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Spectrum of acute clinical characteristics of diagnosed concussions in college athletes wearing instrumented helmets

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Abstract

Object. Concussive head injuries have received much attention in the medical and public arenas, as concerns have been raised about the potential short- and long-term consequences of injuries sustained in sports and other activities. While many student athletes have required evaluation after concussion, the exact definition of concussion has varied among disciplines and over time. The authors used data gathered as part of a multiinstitutional longitudinal study of the biomechanics of head impacts in helmeted collegiate athletes to characterize what signs, symptoms, and clinical histories were used to designate players as having sustained concussions.

Methods. Players on 3 college football teams and 4 ice hockey teams (male and female) wore helmets instrumented with Head Impact Telemetry (HIT) technology during practices and games over 2–4 seasons of play. Preseason clinical screening batteries assessed baseline cognition and reported symptoms. If a concussion was diagnosed by the team medical staff, basic descriptive information was collected at presentation, and concussed players were reevaluated serially. The specific symptoms or findings associated with the diagnosis of acute concussion, relation to specific impact events, timing of symptom onset and diagnosis, and recorded biomechanical parameters were analyzed.

Results. Data were collected from 450 athletes with 486,594 recorded head impacts. Forty-eight separate concussions were diagnosed in 44 individual players. Mental clouding, headache, and dizziness were the most common presenting symptoms. Thirty-one diagnosed cases were associated with an identified impact event; in 17 cases no specific impact event was identified. Onset of symptoms was immediate in 24 players, delayed in 11, and unspecified in 13. In 8 cases the diagnosis was made immediately after a head impact, but in most cases the diagnosis was delayed (median 17 hours). One diagnosed concussion involved a 30-second loss of consciousness; all other players retained alertness. Most diagnoses were based on self-reported symptoms. The mean peak angular and rotational acceleration values for those cases associated with a specific identified impact were 86.1 ± 42.6*g* (range 16.5–177.9*g*) and 3620 ± 2166 rad/sec2 (range 183–7589 rad/sec2), respectively.

Conclusions. Approximately two-thirds of diagnosed concussions were associated with a specific contact event. Half of all players diagnosed with concussions had delayed or unclear timing of onset of symptoms. Most had no externally observed findings. Diagnosis was usually based on a range of self-reported symptoms after a variable delay. Accelerations clustered in the higher percentiles for all impact events, but encompassed a wide range. These data highlight the heterogeneity of criteria for concussion diagnosis, and in this sports context, its heavy reliance on self-reported symptoms. More specific and standardized definitions of clinical and objective correlates of a "concussion spectrum" may be needed in future research efforts, as well as in the clinical diagnostic arena.

Keywords: concussion, traumatic brain injury, biomechanics, athletes, football, hockey

Abbreviations: ATC = certified athletic trainer; HIT = Head Impact Telemetry; ImPACT = Immediate Post-Concussion Assessment and Cognitive Test; NCAA = National Collegiate Athletic Association.

Sports concussions have been the focus of intense attention in recent years, in part related to concerns about catastrophic second-impact syndrome, shortand long-term neurocognitive effects, and the possible contribution of repeated concussions to delayed brain deterioration.[19,20,22,37,40] Because of these concerns, more than 26 states to date have enacted legislation requiring students with concussions to be evaluated by appropriately trained personnel before returning to sports participation. However, the definition of concussion has evolved over time and also varies among medical specialties, presenting difficulties with knowing exactly which players meet the criteria for this diagnosis and require mandated evaluation. Specifically, the definition has ranged from requiring a loss of consciousness or amnesia for the event, to including varying degrees of alteration in level of consciousness, to including any symptoms such as headache or dizziness after head impact or head motion. [2,13,15,32,34,39,43] Even in the context of consensus definitions, how diagnostic criteria are applied or ascertained is not always clear and may be changing over time.[1]

Between the fall of 2007 and spring of 2011, our group has studied the biomechanical basis of concussion and the effects of repetitive head impacts on 450 helmeted athletes in 3 NCAA athletic programs (Brown University, Dartmouth College, and Virginia Tech). In this comprehensive investigation, from which the data in the current report are drawn, athletes underwent a clinical screening battery—including measures of symptom reporting, cognition, and, at some sites, balance testing, gene sampling, and neuroimaging—prior to their athletic season, following a diagnosed concussion, and postseason.

The goal of the present study was to analyze the spectrum of clinical presentations that were used by the team medical personnel to make the diagnosis of sports-related concussion within this single multisite study of helmeted college athletes. We sought to characterize the reported histories and signs and symptoms recorded by team medical staff that were used in making a concussion diagnosis, as well as their association with other measured parameters used in this study, including head impact biomechanics. While detailed biomechanical correlates have been published elsewhere or are under review, the specific focus of this report is to characterize the clinical criteria used operationally to diagnose concussion in this study of athletes with repetitive head impacts.

Methods

A total of 450 athletes who had signed informed consent forms approved by their college's institutional review board participated in the study, which was approved by the Dartmouth, Brown, and Virginia Tech institutional review boards. During the season, athletes participating in contact sports (football, ice hockey) wore instrumented helmets to record their head impact exposure (impact frequency, location, and magnitude) during all organized sessions of play (practices, scrimmages, and games). In the event that a diagnosis of concussion was made, the injured athlete and subject-matched controls from both contact and noncontact sports were subjected to the same clinical examinations. In this communication, we focus only on athletes who were diagnosed by team medical personnel as having a concussion during the seasons under study, and we report on the clinical observations and symptomatology that led to the diagnosis of concussion.

Clinical Assessment and Diagnosis of Concussion

Because the intent of the larger, overall study was to measure biomechanical correlates of diagnosed concussions in collegiate athletes under contemporary conditions of play, the operational definition of what constitutes a concussion was left to the discretion of each team's medical staff (certified athletic trainers [ATCs] and team physicians), according to the guidelines currently in use at that institution during the period of study. Specifically, no attempt was made to influence the recognition, diagnosis, or management of injuries, nor return to play guidelines used, during the study. It was felt that in this way, the most accurate representation of the current state of diagnosis and management would not be altered by the performance of the research.

Each of the 3 institutions had general guidelines already in place at the time of the study for the identification and management of concussion. Certified athletic trainers were present at each session of play. All schools agreed with previously published definitions of concussion as a process affecting the brain induced by traumatic mechanical forces and resulting in the rapid onset of short-lived impairment of neurological function, often accompanied by additional characteristic signs and symptoms.32 For the purposes of this study, "diagnosed concussion" was defined as a specific diagnosis of an acute or subacute concussion for an individual player by a member of the team's medical staff, using their standard operational definition in use for that team at the time of the study. Athletes who were identified as or suspected of having a concussion were assessed with standard protocols, as follows.

1. For athletes with suspected concussion diagnosed during a session, the ATC generally assessed the athlete on site immediately and at regular, frequent intervals for the development of mental status abnormalities and/or postconcussive symptoms at rest and also with exertion if appropriate. The exact tools used for the sidelines assessment varied among institutions and between sports, with schools typically using tools derived from standardized symptom checklists,[32] assessment of answers to specific questions involving orientation and memory,[31] and additional on-field assessments, such as balance testing.[23]

2. Athletes who reported symptoms after, rather than during, the session were assessed in the training room at the discretion of the ATC, typically using a symptom checklist, brief neurological screening, and in some instances, balance testing.

3. The team medical staff (ATC or physician) used a symptom checklist for each subsequent follow-up assessment, typically until all signs and symptoms were absent at rest and during physical exertion.

4. In addition to these preexisting standard team guidelines, as part of the study protocol, all participants completed a preseason evaluation that included symptom checklists, computerized ImPACT testing and, at one site, more detailed paper and pencil neuropsychological evaluations. ImPACT (Immediate Post-Concussion Assessment and Cognitive Test) is a widely used computerized neuropsychological screening tool for sports-related head impact assessment.[25,38]

Presenting Symptoms and Timing Documentation

Athletes identified by the medical staff as having suspected injuries were assessed and their findings documented on the sidelines or at the time of clinical presentation by the usual methods employed at each participating site; documentation typically included a free-text form or notes describing the events and/or complaints. These trainer assessments were used to collect descriptive data about the specific signs and symptoms exhibited, their timing and relationship to identified contact events, and the time of diagnosis. Some, but not all, trainers documented sidelines checklist results obtained on site; this was not required by the overall study protocol. Additionally, basic demographic and anthropometric data (age, height, weight), history of prior concussion, and date of symptom resolution were provided for the study database.

Once an athlete had been diagnosed as having a concussion, the athlete was instructed per study protocol to report for assessment in the training room within 24–72 hours of the event. Any additional documentation regarding symptom onset and circumstances that was collected during this assessment was reviewed for the study. Using all available on-site and initial training room presentation information, specific data about injury circumstances, symptom type, onset, and diagnosis were analyzed. Follow- up data collected as part of the ongoing larger study (such as serial ImPACT testing, more detailed neuropsychological tests, and/or brain imaging) were not used in the present analysis.

Head Impact Measurement

During all practices and games, players wore either football (Riddell Sports) or hockey helmets (Easton Stealth S-9, Easton Sports; CCM Vector, Reebok) instrumented with the Head Impact Telemetry (HIT) System (Simbex). The HIT System was designed to record in-vivo acceleration of the head following impact, and both its function and validation have been previously described.[4,10,12,14,18,21,22,26] In brief, each accelerometer is positioned against the head to isolate the head from helmet vibrations, and, when an impact is detected, data are transmitted to a sideline receiver connected to a laptop computer. Accelerometer data recorded from each impact are processed using an optimization algorithm to solve for the linear and rotational acceleration at the head center of gravity and impact location.[8,9] From these available data, descriptive statistics were calculated for athletes in whom concussion was diagnosed; these statistics included the number of impacts sustained on the day of injury and within 7 days of injury, the peak linear and angular acceleration of specific identified impacts associated with a diagnosed concussion, and the location of the specific impacts (separated into 4 general head regions—front, back, top, and side).

Data Element Definitions and Analysis

To analyze the degree to which concussions were associated with an identified impact event, concussion events were characterized as a) attributed by the player or observers to a specific identified impact (or, in some cases, impact sequence of more than one hit in close temporal proximity, such as head-to-head followed immediately by head-to-ground); b) no specific impact event identified; or c) unknown. For the purposes of the present report, data collected from the helmet accelerometer array were not used to characterize whether a specific identified impact event occurred in association with symptom onset.

To analyze timing of onset of signs and/or symptoms in relation to the impact event, onset of symptoms relative to a causative impact was categorized as a) immediate or near immediate; b) onset delayed, with the specific timing of onset noted; or c) unknown. For purposes of this study, "immediate or near immediate" refers to those events in which the athlete left a session for assessment by the trainer. To further assess the relationship of onset of symptoms relative to impact, the overall group of 48 concussion cases was divided into those that could be associated with a specific impact by either the athlete or observers (31 cases), and those in which the available descriptions state specifically that there was no specific identified impact (13 cases). Four additional diagnosed concussions had insufficient data regarding an identified impact, so these were excluded from this part of the analysis.

Timing of diagnosis was categorized as a) immediate or near immediate; b) delayed, with timing noted; or c) unknown. "Immediate or near immediate" diagnoses included those events in which the player left the session for assessment by the trainer. Delayed diagnoses were those in which ongoing symptoms were brought to the attention of the trainer at a later time, as well as situations in which the player had delayed onset of symptoms.

Mental status was categorized as a) no change; b) subjective change such as "feeling in a fog," trouble with memory, difficulty concentrating, or drowsiness; c) objectively observed by others; or d) unknown. The number of player-reported prior concussions was listed or was designated as unknown.

The methods used to ascertain the clinical characteristics of players in whom concussions were diagnosed in this study are descriptive. More detailed analyses of the biomechanical forces experienced by helmeted athletes, the cognitive correlates of diagnosed concussions as well as the corresponding data from matched controls, and the relationship between these factors have been previously reported or are ongoing.[3–5,10,28,35,36]

Results

During the 4 years of data collection, 12 team seasons (3 teams for 4 seasons) were monitored in football, 6 team seasons (2 teams for 3 seasons) in female ice hockey, and 4 team seasons (1 team for 3 seasons and 1 team for 1 season) in male ice hockey. A total of 486,594 head impacts were reported from the 450 participating athletes. Fortyeight separate concussions were diagnosed in 44 individual players, with 4 players sustaining 2 concussions each during the study period. Of these diagnosed concussions, 40 were in football, 7 were in women's hockey, and 1 was in men's hockey (Table 1).

Relation to Identified Impact Events

Thirty-one of 48 diagnosed concussions were associated with an identified impact event by report of the player or observers, while in 13 concussions, no specific impact event could be identified. Four additional events had insufficient descriptive data to characterize whether a specific impact was correlated with symptom onset (Table 1).

Table 1. Clinical and biomechanical characteristics of athletes diagnosed with concussion by team medical staff*

Characteristic	Value
incidence	
no. of impacts recorded	486,594
no. of participating athletes	450
no. of diagnosed concussions (40 football, 7 women's hockey, 1 men's hockey)	48
no. of athletes w/ concussion diagnosis	44
presenting symptoms/signs	
loss of consciousness	1
mental slowing, confusion, "in a fog"	36
headache	29
dizziness	19
neck pain	11
head or neck pain only—no change in mentation	7
identified impact & timing of symptom onset	
specific impact event identified by player/observers	31
immediate onset of symptoms	19
delayed onset of symptoms	5
unknown onset of symptoms	7
no specific impact event identified by player/observers	13
immediate onset of symptoms	5
delayed onset of symptoms	6
unknown onset of symptoms	2
timing of diagnosis	
immediate or w/in minutes	8
later same day	19
next day	10
2–4 days	9
prior concussions	
none	15
1	13
2	4
3	1
unknown	15
biomechanics	
peak linear acceleration *(g)*	
mean	86.1 ± 42.6
range	16.5–177.9
peak angular acceleration (rad/sec^2)	
mean	3620 ± 2166
range	183–7589

* Values refer to concussions unless otherwise indicated.

Presenting Symptoms

The majority of concussions were diagnosed on the basis of subjective complaints voiced to the team medical staff, usually the ATC, and recorded descriptively at the time of diagnosis; most often one or two major symptoms were reported (Table 1). Immediate or delayed symptoms of variable degrees of mental slowing, "clouding," confusion, difficulty concentrating or remembering, or feeling "in a fog" were described at the time of presentation by the athlete in 36 cases. Headache was reported in 29 cases; dizziness in 19; and neck pain in 11. While few players presented to the trainer with stated chief complaints of imbalance, fatigue, irritability, emotional lability, nausea, hearing, or vision problems, these were endorsed with variable frequency in those players for whom symptom checklists were obtained at the time of injury, with "fatigue," "balance difficulty," and "blurred vision" being the most common (18, 15, and 15 players, respectively). Some athletes presented with complaints using vernacular or nonspecific descriptors such as feeling "messed up," "weird," "out of it," or "not right." Seven athletes in whom concussion was diagnosed reported no change in any aspect of mental status or cognition, having somatic complaints only (for example, headache or neck pain). In 3 athletes there was inadequate information to determine mental status changes.

Observed Signs at Time of Diagnosis

In addition to subjective reported symptoms, some athletes had witnessed signs of concussion (that is, signs observed by other people), but this occurred in the minority of diagnoses. In one concussion event there was a 30-second loss of consciousness, but all other players retained alertness. In 7 athletes (including the player with loss of consciousness), changes in speech, affect, or mentation were noted by other observers (Table 1).

Timing of Onset of Signs and/or Symptoms

Nineteen of the 31 diagnosed concussions that were associated with an identified specific impact were characterized by immediate or near-immediate onset of symptoms. In 3 of 31 events, symptoms were specifically described as delayed in onset on the same day (later in the session, after the session, or that night), and in 2 instances the symptoms were first noted on the next day. In an additional 7 diagnosed concussion cases, the timing of onset of symptoms was unknown.

In contrast, of the 13 players with diagnosed concussions without a specific identified single impact, the descriptions of signs and symptoms by the trainers suggested that 5 players had relatively acute symptom onset during play/practice, 6 had delayed symptom onset after play (after session or in subsequent days), and in 2 the timing of symptom onset was unknown (Table 1).

Timing of Diagnosis

In 2 of the 48 diagnosed concussions, there was insufficient information to estimate time of diagnosis. Of the remaining 46 diagnosed concussions, 8 were diagnosed immediately or within several minutes of the event, and 38 were diagnosed after a delay ranging from 10 minutes to 4 days (mean 23 hours; median 17 hours). Of the 38 concussions with delay to diagnosis, 19 were diagnosed on the day of the event, 10 were diagnosed on the next day, and 9 were diagnosed between 2 and 4 days after the event (Table 1).

Prior Concussions

Fifteen players with diagnosed concussions had no prior concussions by self-report, 13 had 1 prior concussion, 4 had 2 prior concussions, 1 had 3 prior concussions, and in 15 players the prior concussion status was unknown.

Biomechanical Parameters of Diagnosed Concussions

For those players with diagnosed concussions associated with a specific impact event, the mean peak linear acceleration was 86.1 ± 42.6*g* (range 16.5–177.9*g*) and the mean peak angular acceleration was 3620 ± 2166 rad/sec2 (range 183–7589 rad/sec2) (Table 1). Impacts to the front of the head (n = 13) accounted for the most impacts associated with diagnosed concussion, followed by the top (n = 9), back (n = 8), and side (n = 5).

The total number of impacts on the day of injury and in the previous week were available for 35 of the 48 instances of diagnosed concussion; the respective mean values were 19.5 ± 15.7 (for number of head impacts on the day of injury, range 2–53) and 49.7 ± 43.7 (for the number of impacts within 7 days of injury, range 4–181).

Discussion

The main findings in this report were that many players had delayed onset of symptoms after an impact event, the majority of players had delayed diagnosis (delays of hours to days), more than a third of diagnosed concussions were not associated with a specific impact event, and biomechanical correlates, while averaging at the high end of the spectrum, showed significant variability. These observations may raise questions about whether current diagnostic methods and operational definitions of concussion in the context of athletics, based largely on self-report of specific clinical symptoms, capture those individuals actually at risk for short-, intermediate-, and long-term consequences of injury. The findings also point out the differences between the diagnosis of concussion in the context of sport and the cases typically seen by consulting neurosurgeons in emergency departments, in which a single clearly identified event is associated with immediate onset of symptoms including alteration in mental status. The potential consequences of these differences for medical decision making and for further research are explored further below.

Concussion Definitions

Although concussion has been the focus of a great deal of recent attention, the entity has been difficult to define, both operationally and with respect to underlying pathophysiology. Clinical criteria for the diagnosis of concussion have varied over time and among specialties. Historically, concussion was defined as a brief loss of consciousness sustained after head impact.[13,42] These clinical events could be demonstrated by large-animal modeling to occur at the lower magnitudes of a spectrum of angular deceleration, which, at higher magnitudes, leads to diffuse axonal injury and prolonged coma.[15,34] Theories of why consciousness is impaired after head impact have included vascular, reticular, centripetal, pontine cholinergic, and convulsive hypotheses, but the actual situation in vivo remains incompletely understood.[39]

The definition of concussion later was widened to include transient alterations in consciousness without actual loss of consciousness, with the recognition that similar postconcussive symptoms, including amnesia, could occur in both scenarios.[43] The relatively recent attention to sports injuries has contributed to further evolution of operational criteria used to make a concussion diagnosis. In part because of concerns about under-recognition, consensus conferences such as the Zurich Conference formulated a new definition, which included any type of alteration in mentation, such as confusion, disorientation, or mental clouding, as opposed to relying specifically on loss of consciousness or amnesia.[32]

Studies of series of patients with concussion have grouped postconcussive complaints into categories, including somatic, emotional, cognitive, and sleep.[16,17] Operational definitions of concussion used by some sports personnel more recently have included the occurrence of any of these types of symptoms, whether any specific loss of consciousness, amnesia, or alteration of mentation occurs. Thus, a player with, for instance, transient headache or dizziness only, may be diagnosed as having a concussion in some contexts. While broadening the scope of symptoms used to make a diagnosis, these approaches have not specifically addressed variability in timing of onset of symptoms, nor do they guide the clinician in how to handle the situation in which symptoms are reported without being associated with a specifically identified impact event. This has led to confusion on the part of coaches and trainers, parents, and clinicians, with respect to what exactly constitutes a concussion and who needs to be referred for evaluation.

Variability in Concussion Diagnostic Criteria

The data collected in this study reflect diagnostic criteria used for concussion in the context of collegiate sports, which may have unique characteristics compared with other medical settings for concussion diagnosis. In this study, while athletes typically sustained multiple impacts on the day of injury, only about two-thirds of diagnosed concussions were attributed to a specific impact event by the player or team staff. A minority of diagnosed concussions had objective neurological signs including only one with loss of consciousness, and 7 players had no mental status changes. While half of players with concussion had immediate onset of symptoms, many specifically reported delayed symptom onset, and more than 80% of concussion diagnoses were made after a delay, in some cases up to several days. Despite this variability, symptoms did cluster along the lines described by previous researchers, with a preponderance of subjective transient alteration in cognition and headache.[24] The operational diagnosis of concussion used in the sports setting may not reflect the same injury spectrum seen by neurosurgeons in an emergency department or hospital, where a single impact event associated with clear loss of consciousness is more likely to be the reason to obtain neurosurgical consultation. This may result in potential differences between disciplines in patient populations described by the same terminology.

Variability in Biomechanical Correlates

For those diagnosed concussions that were attributed to a specific contact event by the athlete or observers, the measured accelerations in the present study clustered at the high end of the spectrum seen in these sports overall, but considerable variability was encountered. The mean peak linear and angular accelerations for contact events associated with diagnosed concussion (Table 1) were greater than the 95th percentile for peak linear acceleration reported previously in football (62.7*g* and 2975 rad/sec^2) and for hockey (43.7*g* and 4674 rad/sec^2 for males; 44.9*g* and 3709 rad/sec^2 for females).[5,11] However, there were a number of contact events associated with a diagnosis of concussion that demonstrated considerably lower accelerations. Conversely, many players had similar or higher accelerations recorded and did not report symptoms or have neurological signs reported by other observers.[11]

The variability in measured accelerations in players with diagnosed concussions might reflect a number of factors. First, multiple biomechanical variables exist (number of prior impacts, linear acceleration, rotational acceleration, impact location, impact duration, and plane of rotation), each of which may influence injury, and the combination of these factors may result in different clinical presentations. Prior impact history may precondition the brain to development of subsequent symptoms with additional lower magnitude accelerations, or, conversely, may be responsible for meliorated or delayed symptoms. Variability in symptom reporting among players may limit correlation between measured accelerations and symptoms. Host factors including neuroanatomical, vascular, maturational, and genetic factors affecting injury response and repair may influence the experience of specific signs or symptoms. Additionally, while head kinematics obtained from the HIT System can be combined with finite element models to obtain estimates of brain tissue motion following impact, there is at present no technology available that can measure actual strains experienced by the brain in vivo, which may vary despite similar head accelerations.30,41 Finally, while it has been demonstrated that head impact kinematics obtained from the HIT System are highly correlated with laboratory surrogates, measurements for any single impact should be assumed to contain error dependent on both the measure of interest and impact conditions.[4] More detailed analysis of these biomechanical factors and their relationship to clinical signs and symptoms using data from the helmet accelerometer studies is ongoing.[3,28,30,36]

Implications for Prevention and Intervention Trials

The rationale for accurately diagnosing "concussion" is to adequately prevent and manage both short-term and more long-term consequences of injury. Concerns over acute impairments after head injury that could put performance at risk both in sports and in the military have led to the development of a variety of strategies to enhance immediate diagnosis, ranging from sideline cognitive tests to sophisticated neurophysiological and biomarker measures. [16,27] Return to play after unrecognized hemorrhage or vasomotor instability is thought to increase the risk of the rare but highly morbid second-impact syndrome, which can occur over an acute to intermediate time frame, up to several weeks after initial injury.[7,37] Likewise, exacerbation of cognitive dysfunction due to potentially synergistic effects of repeated injuries during this intermediate time frame has been hypothesized.[6,29] More recently, it has been suggested that mechanical trauma may begin a chain of events, at least in some susceptible individuals, leading to more chronic changes, including psychiatric disorders and dementia.[33]

One of the main goals of diagnosis of clinical or subclinical brain dysfunction is to prevent those events that can cause acute, intermediate, and/or long-term harm. Historically, diagnosis has rested on specific clinical signs and symptoms, but these may be unreliable indicators of actual cellular, subcellular, or vascular injury or predictors of subsequent adverse consequences after head impact events. It is possible that deleterious pathophysiological cascades are initiated even when signs and symptoms are absent. Conversely, some symptoms may not, in fact, predict increased risk for specific deleterious consequences. Thus, different symptoms may reflect different networks or processes, each of which may expose individuals to specific acute or delayed risks, and may have different temporal profiles for repair and resolution. Current use of return to baseline neurocognitive scores, along with lack of signs or symptoms at rest and exertion, as a gate for return to play has not yet been validated as an indicator that the various potential risks of adverse consequences from return to play have passed. It is possible that technological adjuncts that can measure mechanical loads, biomarker arrays, cerebrovascular reactivity, or other parameters may be better predictors of risk and prognosis than are clinical signs and symptoms.

Treatment trials also rely on appropriate prediction of risk factors for poor outcome and on identifying interventions that can improve on current management. If a trial includes both patients who are at high risk for an outcome and those who have minimal risk, the treatment effect will be diluted, and potential efficacy difficult to discern.

For all these reasons, the single term "concussion" as currently used in clinical practice may encompass such a wide spectrum of entities that it may be of limited use in furthering understanding of traumatic brain dysfunction/ injury at the milder end of the severity spectrum. Having better descriptive and diagnostic tools to characterize these events, to predict specific outcome parameters, to prevent reinjury, and to stratify treatment trials would be welcome, and likely would involve refinement in clinical definitions as well as the use of adjunctive diagnostic tests. A more encompassing term such as "concussion spectrum" may reinforce the idea that specific characterization tools for individual patients still need to be defined to reflect potentially different pathophysiological entities and their various associated consequences. It is conceivable that multiple repetitive head contacts, such as those analyzed in this study, have a significantly different pathophysiological and/or temporal profile compared with the single-event, loss-of-consciousness concussion seen very commonly in emergency departments. These data also suggest that at the present time, the presence or absence of concussion "symptoms" cannot be strictly equated with the presence or absence of cellular, subcellular, or neurovascular injury or damage to the brain.

Conclusions

This study demonstrates the wide variety of presenting symptoms, timing of symptom onset and diagnosis, and biomechanical correlates of diagnosed concussion as defined in contemporary collegiate sports. Many players had delayed onset of symptoms, and most had delayed diagnosis. It remains unclear to what extent these various clinical criteria actually predict acute, intermediate, and long-term risks after mechanical loading of the head, compared with the risks in players with similar mechanical loads who do not experience or report symptoms. Further work is ongoing to determine whether specific clinical profiles, biomechanical parameters, test scores, imaging features, or genetic characteristics best predict those patients at risk for adverse consequences from participation in contact sports.

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