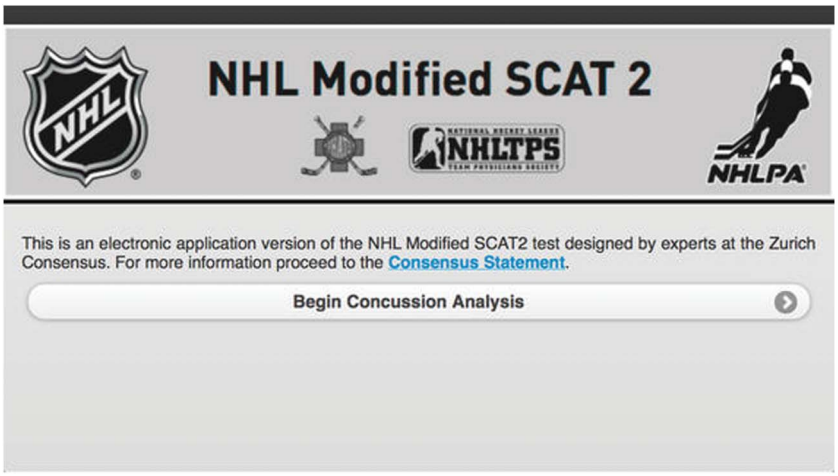

FIGURE 4. *National Hockey League (NHL) modified Sports Concussion Assessment Tool (SCAT)-2 application.*

immediately after competition, which suggests that K-D testing in athletes is relatively specific for concussion.[38] The K-D test is not specific, however, to concussion evaluation and is used to assess a certain constellation of signs/symptoms that are often associated with concussion. As such, like many assessment tools, there are no set criteria for diagnosing concussion. Instead, the test relies largely on comparing differences between baseline tests and postinjury tests. As it is still in the preliminary stages of validation for concussion, at this point in time, there is not a standard difference in score from baseline testing that determines whether an athlete has sustained a concussion. Although the K-D test alone is unlikely to provide sufficient diagnostic information for concussion assessment, it may prove to be an effective, rapid, and objective tool to complement existing standard sidelines assessment tools.

Sensory Organization Test

As previously stated, maintenance of balance is one of the key factors necessary for athletic performance and is routinely affected by concussion. The Sensory Organization Test (SOT) (NeuroCom International, Inc, Clackamas, Oregon) evaluates the vestibular, visual, and somatosensory systems, which are the 3 sensory systems responsible for postural stability and maintenance of balance.[39-42] The test isolates each of the 3 systems by placing the patient on either a fixed surface or a calibrated sway reference support and introducing 6 different sensory conditions in the setting of either eyes open or eyes closed. The sway reference can modulate proprioceptive input, and the eyes open/closed situations modulate visual input, thus isolating vestibular input. As a result, vestibular dysfunction, as seen in athletes with concussion, is elicited. Further, by exaggerating vestibular dysfunction, the SOT is also capable of assessing the ability of the athlete to compensate for and adapt to vestibular dysfunction. The SOT could be an effective means of eliciting even subtle balance abnormalities in the concussed athlete that could be missed by less rigorous balance testing used in many of the concussion-testing batteries. Although many current concussion assessment tools grossly assess balance, the SOT assesses the integrity of the entire balance system by testing each component.[2,39-43] This provides very specific information regarding which types of environments (ie, low-light settings or night games and uneven surfaces) may be particularly problematic for the concussed athlete. The SOT comprehensive report consists of 5 items: (1) equilibrium score: quantifies center of gravity and assesses overall performance; (2) sensory analysis: consists of 4 ratios determined by combining various scores of the 6 conditions and assesses individual sensory systems, (a) somatosensory: ability to incorporate somatosensory input into balance, (b) visual: ability to incorporate visual input into balance, (c) vestibular: ability to incorporate vestibular input into balance, (d) preference: degree to which the patient relies on visual input; (3) strategy analysis: assesses compensation mechanisms by analyzing whether a patient relies primarily on ankle or hip movement to maintain balance in unsteady conditions; (4) COG alignment: measures the athlete's center of gravity relative to the center of the support surface; (6) graphic illustration of each condition and each reportable item.

Immediate Postconcussion Assessment and Cognitive Testing

The ImPACT program is an extensive computerized neuropsychiatric test inspired by concussion management in the NFL and developed in Pittsburgh, Pennsylvania. The ImPACT test is one of the most widely used testing modalities in the United States and internationally. It consists of 4 sections, with the first section involving demographic information and health history and the last section containing a graphic representation of the results. The second section includes standard questions regarding signs/symptoms of concussion as well as a standardized PCSS tool.

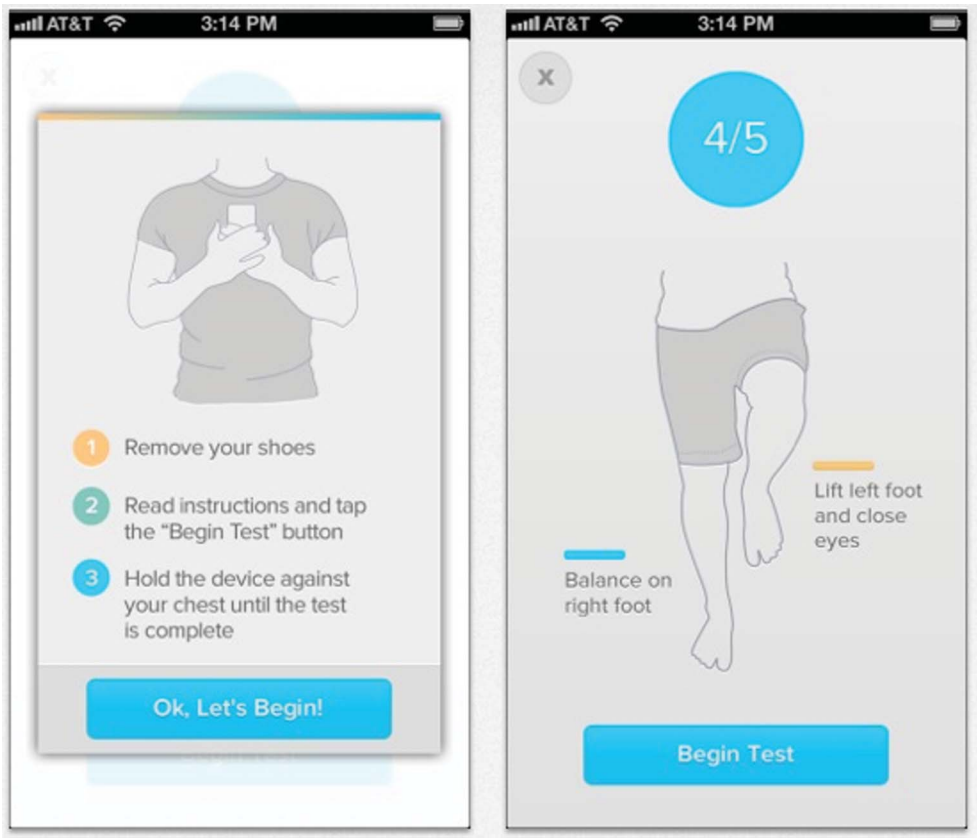

FIGURE 5. *Sway balance application.*

The third component is a visuospatial component that assesses visual and verbal memory, reaction time, and processing speed. This component consists of 6 modules: word discrimination, design memory, Xs and Os, symbol matching, color matching, and 3-letter memory. To ensure the most accurate testing, a presports participation baseline examination is optimal to be able to compare preinjury scores with postinjury scores and make a valid return-to-play determination. However, if for any reason a baseline study is not obtained, comparative data may be extrapolated from the 5 million baseline tests already accumulated in the ImPACT system.

1. ImPACT has been studied extensively in the literature. Several studies have demonstrated that ImPACT has good test-retest reliability and functions as a valid and reliable tool in the assessment of concussion and for monitoring recovery.[20,44,45] In 1 study, Schatz et al[46] found the sensitivity and specificity of the ImPACT test to be 81.9% and 89.4%, respectively, validating it as a potentially useful tool for the neurocognitive evaluation of concussed athletes. Additional studies have suggested that ImPACT is a reliable means of evaluating attention and processing speed in the postconcussive setting. ImPACT, like most concussion assessment tools, has its limitations. Despite demonstrating good construct validity and sensitivity to the cognitive deficits associated with concussions, it has been criticized for being limited in scope compared with standard comprehensive neuropsychological testing batteries, which makes the interpretation of the data difficult. Specifically, Maerlender et al[47] found ImPACT to be deficient in its ability to assess sustained attention and auditory working memory compared with a standard neuropsychiatric testing battery. As a result, some experts believe that ImPACT should ideally be used as a screening tool rather than a primary diagnostic and management tool.

The ImPACT program is now available as an application for Smartphones and tablets, which provides sidelines concussion specialists with a mobile and highly efficient means of assessing athletes for concussion in the immediate postconcussion setting. The application allows the athlete to complete the test on the device, which then stores the data and provides real-time statistical information as well as prognostic data.

Electronic Applications

As stated previously, many of these concussion assessment tools have been converted to electronic application formats for use with Smartphones and tablets to enhance their portability and provide medical personnel with a more efficient means of evaluating athletes for concussion on the sidelines. Two of the most

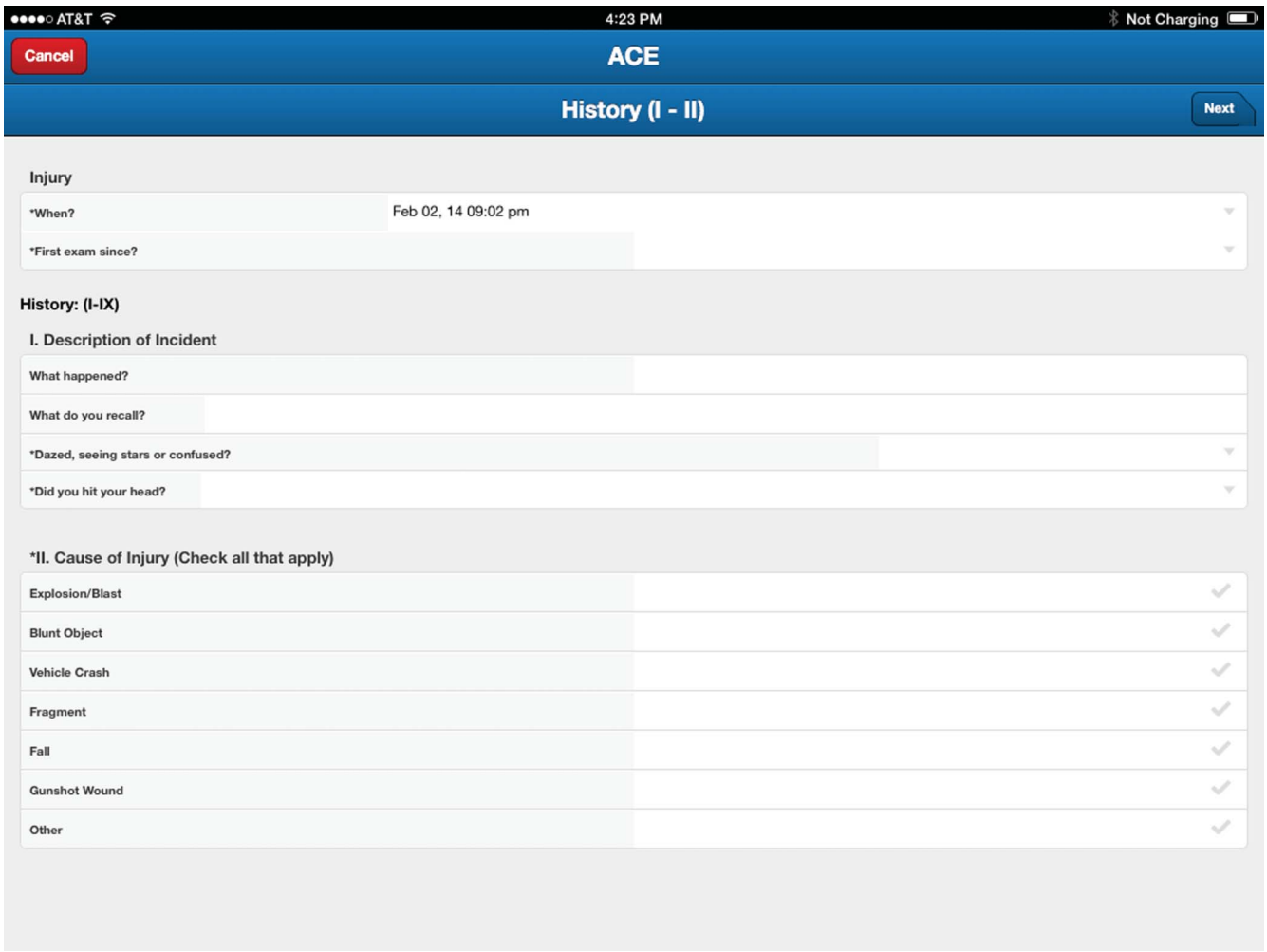

FIGURE 6. *Acute concussion exam application.*

commonly used tests that have been converted to application platforms are the SCAT-2 app by Innovap, Inc (Figure 2) and the Sideline ImPACT app by ImPACT Applications, Inc (Figure 3). The NHL has adopted its own modified version of the SCAT-2 app (Figure 4), which has been widely used as a sideline assessment tool in professional hockey. However, the SCAT-2 app is currently being replaced by the newly created SCAT-3 test, which has not yet been converted into an electronic application. The Sideline ImPACT app is accompanied by the Mobile ImPACT Customer Center app, which serves as a database for the test results and statistics of each athlete evaluated by a specific health care professional. These apps require a customer center account through which the health care provider can purchase electronic baseline tests for $10 each or electronic postconcussion tests for $20 each to be used with the Sideline ImPACT app. Sway Medical, LLC has created an app for the Sway Balance test (Figure 5) exclusively for the iPhone using the device's internal motion sensors to evaluate an athlete's vestibular function as a means of initial concussion assessment as well as tracking an athlete's recovery after a concussion. The Sway Balance app requires the user to purchase an account with Sway Medical to gain access to the app's assessment tools. Recently, ImPACT incorporated the Sway Balance test as well as the K-D test into its electronic concussion assessment.

In addition to the more standard testing modalities listed previously, a number of additional apps, including the Acute Concussion Exam app (Figure 6) by Total Network Solutions, LLC and the Concussion Recognition & Response app by PAR, Inc (Figure 7) have been created by independent groups for concussion evaluation and are available to the general public at a reasonable price. The Concussion Recognition & Response app includes a Coach and Parent version to aid in

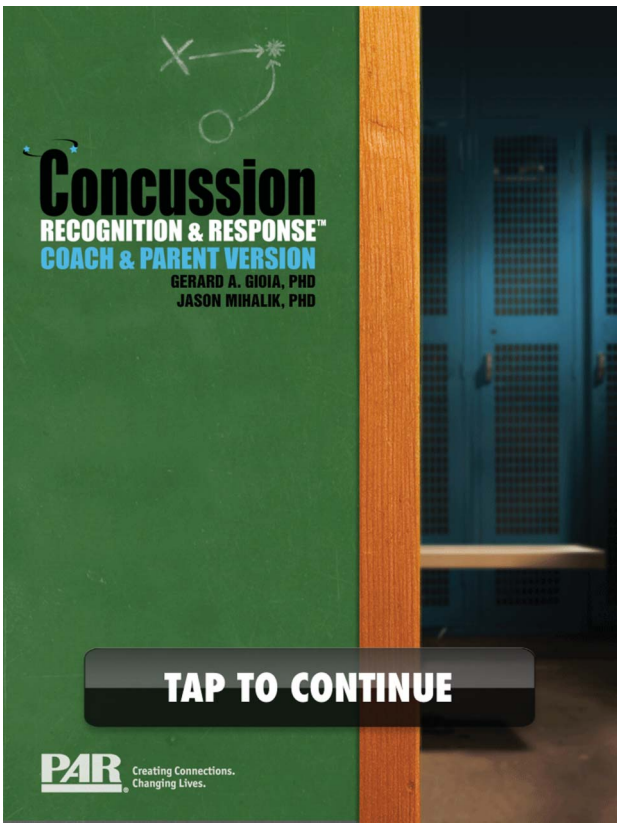

FIGURE 7. *Concussion Recognition and response application.*

concussion evaluation at home or on the sidelines in the absence of a health care professional.

Biosensors

Over the past several years, there has been substantial interest in biosensors, force detection systems, and accelerometers. Significant research on these technologies has lead to the creation of a large number of systems that incorporate biosensors into mouth guards, helmets, and patches that can be worn discreetly by athletes and provide feedback regarding impact force and acceleration during competition. One example is the Head Impact Telemetry System, developed by researchers from Virginia Tech and Dartmouth in 2002, which is a software system consisting of 6 battery-powered electrodes situated in strategic locations inside the padding of the football helmet. The vast majority of these systems alone are not suitable for sideline assessment because they provide raw data, require extensive data analysis, and lack a correlative symptom assessment test. X2 Biosystems, Inc. (Seattle, Washington) has developed a sensor module for athletes, small enough to be worn as a patch behind the mastoid, which is capable of measuring impact acceleration in 6 total axes (3 axes of linear acceleration and 3 axes of angular velocity). The information gathered by the sensor module is instantly transmitted to a cloud-based server and relayed to authorized mobile devices, allowing for real-time feedback regarding head trauma during athletic competition. This information is accompanied by an iOS-based application, the X2 Interactive Concussion Examination, or X2 ICE (Figure 8). The X2 ICE is a comprehensive concussion assessment tool based on the SCAT2, SCAT3, and NFL concussion assessment protocols that can be used to correlate raw physical data during a competition with clinical signs and symptoms. Data from the X2 ICE assessments is stored in the same cloud-based server, enabling concussion specialists to accumulate extensive profiles on athletes throughout their careers. These data, which are unique to each athlete, could be quite powerful for evaluating future concussions, tracking recovery, and making return-to-play recommendations. This past season, the NFL adopted this technology as part of its own concussion assessment protocol. This system, which is accompanied by a comprehensive concussion assessment tool, could provide correlative information between the magnitude of impact and the severity of concussion. However, further studies are needed to validate this tool for concussion assessment.

Biomarkers in Brain Injury

Still in a developmental stage, many researchers have begun to investigate the various roles of blood and cerebrospinal fluid (CSF) biomarkers as a means of evaluating varying degrees of TBI as well as concussion. Similar to other areas of investigation, biomarkers could provide valuable objective data regarding assessment of concussion severity and potential return to play guidelines. Although not purely sidelines tests per se, serum biomarkers could be obtained by medical personnel in the locker room after the completion of initial sidelines assessment. Although still in the early stages of investigation, biomarker levels could be obtained immediately after concussion and serially thereafter to monitor severity and recovery. Potential biomarkers for concussion include compounds related to the neuroinflammatory response to brain injury, such as interleukins and acute phase reactants, as well as breakdown products from central nervous system tissues, such as glial fibrillary acidic protein and myelin basic protein.[17,43,48] Previous studies have found, for example, that the total CSF tau protein level peaks at 4 to 10 days after injury.[48-50] Similarly, CSF levels of other proteins such as amyloid-β, S100-B, and neurofilament light polypeptide have been quantified after TBI.[48-50] Other potentially important biomarkers include γ-enolase, spectrin breakdown products, and ubiquitin carboxyl-terminal hydrolase isoenzyme L1.[48] A recent study demonstrated increased levels of α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid receptor peptide in concussed athletes compared with control athletes. Additionally, this study has found that poor ImPACT scores correlate with increased levels of α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid receptor peptide.[51] Additional studies are in process to investigate the association between genetic polymorphisms and risk/severity of concussions. Specifically, there is significant interest in the apolipoprotein E ε4 polymorphism and

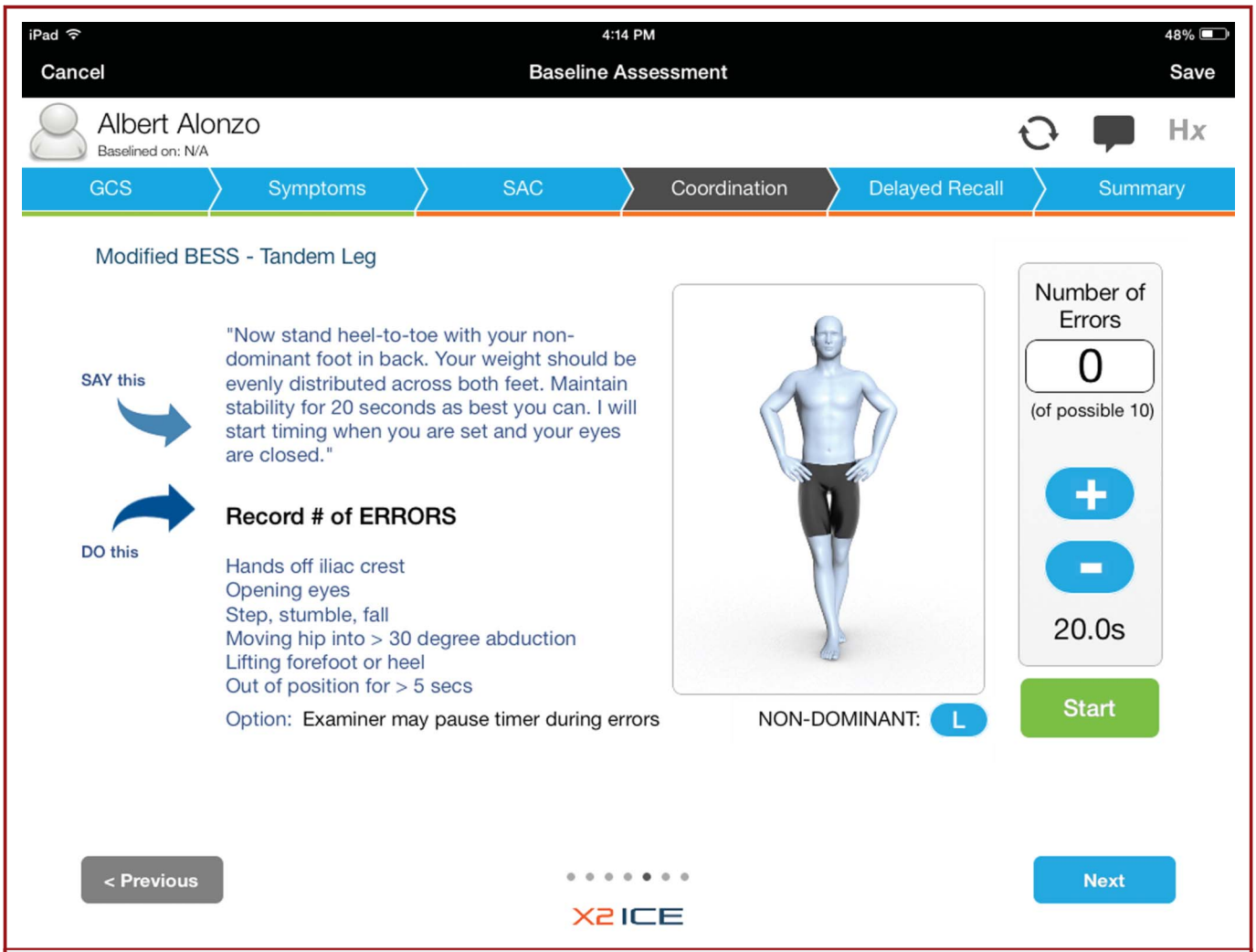

FIGURE 8. *X2 Biosystems integrated concussion examination. BESS, Balance Error Scoring System; GCS, Glasgow Coma Scale; SAC, Standardized Assessment of Concussion.*

APOE G-219T promoter mutation. The practical use of serum biomarkers for the diagnosis/triage of concussion is limited at this stage and requires further investigation.[48,52] Genetics data, however, are somewhat complex because this information requires careful ethical analysis with respect to privacy and disclosure and uncertainty of the impact of the data itself. Further, genetics information is often regulated by state laws.

Neuroimaging

As previously stated, the overwhelming majority of athletes who sustain a concussion have no abnormalities on standard neuroimaging techniques (CT and MRI). However, several imaging modalities in the evaluation and development pipeline such as functional MRI, magnetic resonance spectroscopy, diffusion tensor imaging, and high-definition fiber tracking may prove capable of evaluating structure and function of the brain. Advanced neuroimaging modalities that are able to demonstrate neuronal injury, metabolic abnormalities, and/or functional damage to white matter would provide objective, quantifiable diagnostic options for TBI and concussion. One such modality, magnetoencephalography, has shown promising early results in detecting concussion.[53]

CONCLUSION

Over the past couple of decades, health care professionals and researchers along with outspoken athletes have made several strides to reveal the potential devastating ramifications of concussions. This, in turn, has placed concussions prominently on the public agenda, calling for improvements in prevention, early and accurate

diagnosis, as well as effective management strategies. The presence of a trained concussion specialist on the sidelines is critical to the implementation of early assessment and effective triage and management of athletes immediately after concussion. Further, a dedicated sidelines specialist provides continuity of care leading to appropriate and educated management of concussed athletes in the subacute to long-term recovery process. This allows for improved accuracy with respect to return-to-play guidelines. In the age of modern medical advances and increasingly portable technology such as Smartphones/tablets, the sideline specialist is gaining access to an expanding arsenal of objective and subjective assessment tools. However, many of these tools still remain in the developmental phase, and research into their validity is ongoing. Additionally, classically reliable assessment tools are frequently revised as the details of concussion are better understood. As a result, the rapidly changing and expanding field of concussion assessment creates challenges for the sidelines specialist regarding which tests to use in his or her practice. We have discussed multiple currently available and widely used assessment tools as well as various newly emerging tools to provide a concise resource for sidelines specialists.

Disclosure

Dr Maroon was the codeveloper of the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) concussion assessment tool. The other authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

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