HEAD IMPACT MONITORING: WHAT NEW METHODOLOGIES COULD DO FOR CONCUSSION BIOMECHANICS

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Concussion has become a world-wide concern for sports participants. *In-vivo* head impacts monitoring has long been proposed as a way of identifying and even helping to prevent concussions. Several head impact devices were developed to measure head kinematics on the field, allowing the study of a wide range of sports. However, after fifteen years of data collection and despite a better understanding of injury mechanisms, concussion biomechanics still presents numerous challenges. This study aimed to summarize current knowledge of head impact monitoring via narrative and systematic reviews. The discussion was focused on how technology might have limited previous research, and how innovative analyses approaches might provide new opportunities to further our appreciation of concussion biomechanics.

KEYWORDS: Traumatic brain injury, accelerations, machine learning.

INTRODUCTION: Concussion has become a world-wide concern for collision and contact sports participants (McCrory et al., 2017). It is one of the most commonly reported injuries in sports such as American Football (Dompier, Kerr, Marshall, & et al., 2015) or rugby (Fuller, Taylor, Kemp, & Raftery, 2016). Recent research has revealed that a history of concussions is associated with long-term health impairments (Hume et al., 2016). Concussions are defined as a mild subset of traumatic brain injuries, and typically occur following a direct impact to the head or an impact elsewhere on the body with an “impulsive” force transmitted to the head (McCrory et al., 2017). The forces resulting from such impacts are conveyed to the brain and generate internal strains that have been proposed as the main injury mechanisms (Holbourn, 1943). Current technology does not yet facilitate the measurement of brain strains *in-vivo*, so devices measuring real-time head kinematics have been developed (Duma et al., 2005; King, Hume, Brughelli, & Gissane, 2015). Acceleration instrumented devices have allowed the collection of thousands of head impacts, with the hope of finding injury thresholds that enable the identification or prevention of concussions.
The aim of this research was to capitalize on fifteen years of head impact monitoring, describe results, expose limitations, and explore directions for future research.

METHODS: A narrative review was first conducted to provide an overview of the current state of knowledge around head impact biomechanics in sports-related concussion research. Subsequently, a systematic review was performed to specifically assess prospective cohort studies that reported *in-vivo* head impact monitoring in sports. The search utilised the keywords: ((head injur*) OR (brain injur*) OR concuss*) AND ((head impact*) OR acceler* OR biomechanic*). Articles were excluded if: (i) full text was unavailable in English or French; (ii) no head impact measurement was performed; (iii) they were a review, laboratory study, case report or case series, commentary or opinion piece; (iv) were not peer-reviewed. For all publications that met the inclusion and exclusion criteria, information was extracted: population details, technology utilised, number of impacts and of concussions recorded, reporting of head kinematics and effects of various factors on head kinematics.

RESULTS & DISCUSSION: A total of 120 articles were retained for the narrative review, and 129 articles met the inclusion and exclusion criteria of the systematic review. The annual number of publications reporting head kinematics has steadily increased in the previous

fifteen years, from 1 in 2005 (Duma et al., 2005) when the Head Impact Telemetry System (HITS) was first utilised, to 36 in 2017. The majority of the research (81%) was conducted in helmeted sports, mainly American Football (55%) and ice hockey (13%), using the HITS. Custom devices were seldomly utilised until the first commercially available instrumented mouthguard (King et al., 2015) and ear patch (McCuen et al., 2015), which led to a 5-fold increase in the number of studies on non-helmeted sports in the following 3 years.
The results presented in this section are focused on male athletes of high school age or older (≥15 years) (N = 67 studies) to allow comparison with previously published studies (Brennan et al., 2016). The most commonly reported variables were the resultant peak head linear acceleration (PLA) and the resultant peak head angular acceleration (PAA) (see Table 1). The mean values for 50th and 95th percentiles of PLA and PAA are presented in Table 1. Attempts have been made to determine concussion injury risk thresholds based on concussive and non-concussive impacts reports. A recent meta-analysis showed that the average values of PLA and PAA for concussed male athletes (high school level and older) were 98.7 g and 5776.6 rads/s^2 (Brennan et al., 2016) (see Table 1). However, concussions in adult male athletes have been associated with impacts as low as than 41g and 3,000 rad/s^2 (Liao, Lynall, & Mihalik, 2016; McAllister et al., 2012). On the opposite side of the spectrum, studies (Merchant-Borna et al., 2016; Stojsih, Boitano, Wilhelm, & Bir, 2010) reporting PLA and PAA values as high as 180 g and 16,000 rad/s^2 did not report any diagnosed concussions. As a result of this variability, the hopes of finding injury thresholds using these single variables were left unfulfilled.

Table 1: Reporting of the main head impact metrics, overall mean (SD) for the 50th and 95th percentiles and reported mean for concussive impacts for male athletes (≥ 15 years) (Brennan et al., 2016).

Reported variable	Percentage of studies reporting (N = 67)	Overall 50th percentile (SD)	Overall 95th percentile (SD)	Mean of concussive impacts (95% CI)
PLA (g)	84%	18.0 (3.8)	52.9 (10.0)	98.7 (82.4 – 115.0)
PAA (rad/s^2)	67%	1621 (671)	5857 (3100)	5776 (4584 – 6969)

SD: Standard deviation; PLA: Peak linear acceleration; PAA: Peak angular acceleration. Overall means are calculated for the studies reporting summary values for the whole cohort, including concussive and non-concussive impacts.

A multitude of factors might explain why the association between head impact biomechanics and concussion remain elusive. Firstly, the diagnostic of concussion itself is imperfect, as it currently relies on injured players reporting their symptoms (O'Connell & Molloy, 2016), unreliable tools (Craton & Leslie, 2014), and a disputed injury definition (Craton & Leslie, 2014). Secondly, several intrinsic risk factors may play an important role in the variability of the accelerations observed in injured players. The only intrinsic risk factor to have been validated with a high level of certainty was the history of concussions (Abrahams, Fie, Patricios, Posthumus, & September, 2014). Other potential aspects to consider include neck strength and pre-injury symptoms. Finally, the measurement and analysis of head kinematics presents numerous limitations.
Head impact devices come with measurement errors, requiring an informed interpretation of the results (Siegmund, Guskiewicz, Marshall, DeMarco, & Bonin, 2016). The most commonly used system, the HITS, presents a technology different to most of the other devices which are typically one unit composed of a triaxial accelerometer and gyroscope. The HITS consists of six single-axis accelerometers recording linear acceleration and uses proprietary algorithms to provide PLA, PAA, the location of the impact, and several injury metrics described below. Important limitations of the HITS may reside in the fact that the algorithms are unavailable to the end user (Allison, Yun Seok, Bolte Iv, Maltese, & Arbogast, 2014) and that angular accelerations are estimated from linear acceleration, using an assumed fixed head rotation point and an approximated head centre of gravity (Siegmund et al., 2016).

Historically, PLA and PAA have been analysed separately but composite injury metrics have been utilised or developed. The Head Injury Criterion (HIC) uses PLA and an arbitrary time interval (Versace, 1971). The Head Impact Telemetry severity profile (HITsp) weights PLA and PAA, HIC, GSI and impact location (Greenwald, Gwin, Chu, & Crisco, 2008).
As shown in Table 1, head impacts are highly skewed towards the lowest acceleration magnitudes, but sports participants can sustain a high number of head impacts per game (King et al., 2015) and the effects of repetitive non-concussive impacts on the occurrence of injury remain unknown. Researchers have developed a cumulative metrics to account for the number or impacts and their magnitude (Eckner, Sabin, Kutcher, & Broglio, 2011; Urban et al., 2013), or the time between successive impacts preceding an injury (Broglio, Lapointe, O'Connor, & McCrea, 2017). However, the accuracy of these metrics in classifying head impacts as concussive or not has not yet been fully investigated.
Supposedly because head impact devices typically provide single, discrete values, such as PLA and PAA, the analysis of the acceleration signals has been severely restricted. As biomechanists, we understand that an acceleration signal is not limited to a set of discrete values from resultant curves but is composed of six time-series for translation and rotation along the three axes of motion. This whole raw signal is now available from several custom as well as commercially available head impact devices, allowing a comprehensive analysis of head kinematics. Various methods of increasing popularity, such as principal component analysis, waveform analysis or machine learning, are now offered to sport scientists. These methods would most likely provide a new understanding of head impacts, and therefore a new understanding of concussion. By analysing other aspects of the waveforms and how these aspects are associated to each other, or to brain strains, we could gain a new appreciation of injury mechanisms. The eventual identification of impact patterns might allow us to differentiate between concussive and non-concussive hits, thus triggering sideline assessments and early identification of concussion. There may now be potential for highlighting dangerous patterns related to improper contact technique which could lead to recommendations for rule changes.

CONCLUSION: Head impact devices have allowed us to measure and study *in-vivo* head biomechanics in sports where concussions are frequent. Fifteen years of research has advanced our knowledge of concussion biomechanics but has also undermined our hopes of defining acceleration-based thresholds that could be used for identifying and preventing injuries. The first developed acceleration technology devices have presented important limitations restricting the possibilities for analysis. New developments and generalisation of innovative analytical approaches should allow sport scientists the ability to assess head impacts in new ways and further our understanding of concussion biomechanics.

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