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A Battery of Easily Accessible, Simple Tools for the Assessment of Concussion in Children

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Objective To determine whether a non-proprietary, novel testing battery can identify recently concussed children within 8 weeks of injury.

Study design In total, 568 clinic outpatients aged 10-18 years were sorted into 3 groups: 316 had never been concussed, 162 had ever been concussed before 8 weeks earlier, and 90 had been recently concussed within 8 weeks. At initial and any subsequent visits, a neurologic examination and 4 procedures were performed: Stick Drop, Wall Ball, Sharpened Modified Romberg (SMR), and Animal Naming. Analysis included inter-group and intra-person performance differences using a series of *t* tests on the Stick Drop, Wall Ball, SMR, and Animal Naming.

Results The recently concussed group performed worse ($P < .01$ for all) on Stick Drop, total Wall Ball bounces and drops, and SMR compared with never-concussed and ever-concussed groups. This effect for Stick Drop, SMR, and Wall Ball but not Animal Naming persisted beyond the 4 weeks commonly stated to define recovery. Of 59 recently concussed subjects who returned for ≥1 visit, there were improvements in Stick Drop average ($P = .004$) and maxima ($P = .02$) as well as SMR ($P = .01$) but not Animal Naming between initial and subsequent visits.

Conclusions This novel, rapid testing battery distinguished groups of children ages 10-18 years who had and had not experienced a recent concussion. A view that physical concussion symptoms resolve within a month of injury may be incomplete. Deployment of this readily available, inexpensive and non-proprietary battery should be compared with other tools and studied further in serial assessments. *(J Pediatr 2021;229:232-9)*.

Concussion is defined as a brain injury induced by biomechanical forces transmitted to the head resulting in rapid onset of transiently impaired neurologic functioning. This definition does not lend itself to discrete clinical diagnosis. The range of clinical symptoms and signs can include somatic, cognitive, emotional, and/or sleep-related disturbances or impairment developing in the first week post-injury in most, but not all, subjects.[1,2] An estimated 1.1-1.9 million concussions occur annually in US children ≤18 years.[3]

Concussion assessment in the pediatric population remains challenging due to a paucity of published clinical assessment data and confounding by both concurrent neurodevelopmental changes, as well as limited validated diagnostic tools in this age group. Despite the availability of more than 2 dozen concussion assessment tools,[4] few are designed specifically with younger children in mind, except the Child Sport Concussion Assessment Tool (SCAT) 3 and Child SCAT5 for ages 5-12 years (**Table I**; available at www.jpeds.com).[5,6]

Proprietary computerized neurocognitive testing, such as Automated Neuropsychological Assessment Metrics,[7] Immediate Post-Concussion Assessment and Cognitive Testing, and Axon,[8] has widespread clinical appeal. This testing offers baseline comparison, online accessibility, centralization of data, standardization of testing components, and rapid scoring feedback.[9,10] However, controversies remain about expense,[11] intentionally poor examinee performance on baseline testing,[12] and level of training/credentialing required for test result interpretation.[13-17] Virtually unknown in the population of children aged 10-18 years is the validity and reliability of such testing,[5] as well as whether the sensitivity of computerized testing in this population is sufficient to detect a performance decrement in the days to weeks following injury. The value in college-age athletes is similarly suspect.[14,18] The aim of our current study was to determine whether a novel battery of 4 easily administered clinical procedures could distinguish concussed children aged 10-18 years from those without concussion.

Methods

We enrolled children aged 10-18 years who were ambulatory, spoke English as their first language, and who presented either to a subspecialty pediatric

AUC	Area under the curve
BESS	Balance Error Scoring System
SCAT	Sport Concussion Assessment Tool
SMR	Sharpened Modified Romberg

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neurology or pediatric sports medicine concussion clinic between November 2013 and December 2017. Sex, age, handedness for throwing, and date of most recent concussion were recorded along with the number and details of previous concussions. Concussion was defined according to the 5th International Conference on Concussion in Sport guidelines.[1] Subjects received complete physical and neurologic examinations and were separated into 1 of 3 categories: never concussed, ever concussed (any concussions occurring >8 weeks before initial evaluation), and recently concussed (any concussion occurring ≤8 weeks before their initial evaluation). We excluded subjects with neurodevelopmental delay or disability, behavioral or mood disorders, current orthopedic injuries limiting postural stability testing, chronic medications, or pre-existing neurologic conditions apart from migraine or tension headache. Subjects were divided into 3 age categories: 10-12, 13-15, and 16-18 years. As this was an observational rather than interventional study, the need for follow-up was determined by provider's assessment of medical necessity. All subjects for whom a follow-up visit was required attended that visit.

Human subjects research review and approval to carry out the study was obtained from each of two institutional review boards at Brown University and Rhode Island Hospital. Written informed consent was obtained from parents and guardians of study subjects, and each subject provided written assent for participation. This work was carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for research involving human subjects.

Four study procedures were administered at initial and any subsequent visits: Stick Drop, Wall Ball, Sharpened Modified Romberg (SMR), and Animal Naming.

Stick Drop

The subject is seated next to an examination table on an adjustable stool such that the elbow of their dominant arm is resting on the corner of a table with the hand and forearm extending past the table edge parallel with the floor. He or she is directed to hold the fingers of the hand "as if you are holding a can of soda." Using a $^3/_4$ -inch wooden dowel (1-m long) with an attached 1-inch diameter circular felt furniture pad at the bottom, the investigator manually suspends this in a vertical orientation such that the inferior-most padded end is positioned level with the superior-most aspect of the participant's open hand, at the level of the webbing between the thumb and index finger, with the participant touching no part of the stick. The subject is asked to direct their gaze at the stick and their own hand to watch for any downward displacement of the stick, and at the first sign of this to "grab the stick as quickly as possible." The investigator holds the stick in one hand with this hand out of the view of both examiner and subject. The stick is released at a random time to prevent the participant from anticipating the release moment (in any event no longer than 10 seconds), and the participant must respond to the stick fall by grabbing the stick within a closing hand as quickly as possible. The point of contact on the ruled stick of the superior-most aspect of the closed hand again at the level of the webbing is then recorded as a distance in centimeters from the bottom of the stick. After a single practice grab, 5 consecutive separate trials are performed, and distances recorded. The measures of interest were the average, maximum, minimum, and range of stick drop (centimeters) across the five trials.

Wall Ball

The subject stands 6 feet from an unobstructed wall with an unused tennis ball in the dominant hand. He or she is directed to throw the ball underhand against the wall, and to catch the rebound in their opposite hand, which combination is then used to repeat the bounce and catch repeatedly as many times as is possible in 30 seconds, the investigator timing with a stopwatch and recording how many successful wall-bounces and unsuccessful drops are made during that period. The subjects are directed not to attempt to count themselves, and further told that should the ball drop to the floor, the subject should pick it up and continue the trial. Errant balls that became stuck or hidden require a trial restart. The subject is permitted to practice the procedure prior to the start of the trial until three successful bounces with no drops have occurred. The number of drops and successfully completed bounces within 30 seconds is recorded after a single trial.

SMR

The subject is asked to stand with no shoes, and feet together, eyes open, hands at their sides, then observed for wavering or imbalance. This is the first of 8 steps in the test. The patient is then asked to assume the same position, though this time with the eyes closed. The examiner stands or sits on a stool close to the subject to prevent falling in the event wavering or imbalance occurs. "Falling" in this procedure is defined as removing either foot completely from, or moving either foot along, the floor. A sequence of steps of increasing postural difficulty is performed, each first with the eyes open then closed, each step maintained for 10 seconds. These are: (1) feet together, arms at their sides; (2) feet aligned, tightrope fashion, one in front of the other, with the heel of one foot touching the toe of the other, arms at one's sides; (3) feet aligned in tightrope fashion but with arms crossed in front of the chest, elbows near the hips, and hands near the shoulders; and (4) feet aligned in tightrope fashion, arms crossed as in step 6, but chin up so that their direction of gaze is vertically upwards. The subject is permitted only once to take a step followed by one reattempt. If the subject steps a second time, the position of the last successfully completed portion of the procedure is recorded and the test stops.

Animal Naming

The subject is asked to "say out loud, so that I can hear you, the names of as many animals as you can in 60 seconds." The investigator uses a stopwatch to begin and end the trial, and as the words are spoken, records each one on paper. The list of animals, number of animals recited, number of errors made (repeated names, or things that are not animals) are recorded. Subsequent to this, the investigator reviews the list to determine the number of animal clusters (groups) and) the number of switches made (animal categorical changes). Clusters are defined as 2 or more related words.[19]

Statistical Analyses

Descriptive statistics were conducted using the Student t test or the Fisher exact χ^2 test and presented as means with SDs or medians with IQR or frequency and percentage. Data analysis was performed using SAS, version 9.4 (SAS Institute). Unadjusted analyses using a series of generalized linear regression models to accommodate difference in sample size between the 3 categories of concussion status groups (never concussed, ever concussed, recently concussed) were conducted to assess differences in performance on the Stick Drop, Wall Ball, SMR, and Animal Naming tests by concussion status. Subsequent adjusted analyses were conducted on the significant unadjusted models in which sex, age group (10-12, 11-15, 16-18 years), and handedness were entered as covariates and concussion status group as the predictor variable. Interactions between concussion status group, sex, and age group were also examined. Contrast effects of performance on all outcome measures across all concussion status groups were assessed. Separate analyses, using a series of t tests, were conducted on the recently concussed group to determine changes in performance at the second office visit conducted within 4 weeks of the initial assessment. The sensitivity and specificity of tests that showed significant differences between the never concussed and recently concussed groups also were conducted to demonstrate the maximum test performance metrics between these 2 groups. Sample size was based upon the estimated difference in test performance of participants of recently concussed and never concussed. Assuming a mean difference equivalent to moderate effect size of Cohen d = 0.40, a minimum statistical power to

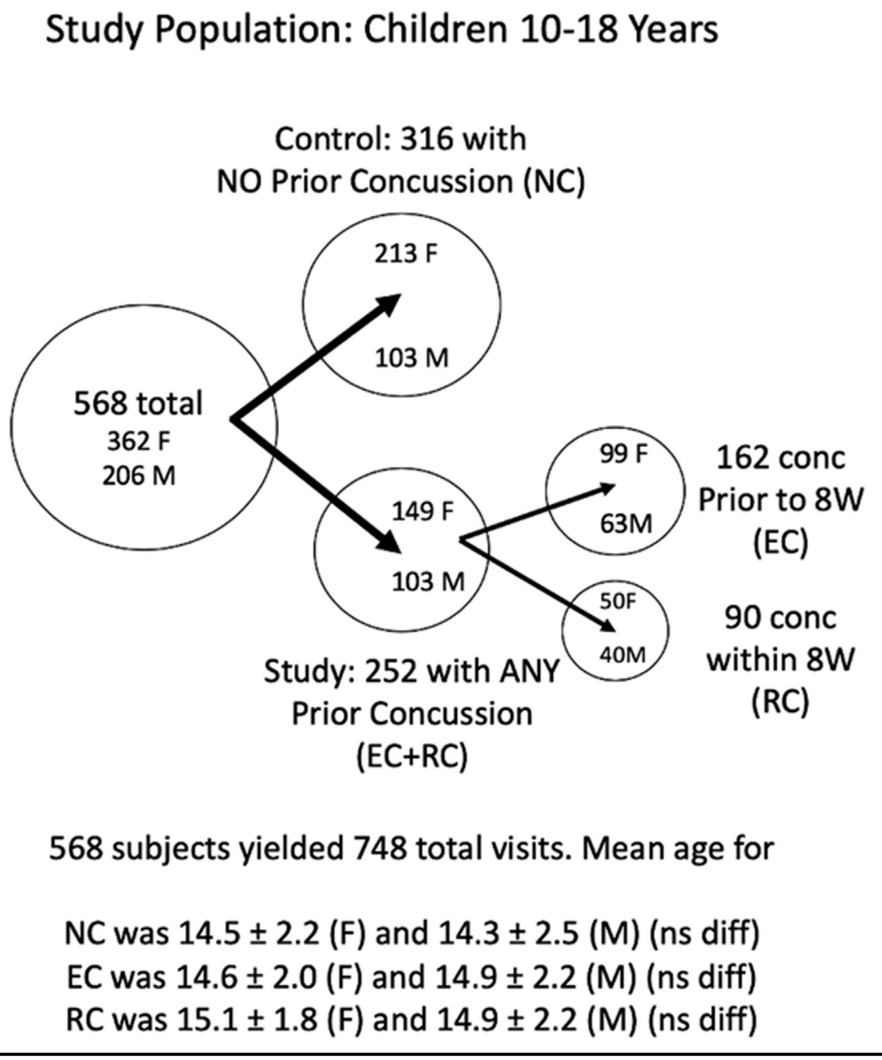

Figure. Grouping sizes in study population. *EC*, ever concussed; *F*, female; *M*, male; *NC*, never concussed; *RC*, recently concussed.

detect differences (β = 0.80, α < 0.05) required a minimal sample size of 87 participant per group to determine a significant difference in performance across the measures between groups.

Results

Overall, 568 subjects participated during 748 office visits (range 1-9 visits). At the initial visit, 316 (55.6%) children had no previous concussion and 252 (44.4%) had experienced at least one. Ninety of 252 (35.7%) had been concussed ≤8 weeks of the initial visit (mean = 2.9 weeks [SD = 2.14]), and 162 (64.3%) had experienced a concussion >8 weeks before initial assessment (mean = 93 weeks ± 12.5) (**Figure**).

Table II shows the subject demographics by concussion status at the initial visit. There were more female patients than male patients across all 3 concussion status categories. The mean age across the sample at the initial visit was 14.6 years (SD = 2.20), with the never concussed subgroup having a significantly lower mean age (14.4, SD = 2.1) compared with the recently concussed subgroup (14.9 years, SD = 2.1, *P* < .004) There were significantly fewer children in the younger age group (10-12 years) in the ever-concussed compared with the other 2 groups (χ^2 [4] = 19.4, *P* = .001). Overall, 93.3% of the sample was right-handed, and this was not significantly different by concussion status at the first office visit (*P* = .16).

Table III summarizes mean performances across the 4 tests (Stick Drop, Wall Ball, SMR, Animal Naming) by concussion category at the initial visit. There was significantly worse performance from the recently concussed compared with the never-concussed and ever-concussed groups on each of the Stick Drop test measures average drop (never concussed, mean = 31.9 ± 7 cm; ever concussed, mean = 32.2, ± 8.1 cm; recently concussed, mean = 34.9 ± 12.7 cm), Stick Drop maximum drop (never concussed, mean = 41.2 ± 11 cm; ever concussed, mean = 41.9 ± 12.1 cm; recently concussed, mean = 46.3 ± 19 cm), and Stick Drop range (never concussed, mean = 16.9 ± 8.8 cm; ever concussed, mean = 17.5 ± 8.8 cm; recently concussed, mean = 21.2 ± 13.2 cm). Performance on the Wall Ball tests was mixed, with never concussed and ever concussed having a significantly different performance than recently concussed on the number of bounces (never concussed, mean = 18.7 ± 5.6 cm; ever concussed, mean = 20.4 ± 5.2 cm; recently concussed, mean = 17.8 ± 5.5 cm), but ever concussed performing significantly better than never concussed and recently concussed on the number of drops. Recently concussed subjects performed significantly worse on SMR than never concussed/ever concussed subjects by more than a full procedural step (5.81 ± 2.03 vs 6.98 ± 1.39, *P* = .01). There were no significant differences between the 3 groups across the Animal Naming test. A series of adjusted regression analyses (not shown) were conducted, and after adjusting for sex, age group, and, handedness entered as covariates, concussion status remained a significant predictor of better never concussed and ever concussed vs recently concussed performance in Stick Drop average (*P* = .003), Stick Drop maximum (*P* < .001), Stick Drop range (*P* < .001), Wall Ball (*P* < .0001), and SMR (*P* < .001).

Of the 90 subjects in the recently concussed subgroup, at the direction of the medical provider for medical necessity, 59 (66%) returned for at least 1 additional study visit (range 1-9 post-initial office visits). Mean time to return was 3.2 weeks (SD = 2.2; range 0.4-7.8 weeks); 66% of those were female and 56.8% were age between 13 and 15 years. Performance of the recently concussed subgroup (n = 59) at initial and subsequent study visits were compared with all the tests that were significantly different between the never concussed and ever concussed (>8 weeks at index office visit). Results of the mean differences in performance

Table II. Concussion status at initial visit

Characteristics	Never concussed n = 316	Ever concussed n = 162	Recently concussed n = 90
Sex n (%)			
Female	213 (67.4)	99 (61.1)	50 (55.6)
Male	103 (32.6)	63 (38.9)	40 (44.4)
Mean age, y (SD)			
Female	14.5 (2.2)	14.6 (2.0)	15.1 (1.8)
Male	14.3 (2.5)	14.9 (2.2)	14.9 (2.2)
Age group n (%)			
10-12 y	100 (31.7)	22 (13.6)	21 (23.3)
13-15 y	125 (39.6)	85 (52.5)	39 (43.4)
16-18 y	91 (22.7)	55 (33.9)	30 (33.3)

Table III. Initial visit test results by concussion status

Measures	Never concussed n = 316	Ever concussed n = 162	Recently concussed n = 90	*P* value
Stick Drop, cm (SD)				
Drop average	31.92 (7.03)	32.17 (8.11)	34.92 (12.71)	.01*
Drop maximum	41.24 (11.02)	41.90 (12.11)	46.33 (19.04)	.004*
Drop range	16.94 (8.77)	17.52 (8.75)	21.17 (13.23)	.001*
Wall Ball				
Number of drops	2.32 (1.82)	1.87 (1.68)	2.26 (1.76)	.03†
Number of wall bounces	18.65 (5.61)	20.39 (5.15)	17.82 (5.46)	.02*
SMR				
Completed steps (of 8 maximum)	6.98 (1.39)	6.72 (1.73)	5.81 (2.03)	.01*
Animal Naming				
Total animals named	21.7 (5.07)	21.3 (5.81)	22.43 (5.01)	.35
Number of clusters	5.41 (1.61)	5.35 (1.60)	5.35 (1.52)	.36
Number of switches	8.16 (2.65)	7.86 (2.47)	7.68 (2.91)	.55

Ever concussed; most recent concussion >8 weeks before initial visit.
Recently concussed; most recent concussion ≤8 weeks before initial visit.
*Recently concussed significantly different from never concussed and ever concussed; never concussed = ever concussed.
†Ever concussed significantly different from recently concussed and never concussed; recently concussed = never concussed.

Table IV. Change in performance between initial and first subsequent office visit for recently concussed children

Measures	Initial visit, n = 59	Subsequent, visit n = 59	P value
Stick Drop, cm (SD)			
Average	34.56 (10.48)	29.61 (7.25)	.004*
Maximum	43.81 (15.17)	38.08 (10.72)	.02*
Range	17.81 (11.24)	15.25 (8.93)	.18
Wall Ball			
Number of drops (SD)	1.78 (1.62)	1.61 (1.40)	.54
Number of wall bounces	18.78 (5.39)	19.86 (5.40)	.28
Completed steps (of 8 maximum)	5.63 (2.26)	6.63 (1.88)	.01*

*Significant difference between initial and subsequent visits.

between the index and subsequent office visit are shown in **Table IV**.

The recently concussed children at their second visit had a significantly better performance compared with their initial visit on the Stick Drop average (29.61 ± 7.25 cm vs 34.56 ± 10.48 cm, t [372] = −2.38, P = .004), and on the Stick Drop maximum (38.08 ± 10.72 cm vs 43.81 ± 15.17, t [372] = −2.04, P = .02), as well as on the SMR (6.63 ± 1.88 vs 5.63 ± 2.26, t [372] = −1.53, P = .01). Overall, for the tests that showed significant change, there was an average 14.3% improvement in the Stick Drop average measure, a 13.1% improvement in the Stick Drop maximum, and a 15.1% statistical improvement in the SMR test.

An optimal performance score to maximize the sensitivity and specificity for determining concussed vs not concussed was calculated using the never concussed and recently concussed groups' scores on the tests that were significantly different on and had an area under the curve (AUC) value of >0.50. The Stick Drop average test had an optimal cut-off score of <34.8 cm for a specificity of 0.71 and sensitivity of 0.42 (AUC = 0.55), Stick Drop maximum a cut-off score of <44 cm had a specificity of 0.81 and sensitivity of 0.22 (AUC = 0.53). Stick Drop range test had an AUC = 0.50. The SMR test optimal cut-off score >4 steps had specificity = 0.99, and sensitivity of 0.15 (AUC = 0.67).

Discussion

Four tasks were administered to children aged 10-18 years of age with a concussion <8 weeks before their initial specialty visit for concussion. These were chosen to be easy to administer, require little to no training, be inexpensive, add no more than a few minutes to the office visit and mitigate the problem of intentionally poor test performance on computerized neurocognitive testing by administration of physical tasks that "incentivize" or "improve motivation"[20] to perform well in direct view of others.

Performance on 3 of 4 tasks we administered to concussed children was impaired when considered as a group and compared with controls. Each of these 3 tasks were physical tasks; the 1 task undifferentiable from never concussed controls was the Animal Naming cognitive task. Perhaps this latter finding is related to the fact that implementation of neuropsychological tasks to detect cognitive impairment is most helpful once post-concussive symptoms have already resolved,[21] but the absence of any signal in our study suggests the animal naming task is not useful for identifying concussed from unconcussed groups, or that individual rather than population-derived differences could be more discriminatory.

Persistence of measurable performance impairment in children 10-18 years of age for Wall Ball, Stick Drop, and SMR as long as 8 weeks following the concussion is in line with prior studies in adults using stick drop measures[22] and assessment of postural stability after concussion.[23] Assessment batteries such as Immediate Post-Concussion Assessment and Cognitive Testing,[14] the Standardized Assessment of Concussion, and SCAT[24] are able to identify impairment within 24 hours of injury in college athletes but tend to normalize within 2 days and are of uncertain subsequent value. Similarly, the sensitivity of Balance Error Scoring System (BESS), the postural control assessment, drops over several days following a concussion with most concussed individuals normalizing within 3 to 5 days.[25] And yet in our study, Stick Drop, Wall Ball, and SMR all showed evidence of impairment as long as 8 weeks after the injury and would appear to be more effective discriminants of concussion status/physiological perturbation than pen and paper neurocognitive tests, computerized neurocognitive tests, and formal protocols for assessment of postural stability. There is a single case report of an 11-year-old girl with measurable performance impairment in 3 tests of posture/balance (Bruininks–Osteretsky Test of Motor Proficiency, the Pediatric Clinical Test of Sensory Interaction of Balance, and Postural Stress Test) up to 2 months following the concussion, but only one of these, the Postural Stress Test, continued to be abnormal 3 months following the injury.[26]

Eckner et al first reported the use of Stick Drop as a surrogate for reaction time in the assessment of concussion in collegiate athletes in 2010,[12] and found that Stick Drop confirmed others' documentation of reaction time prolongation after concussion[22,27-32] and response variability[28] and further found that this prolongation parallels the persistence of postconcussive symptoms followed by return to baseline.[29,30] In our study, there was a clear prolongation of reaction time in subjects presenting with a recent concussion followed by improvement at subsequent visits. We showed in children 10-18 years that reaction times as measured by the Stick Drop test are delayed following concussion as they are in college- and adult-aged subjects. We also show that recently concussed subjects can be differentiated from ever-concussed and neve-concussed subjects using the Stick Drop test at presentation within 8 weeks of the concussion using any of the 3 Stick Drop measures (average of 5 trials, maximum Stick Drop distance, Stick Drop range [maximum – minimum distance]) (**Table III**) and in that way imply evidence of concussion-associated physiological change.

We chose Wall Ball as a marker for dyscoordination, and it proved to be useful in the assessment of concussion in children. Beashel et al[33] and Mackenzie[34] originally described this test as a training tool for athletes, providing control data for athletes aged 15-16 years of age ("high" = >35; "above average" = 30-35; "average" = 25-29; "below average" = 20-24; "low score" = <20), whereas Taha and Chong[35] refined this, showing that regular practicing results in a shorter reaction time (0.16-0.18 $\pm$ 0.01 seconds); it took, however, 5 weeks for this effect to be found and their conclusion was only that it was useful to enhance "visual concentration, flexibility, agility, hand eye coordination, and reaction time in athletes." We provide control data for a larger age range (10-18 years) and show that recently concussed children are not able to generate as many successful bounce cycles as never-concussed or ever-concussed children (**Table III**), but they did not, as they did with Stick Drop, show improvement at their follow-up visit, suggesting a prolongation of impairment.

The SMR employed here is a variation on the theme first described in adults by Romberg in the early 1850s. The subject stands with feet together while being observed by the examiner for body sway with the eyes open and closed.[36] Despite widespread clinical use at the bedside, the traditional Romberg has not been useful to screen for vestibular impairment,[37,38] leading some to suggest alternative procedures such as the Sharpened Romberg (dominant foot behind the other for 10-60 seconds) or while also crossing arms so that the open palm falls on the opposite shoulder,[39,40] and in so doing claim additional sensitivity in assessing change over time.[41] The SMR, unlike the BESS, does not require specialized equipment of proscribed dimensions or thickness by a specified manufacturer, a third-party spotter, proprietary score card, or training in the use and scoring of a protocol, and in this way is true to our stated desire to keep the battery as simple and accessible as possible. Similarly, a shorter duration of time (10 vs 20 seconds for the BESS) required to maintain each SMR step abbreviated total test administration time, and, although not measured directly, it was our observation that if a subject was to fail an SMR step it was in the first few seconds after being asked to assume the position. There has been some controversy about the existence of learning effect in the Sharpened Romberg,[42] but this argument has been refuted[41] and in 2003 Diamantopoulos found no learning effects to be present in adult subjects practicing the tandem Romberg over a 10-day period.[43] In our sample, the recently concussed children showed clear evidence of impaired balance when compared with never concussed or ever concussed children and a full-step improvement at the subsequent visit (**Tables II-IV**). These findings suggest that although the original Romberg may not be useful to screen for vestibular dysfunction, the serial measure of SMR as deployed in this study in the setting of recent concussion in children 10-18 years is valuable as well.

Animal Naming was the only measure of cognitive performance that we used, and none of the measures (cluster size, category switches, numbers of animals named) proved to be in any way helpful as either a discriminatory measure of concussion within our population. We were surprised by this, given its utility in formal neuropsychological assessments and published lists of norms for children wherein performance is influenced not only by age but by the number of years of school completed,[44-47] although the utility of brief cognitive tests in general for this population has been repeatedly disappointing. The strategy by which children produce a list of animals appears to be independent of the language spoken[48,49] and to be on a par with that of adults by age 11-12 years.[48,50] The strategy is to list animals by the environment in which they are experienced,[47] a process thought to involve both the temporal (clusters of animals from a particular environment) and frontal (selection of a new animal environment) lobes.[48] We chose Animal Naming as a functional screening tool this reason as well as that it could be performed by all children without proprietary documentation. Although there were individual examples in our group of recently concussed children who demonstrated obvious impairment of this task when compared with their known baseline, as a group these failed to reach statistical significance and can be considered a negative result.

Although a tennis ball, stopwatch, and a dowel are required, these items are not commercial products, are easy and inexpensive to procure, and familiar to all children. Furthermore, the battery's deployment requires no more than 5 minutes to complete. The physical performance of these tasks in front of others we suggest is motivating to the children not only to demonstrate prowess but also to show readiness to return to regular activities. These such activities are often athletic in nature, and we found that poor performance when asked to demonstrate balance, ball handling skills, or stick catching were quantifiable and made conversations with the child and caregiver about athletic and school readiness much easier.

Statistically significant decrements in measures of performance for each task following a recent concussion were found when compared with children who had never had a concussion. There appeared to be no difference in performance between children with no lifetime history of concussion when compared with those who had ever been concussed, making these tasks particularly useful in discriminating the apparently negligible effects of any preexisting concussion from those of a recent concussion. In addition, performance impairment for Stick Drop, Wall Ball, and SMR was present up to 8 weeks after the inciting injury and suggests that a traditional view that resolution of physical concussion symptoms within a month of injury may be incomplete. Sensitivity and specificity results suggest that our tests are better at determining who is not concussed and under perform as screening tests. Ongoing development of the test content and broadening the scope of sampling may prove effective in improving how these tests perform.

Limitations of the study include a failure to account for the variety of athletic abilities in children, the impact of habitus on performance, the lack of proscribed follow-up intervals, the clinical meaning of fractional performance of ordinal numerical values that are statistically distinct, and the possibility of a practice effect. Child athletes may have been overrepresented in the ever-concussed group accounting for their better than expected performance on the Wall Ball test than children in the never-concussed or recently concussed group. Subjects were not told that they would be repeating the tasks at future visits, but were not questioned as to whether they had practiced at home for follow-up. The extent to which this may have affected performance in Animal Naming in particular is unknown. Similarly, data regarding the effect of the time of day, degree of sleep attained the night before testing, and other environmental factors expected to affect physical performance were not collected. Eligibility for study entry and the time of the initial visit was determined upon first clinic appearance after medical referral rather than at a specified time interval following the concussion, making the initial visit assessment results more heterogeneous than would have been the case had subspecialty assessment been more rapid.

These tests may be best interpreted if there is baseline data collection when there has been no concussion within 2 months of the office visit. In this study, we provide control data for Stick Drop and Wall Ball measures for children with no history of prior concussion and propose that post-concussion test performance is likely to be clinically meaningful if there is >1 step decrement in the SMR; a >3 cm increase in Stick Drop average over 5 trials; a >5-cm increase in the farthest Stick Drop distance on any 1 of 5 trials; and a >4 cm in the range across 5 trials for Stick Drop. Although Wall Ball results were statistically significant, they appeared to be of little practical utility because of within-person performance variability. The Stick Drop and SMR will be useful in serial assessments following concussion is unclear in this study. ■

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Table I. Concussion assessment instruments commonly deployed in children

Instruments	Acronym	References
Acute Concussion Evaluation Inventory	ACE	Gioia et al[1]
Automated Neuropsychological Assessment Metrics	ANAM	Reeves et al[2]
Axon Sports Computerized Cognitive Assessment Tool	CCAT	Louey et al[3]
Balance Error Scoring System	BESS	Davis et al[4]
Child SCAT 3	Child SCAT3	McCrory et al[5]
Immediate Post-Concussion Assessment and Cognitive Testing	ImPACT	Lovell et al[6]
King Devick Test of Visual Tracking	K-D	Heitger et al[7]
Maddocks Questions		Maddocks et al[8]
Post-Concussion Symptom Inventory	PCSI	Sady et al[9]
Post-Concussion Symptom Scale	PCSS	Lovell et al[10]
Reaction time	RT	Eckner et al[11]
Sports Concussion Assessment Tool 5	SCAT5	Davis et al[12]
Standardized Assessment of Concussion	SAC	McCrea et al[13]
Vestibulo-Ocular Motor Screen	VOMS	Cicerone et al[14]

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