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Editors

Concussions in Athletics

From Brain to Behavior

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Foreword

I recently saw a 16-year-old cheerleader who had suffered five concussions. She has dropped from an A student to a C student who needs special help. Another patient, a 12-year-old former cheerleader, after two concussions had to drop back to the first grade level in school.

Concussion in sport is a big deal. It is a common problem with consequences. There is the short-term issue of a period when the athlete cannot continue to play. But then there are longer term issues of post-concussive symptoms including increased sensitivity for subsequent concussions (second impact syndrome). And, even though there is no obvious damage to the brain on routine neuroimaging, there may well be brain damage leading to reduction in cognitive abilities or even, in severe cases, posttraumatic encephalopathy. It's a big deal for another reason; it is a problem with children and young adults, and concussion can change their lives forever. Of course, concussion can also occur with auto accidents and with war injuries, as well as everyday life, and similar issues emerge. Studies of athletes can well be generalized to other situations.

With an acute injury, it is important to recognize that a concussion has occurred and determine its severity. There can be a variety of symptoms including difficulty in thinking, concentrating or remembering, headache, nausea, dizziness, and imbalance. Clinical assessment can include drowsiness, disorientation, slow reaction time, memory loss, difficulty with balance and coordination, and emotional lability. In the post-concussion syndrome all these symptoms and signs can persist for variable periods of time.

There are approximately 300,000 sports-related concussions annually in the USA. It is interesting to consider in what sports they occur. A nice paper by Marar et al. [1] looked in detail at the epidemiology of concussions in high school athletes. They reported on 1,936 concussions in 7,778,064 athletic exposures. Boys' football gives the largest number of concussion with more exposures and with the highest rate overall. After that in numbers of concussions are girls' soccer, boys' wrestling, girls' basketball, and boys' soccer. After boys' football, the next highest rate is boys' ice hockey, then boys' lacrosse.

Chapter 3
Neuropsychological Testing in Sports Concussion Management: An Evidence-Based Model when Baseline Is Unavailable

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Abstract Since Barth and colleagues' seminal study used baseline neuropsychological testing as a model for sports concussion management, many collegiate sports medicine programs have adopted variations of their approach. However, no evidence-based strategy has yet been clearly articulated for the use of neuropsychological tests in concussion management that involves consideration of cases in which no baseline testing has been conducted. In this chapter, we articulate an evidence-based model for neuropsychological sports concussion management in collegiate athletes for cases in which baseline data are not available. The model involves an algorithm that is based upon base rates of impairment in a typical neurocognitive sports concussion battery, with decision rules that differ slightly for males and females. Although we use our population of collegiate athletes and the tests we administer as a framework to provide concrete values to the proposed algorithm, our evidence-based model could easily be applied to other sports concussion populations and neurocognitive test batteries. Our proposed neuropsychological concussion management guidelines provide an evidence-based model, while at the same time remain consistent with trends in the literature, suggesting that increasingly individualistic clinical concussion management approaches are most prudent.

Keywords Concussion • Neuropsychology • Neurocognitive • Evidence-based • Return-to-play

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Introduction

Barth and colleagues' [1] seminal study using baseline neuropsychological testing as a model for sports concussion management set a standard that continues to be influential today. Many school-based sports medicine programs have adopted variations of their approach, and a range of recommendations have been made for the use of neuropsychological testing within that framework. Although the literature is variable regarding how best to use neuropsychological testing, most investigators recommend the use of pre-injury baseline neuropsychological testing as the best practice for sports concussion management [1–7]. Still, baseline data is not always available and there is recognition that guidelines are needed for interpretation in such cases. In their "Consensus Statement on Concussion in Sport" article, McCrory and colleagues [6] suggested that an important area for future research was determining "best-practice" neuropsychological testing in cases where baseline data are not available. Also, in a position paper published under the aegis of the National Academy of Neuropsychology (NAN), Moser et al. [3] noted that neurocognitive tests can play a meaningful role in concussion management even in these cases. Nonetheless, neither article provides guidelines for how neuropsychological tests should be used when no baseline testing has been conducted.

The central goal of this chapter is to provide an evidence-based model for using neuropsychological testing in the management of sports-related concussion when no baseline is available. We will first summarize and evaluate existing approaches, focusing on the merits and limitations of baseline testing, the timing of testing post-concussion, and the "value-added" of neuropsychological tests in a sports concussion context. We then lay out the framework of our model. It is not our intent to suggest that the model presented in this article should replace the baseline model. Furthermore, a discussion of the case for or against the use of neurocognitive testing in a sports concussion framework goes well beyond the scope of this chapter and has been discussed at length by other investigators [8, 9]. However, we do touch upon the merits and limitations of such tests, as well as the pros and cons of conducting baseline testing.

Summary of Literature Recommendations for the Use of Neuropsychological Testing in Sports Concussion

Use of Baseline Testing

Although the literature is variable regarding how best to use neuropsychological testing, most investigators recommend the use of pre-injury baseline neuropsychological testing as best practice for sports concussion management [1–7]. As Guskiewicz et al. [2] and others [10] have articulated, the use of baseline testing for comparison with post-injury scores helps to control for idiosyncratic interindividual differences at baseline (e.g., ADHD, possible cumulative cognitive impact of prior concussions, cultural/linguistic differences, learning disorders, age, education, proneness to psychiatric issues). Controlling for such extraneous factors by using baseline testing should make neuropsychological tests more sensitive to the impact of concussions on specific individuals.

Still, the baseline paradigm for sports concussion is not without limitations. It has been criticized because there is no empirical evidence that the use of baseline testing improves diagnostic accuracy [8, 11], reduces risk of further injury [9], or predicts decline better than would be expected by chance alone [10].

Another significant limitation of the baseline model is the fact that most individual neuropsychological measures do not have well-established test–retest reliability for the types of intervals often used in sports concussion testing, when baseline and post-injury intervals can be years apart [9, 12–14]. As Mayers and Redick [13] note, a minimal standard for test–retest reliabilities for tests used to make clinical decisions is 0.70 and above. Test–retest reliability studies of the most commonly used computerized measure—the ImPACT—have been mixed. One study on the ImPACT [15] found generally acceptable levels of reliability (0.65–0.86 for the primary summary indices) when a group of healthy controls was tested 1–13 days apart. However, other investigators have found much lower test–retest reliability coefficients when using a longer interval between test administrations—between 0.23 and 0.38 for a 45-day test–retest interval [14], and between 0.30 and 0.60 for a 2-year test–retest interval [16], though the latter study reported somewhat higher values when intra-class correlations were used.

Test–retest reliabilities have generally been found to be acceptable for more traditional paper-and-pencil neuropsychological tests such as the Digit Span Test (0.80–0.91), Symbol Digit Modalities Test (SDMT) (0.72–0.80), Hopkins Verbal Learning Test-Revised (HVLT-R) (0.78), PASAT (0.80–0.90), and the COWAT (0.70–0.88) [12]. Despite these generally acceptable values, it is important to note that the time interval for establishing these reliabilities was considerably shorter than what typically occurs in the sports concussion framework.

Consideration of test–retest reliability coefficients such as these is critical because they are central to calculating the reliable change indices (RCIs) that are typically used to determine clinically significant change. If these reliability coefficients are low, then confidence intervals will be large and greater declines will be required post-concussion for change to be detected. Tests with low test–retest reliability coefficients, then, will be less sensitive to changes post-concussion than those with higher values.

An additional limitation of widespread baseline testing is logistical complexity and expense. Also, practice effects from prior test exposure can reduce neuropsychological tests' sensitivity post-concussion. Other limitations of the baseline model are outlined in Randolph et al.'s [9] recent critique. Overall, despite its utility in controlling for interindividual differences, the baseline model does have limitations. Given these considerations, using neuropsychological tests in the sports concussion framework when no baseline has been conducted should be considered.

Timing of Post-concussion Testing

There is no clear consensus on the timing of post-concussion neurocognitive testing. In Guskiewicz et al.'s [2] NATA Position Statement, the authors suggest that neurocognitive testing should ideally be conducted in the acute injury period to help determine the severity of the concussion, and then again when the athlete is symptom-free to help with return-to-play (RTP) decisions. However, they do not provide any clear indication of when during the acute injury period that testing might ideally occur.

In the ImPACT Test Technical Manual [17] on the "Best Practices" page from the ImPACT website (https://www.impacttest.com/pdf/improtocol.pdf), the authors recommend post-concussion ImPACT testing 24–72 h post-concussion to assess whether declines have occurred from baseline and to help with concussion management in general. They also recommend testing after this acute period once the athlete is symptom free both at rest and with cognitive exertion.

From the first consensus conference in sport [4], the participants recognized that the state of knowledge precluded any specific recommendations about timing of testing post-concussion, and they stated that clinical judgment should be applied on an individual basis. From the second consensus conference in sport, McCrory et al. [5] recommended that no neuropsychological testing be conducted until athletes were symptom free. They reasoned that there was nothing that such testing could contribute to RTP decisions, and that testing in the early post-concussion interval could contaminate future testing because of practice effects. They further noted that objective neurocognitive recovery could precede or follow self-reported symptom resolution.

The third consensus conference [6] maintained the recommendation that no neurocognitive testing be conducted until athletes were symptom free by their own self-report; however, these authors provided the caveat that some cases (especially children and adolescents) may warrant neurocognitive testing prior to symptom resolution. They reasoned that such testing could help with school and home management. A recent position statement published by the American Medical Society for Sports Medicine [18] was agnostic on this issue, asserting that the evidence was unclear regarding the optimal timing of post-concussion neuropsychological testing. In sum, the available literature indicates that there is no clear consensus on the timing of neuropsychological testing post-concussion.

The "Value-Added" of Neuropsychological Tests in a Sports Concussion Framework

Some investigators have argued that there is no "value added" to neuropsychological testing in the management of sports concussion, and that RTP decisions should strictly be based upon athletes' self-reported symptoms [8, 9]. However, research on this topic has revealed two important findings that counter such a recommendation: (1) A significant percentage of concussed athletes who report full symptom resolution still show objective neurocognitive deficits—either declines from baseline [19] or, when no baseline is available, worse neurocognitive performance than control subjects [20] and (2) neurocognitive tests can identify concussed athletes in the acute post-concussion period (within two days post-concussion) who deny any symptoms but show objective declines from baseline [7].

Although the "value-added" of neurocognitive tests to the concussion management process is controversial, beyond such considerations there are problems with relying exclusively on self-report of cognitive functioning in guiding RTP decisions. First, athletes have a high motivation to minimize symptoms following concussion because of their desire to return to play, a process articulated in Echemendia and Cantu's [21] "Dynamic Model for Return-to-Play Decision Making." Second, there is extensive literature demonstrating that self-reports of cognitive functioning are only weakly correlated with actual performance on objective cognitive tests, even in individuals who are motivated and who have not experienced any insult to the brain [22].

Harmon and colleagues [18] argue that there are at least three circumstances where post-concussion neurocognitive testing may be warranted: (1) In situations where athletes are presumed to be at high-risk because of prior concussions; (2) with athletes who are likely to minimize or deny symptoms so that they can return to play; and (3) to identify athletes with persistent deficits. Thus, these authors appear to recommend post-concussion neurocognitive testing under limited circumstances. One problem with only administering neurocognitive tests to athletes who are likely to minimize or deny symptoms is that such individuals can only be definitively identified if neurocognitive testing is conducted. Otherwise, how does one know? A limitation of only administering tests to identify athletes with persistent deficits is that, again, how does one know if athletes have "persistent deficits" if they are not actually tested? As indicated above, self-report of symptoms is suspect for a variety of well-established reasons, so relying on an athlete's self-report of symptoms is not going to be useful in identifying persistent deficits.

A Proposed Evidence-Based Model for Neurocognitive Concussion Management when no Baseline Is Available

Following Ellemberg and colleagues' [12] observation that the absence of scientifically validated algorithms for neuropsychological test interpretation has resulted in clinicians and researchers using idiosyncratic decision rules, as well as McCrory et al.'s [6] recommendation for "Best-Practice" guidelines, we articulate a model for the use of neuropsychological tests in a sports concussion framework when no baseline is available. We recognize that our model only represents a step in a process that should continue as new empirical knowledge about this topic accrues.

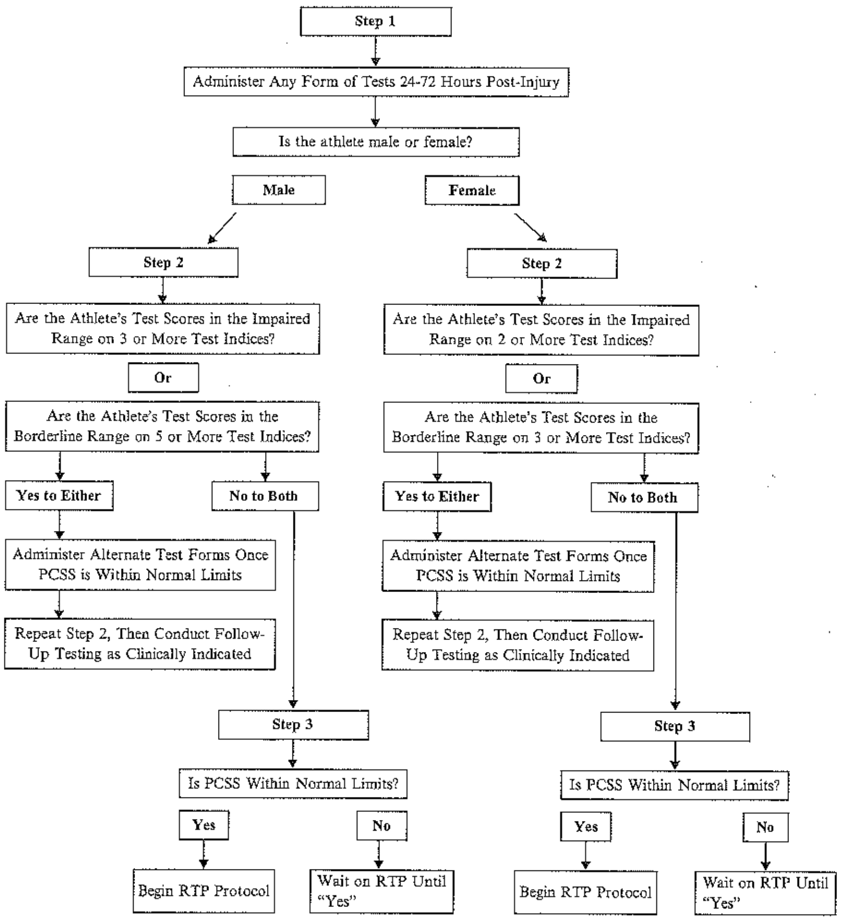

Fig. 3.1 Post-concussion neuropsychological testing algorithm when no baseline is available

Figure 3.1 illustrates our algorithm. Before discussing this in detail, we outline the tests in the battery on which the algorithm is based, which includes both computerized and paper-and-pencil tests. We then describe the evidence basis for each step of the algorithm. Note that there are separate decision rules for males and females. This is due to findings of gender differences in base rates of impairment using this same battery in Division I collegiate athletes [23]. Although there are factors that can influence the interpretation of neurocognitive test results including depression, number of prior concussions, and the presence of ADHD/learning disorders, we do not provide any systematic treatment of these issues, as they go beyond the scope of this chapter. Still, we acknowledge their potential importance in the interpretation

of neurocognitive tests in the sports concussion context. Although the present article is not an empirical research paper, per se, the study on which we base some of the framework of the algorithm [23] was conducted in compliance with University Institutional Review Board requirements and American Psychological Association ethical guidelines.

Measures

The battery we use as the basis for our model includes both computerized and paper-and-pencil measures. Although the use of paper-and-pencil measures can be logistically more complex and expensive than using computerized tests alone because they require fact-to-face administration, including such tests is likely to increase the sensitivity of the battery. Also, if neuropsychological tests are only used post-concussion, then the cost of administration is considerably lower.

Computerized tests. Computerized tests include the ImPACT [24] and the Vigil Continuous Performance Test (CPT) [25]. The following summary indices from the ImPACT are included: verbal memory composite, visual memory composite, visuomotor speed composite, and reaction time composite. Average delay (a reaction time index) is used for the Vigil CPT. Although more recent versions of the ImPACT are available, we based our algorithm on the 2.0 version because of the availability of data for our evidence-based model. This version appears to be highly correlated with more recent (including online) versions of the ImPACT.

Paper-and-pencil tests. These measures include the HVLT-R [26] (total correct immediate and delayed recall), the Brief Visuospatial Memory Test-Revised (BVMT-R) [27] (total correct immediate and delayed recall), the SDMT [28] (total correct within 90 s), a modified Digit Span Test [29] (total correct forward and backward sequences), the PSU Cancellation Task [30] (total correct within 90 s), Comprehensive Trail Making Test Trails 2 and 4 or 3 and 5 (CTMT) [31] (completion times for both parts), and the Stroop Color-Word Test (SCWT) [32] (time to completion for both color-naming and color-word conditions). Thus, across computerized and paper-and-pencil measures there are 17 test indices.

For most of the tests used, we suggest that alternate forms be used. The ImPACT has such alternate forms built into the program; alternate forms are available for all of the above paper-and-pencil tests with the exception of the modified Digit Span Test and SCWT.

Self-report. To measure post-concussion symptoms, we use the Post-Concussion Symptom Scale (PCSS). This measure includes a list of 22 common post-concussion symptoms. Examinees rate the extent to which they are currently experiencing each symptom on a scale from 0 to 6, with 0 indicating the absence of the symptom, and 6 being severe.

Algorithm of Decision Rules

As Fig. 3.1 shows, each step of the algorithm after the initial neuropsychological testing involves a question, and then an action depending on the answer to the question.

Step 1. The action at Step 1 is to administer the test battery at 24–72 h post-injury. The evidence basis for this stems from animal models showing that many elements of the neurochemical cascade in the brain following concussion peak at about 48 h post-injury, and the decrease in glucose metabolism that occurs at about 48 h post-injury is correlated with cognitive dysfunction in adult rats [33–35]. Also, neurocognitive research in humans has shown that the greatest cognitive impact post-concussion typically occurs within 24–72 h post-injury [1, 36–38], though there is considerable individual variability [38]. As such, testing athletes during this time interval should provide a likely estimate of the full impact of the concussion on the brain as manifested by neurocognitive test results. Also, if the athlete is free of neurocognitive impairment at this early stage (relative to base rates), then no further neurocognitive testing would necessarily need to be conducted post-concussion, and the RTP decision could be made based on other factors (e.g., self-reported symptoms, vestibular signs). If the athlete does show signs of neurocognitive impairment at this point, then the objective neurocognitive data could be used to assist in getting temporary academic accommodations while symptomatic (e.g., deferral of exams and other assignments, testing in a room free from distraction, extra time on exams). A more detailed rationale for testing at this early time point post-concussion, and possibly before self-reported symptom resolution, is provided below in the section entitled, "Why Recommend Testing During the Acute Concussion Phase?"

Step 2. The algorithm has different Step 2s for males and females because the study on which these specific decision rules are based revealed slightly different base rates for males and females. In this study, we examined baseline performance in 495 collegiate athletes on the same test battery outlined in this chapter [23], and impairment on a test was defined as performing 2 SDs or more below the mean of other athletes; borderline impairment was defined as 1.5 SD or greater below the mean. These criteria were used since currently there is no agreed upon definition of abnormally poor test performance on neuropsychological tests following concussion, and also to allow for some flexibility in decision making.

In this study, less than 10 % of males had five or more borderline scores, and less than 10 % of females had three or more borderline scores. Additionally, less than 10 % of males had three or more impaired scores, and less than 10 % of females had two or more impaired scores. We used these base rates as a foundation for the decision rules in our model. In light of such data, male athletes who are tested post-concussion who show impairment on three or more tests and female athletes who show impairment on two or more tests evidence highly unusual performance that is likely to reflect the impact of their concussion (see Fig. 3.1). Similarly, male athletes who are tested post-concussion who show borderline scores on five or more tests and female athletes who show borderline scores on three or more tests display highly unusual performance that is likely to reflect the impact of their concussion. The application of these data in decision rules is shown at Step 2 in Fig. 3.1.

Ideally, concussion programs adopting this algorithm would be advised to use a base rate of impairment data collected from athletes participating in their specific programs. In this way, the data used are likely to be most valid for that group of athletes for a particular neurocognitive test battery. If such base rates differ from what we report, relevant values could simply replace what we report from our athletes in the algorithm. If base rates of impairment are not available, it should be noted that other studies using test batteries of comparable length have reported similar base rates of impairment using a similar number of test indices in healthy older adults [39, 40], as well as children and adolescents [41]. Thus, although the direct evidence basis for this recommendation concerning base rates relies only on our one study of collegiate athletes, findings from these other studies suggest that these data are likely representative of base rates of impairment more generally when individuals are tested on a neurocognitive battery similar in length to ours. Also, the data we rely on for concrete decision rules in the algorithm can be thought of as a vehicle for describing the model rather than something to be rigidly applied. Again, ideally, local base rate norms based upon whatever battery of tests is used, if different from what we report, would replace the specific values in the algorithm.

If male or female athletes receive a "yes" response at Step 2, for either the impaired or borderline criterion, then the action is to "Administer Alternate Test Forms Once PCSS is Within Normal Limits." The evidence basis for this stems from findings showing that even when athletes report that they are symptom free, many still show evidence for objective cognitive impairment [19]. Additionally, relying on self-report of cognitive functioning when determining when athletes can return to play is likely to be inaccurate given the consistently replicated low correlation found between objective neurocognitive test performance and self-reported neurocognitive functioning [22]. Thus, any athlete should have to perform within normal limits neurocognitively prior to returning to play, and such decisions should not be based on self-reported cognitive functioning alone. Following this recommendation after a "yes" response, the algorithm indicates, "Repeat Step 2, Then Conduct Follow-Up Testing as Clinically Indicated."

Step 3. If either male or female athletes have a "no" response at Step 2, then the algorithm moves to Step 3 to consider the following question: "Is PCSS Within Normal Limits?" The determination of "within normal limits" is made using normative data from our sample of collegiate athletes at baseline on the PCSS. Similar to our comment above concerning the ideal framework being the use of local norms to determine base rates, normative data from local samples would ideally be applied here to the PCSS. Scores falling within the broad average range (i.e., standard score of 80 or above) are considered "within normal limits." If the answer to this question is "yes," then the recommendation is to begin the RTP protocol. If the answer is "no," then the recommendation is to wait on starting the RTP until the PCSS is within normal limits.

One complicating issue involves cases where athletes have a "yes" response at Step 2 (meeting the below base rate impaired or a borderline criterion), yet report being within normal limits in terms of their symptom report. Given that the recommendation following such an outcome is to "Administer Alternate Test Forms Once PCSS is Within Normal Limits," how does one proceed? There are no clear evidence-based guidelines for how to proceed here in terms of the precise timing of the next post-concussion testing point. A broad guideline would be to recommend testing the athlete again between 5–10 days post-concussion, given that many studies show that most collegiate athletes show full cognitive recovery by that point [1, 30, 36, 37, 42–44]. With that said, other research shows that some collegiate athletes do not recover within that window and take longer than two weeks for their neurocognitive functioning to normalize [44, 45]. Thus, more research will clearly be needed to refine this broad guideline. Studies that examine the duration for normalization of brain functioning in athletes who report being normal in terms of symptom report but show impairments neurocognitively would be ideal. Given the current state of the literature, the most prudent approach would be to rely more on individualistic clinical concussion management strategies employed by skilled clinicians to determine temporal sequencing of testing in these cases [46]. Factors, such as the urgency with which an RTP decision needs to be made (e.g., if a crucial game is imminent vs. the athlete's sport not being "in season"), as well as other individualistic factors (e.g., prior concussion history, the presence of clinically significant depression), would need to be considered. Thus, the model allows for considerable flexibility at this stage not only due, in part, to the absence of clear research evidence to guide decision making, but also due to idiosyncratic factors that are nearly always going to be at play in the clinical management of concussion.

Why Recommend Testing During the Acute Concussion Phase?

One potentially controversial recommendation in our algorithm is to routinely test athletes in the acute stage more systematically post-concussion. Many athletes are likely to still be experiencing some symptoms at the 24–72 h post-concussion point, and some investigators and clinicians have asserted that such testing should be avoided on a number of grounds. First, given that athletes are still symptomatic, some posit that such testing cannot contribute anything to the RTP decision, because clinicians are typically not going to put athletes back to play who are still experiencing self-reported symptoms. Second, it has been suggested that such testing could exacerbate the athlete's symptoms. These are reasonable concerns; however, to our knowledge, there is no published study showing that recently concussed, still symptomatic adult athletes show more of an increase in symptoms following such neurocognitive testing than healthy controls. We assert that the value of such acute

testing outweighs the potential minor risk (as yet empirically undemonstrated) of a temporary increase in symptoms. The caveat to this, of course, involves cases where symptoms are so severe that testing could be harmful in exacerbating already severe symptoms, or where the nature of such symptoms would likely substantially interfere with test performance (e.g., severe dizziness, nausea, or headache, among others). This is where individualistic concussion management again becomes important [46].

One benefit of such testing in the early acute phase is to help document the severity of the concussion. Athletes who show more normative impairments at this acute stage could be managed more conservatively once RTP procedures have begun than those who were back to their likely premorbid cognitive level, or nearly back to such a level. Another benefit, as noted earlier, is that early objective documentation of deficits could result in athletes quickly being able to secure needed academic accommodations during their recovery period. A third benefit of acute testing is that it may show that the athlete is in fact back to baseline neurocognitively, even at this early stage. If this is the case, then more rapid return to play could potentially occur. Although an athlete's medical well-being must always be the most important consideration of sports medicine professionals, athletes performing at a high level of sport (e.g., Division I college, the basis of our algorithm) could suffer significant harm in terms of their status on the team and ability to compete in important games and maintain their scholarships if they are held out of play for an unnecessarily long period of time.

A final benefit of conducting systematic testing during this acute period post-concussion and at other systematic time points is that the neurocognitive results following any future concussion could be compared with the results from the previous concussion to assess whether the range and severity of cognitive impairments increase. If athletes are tested at different points post-concussion, then such systematic comparisons would not be possible. Athletes who suffer multiple concussions and show an increased range and severity of cognitive impairments with each successive concussion can then be treated more conservatively.

Limitations

Our algorithm represents an initial attempt to develop systematic guidelines for decision-making post-concussion in cases where baseline data are not available. Although we provide systematic decision rules, there is much room for individualistic concussion management, and we spell out a number of examples where such factors come into play. The neuropsychological test battery we recommend is relatively lengthy and logistically complex; however, applying it in cases where baseline testing has not been conducted significantly reduces such complexity. Also, the algorithm can be adapted to different test (possibly shorter) batteries and different athlete groups when base rates of impairment data can be derived from such groups.

Future Directions

Future work should include studies to validate the algorithm in other samples independent of our lab group, particularly in test groups of collegiate athletes with and without concussions, followed by testing at the same time intervals as suggested by our model. Examining base rates of impairment on the test battery in individuals with ADHD and/or learning disorders would also be a valuable focus for future work.

More work is also needed concerning the objective impact of undergoing a neurocognitive concussion battery during the acute concussion phase in collegiate athletes. Measuring self-reported post-concussion symptoms prior to and after neuropsychological testing in concussed and non-concussed athletes would be one way of assessing this.

Our recommendations are necessarily tentative, given the limited evidence available for some aspects of the proposed algorithm (e.g., the ideal timing of post-concussion testing during the acute injury period, ideal temporal sequence of testing once athletes are normative symptomologically, but still impaired neurocognitively). However, we hope that our algorithm provides a template for improving neurocognitive concussion management in collegiate athletes.

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Chapter 4
Feasibility of Virtual Reality for Assessment of Neurocognitive, Executive, and Motor Functions in Concussion

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Abstract The purpose of the research presented in this chapter is to investigate if virtual reality (VR) neurocognitive, executive, and motor function assessment tools are susceptible to practice and fatigue effects similar to those currently used in a clinical practice. Fifteen athletically active and neurologically normal Penn State students participated in a VR "practice effect" study. Another 15 Penn State football players participated in an "effect of fatigue" study on neurocognitive, balance, and executive functions. Subjects performed VR tests on several occasions. The statistical analysis was conducted to examine the VR measures as a function of testing session (practice effect) and physical fatigue (prior to and after full contact practices). The number and type of the full contacts during the practices were assessed via a specially developed observational chart. There are several major findings of interest. First, all subjects reported the "sense of presence" and "significant mental effort" while performing the VR tests. Second, neither effect of testing day ($p > 0.05$) nor effect of VR testing modality ($p > 0.05$) was revealed by ANOVA. Third, physical fatigue did not influence the VR measures in the majority of football players under study ($p > 0.05$). However, there was a reduction in several VR performance measures in football players who sustained prior concussive injuries. The findings

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