Title: The influence of head impact threshold for reporting data in contact and collision sports: Consensus needed.

Running title: Consensus needed for reporting impact data in sport.

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Abstract

Background: Head impacts and resulting head accelerations/decelerations are a primary cause of concussive injuries. There is currently no standard for reporting head impact data in sports to enable comparison between studies. Conclusions drawn from data using different impact thresholds have resulted in substantially different conclusions.

Objective: To outline head impact thresholds, and their potential effects on impact data in sport.

Methods: A review of impact thresholds utilised to report data in sport from accelerometer systems. Calculation of the number of impacts for studies based on the percentage of impacts removed compared with a 10*g* impact threshold using data from 38 senior rugby players in New Zealand.

Results: Of 43 studies identified, 16 (37.2%) reported impacts using >10*g* threshold. Application of the varied impact thresholds resulted in 20,687 impacts >10*g*; 11,459 (44.6% less), impacts >15*g*; and 4,024 (80.5% less) impacts >30g. Studies reported descriptive statistics as mean (±SD), median, 25th to 75th interquartile range, and 95th percentile.

Conclusion: The differing descriptive statistics utilised for reporting head impacts in sports limits the use and availability of inter-study comparisons. A consensus on methods of data analysis, including the thresholds to be used in sports impact assessment is needed. Based on the data available to date, the 10*g* threshold is the most commonly reported impact threshold. Validation studies are required to determine the best threshold for impact data collection in sport. Until validation is conducted, the 10g threshold should be standardised for all studies reporting impacts to the head in sport.

1. Introduction

Known as the 'silent injury',[54] and often trivialized by the media and sporting circles as a 'knock to the head',[49] sport-related concussions (hereafter called 'concussion') are a subset of mild traumatic brain injuries (mTBIs)[64] and have become an increasingly serious concern for all sporting activities worldwide.[22, 29, 63] Research into sports-related concussions[52] have been increasing over the years leading to a greater insight into the causes and the effects of these injuries. An area of increasing interest in these injuries are the forces involved and research[5, 20, 24, 38, 41, 45, 53, 65, 78, 87, 88, 90, 91, 97, 109, 110, 112, 113, 119, 120] has been sought to better determine the head linear and rotational accelerations involved in these injuries. Head impact dynamics have been analysed through the use of video analysis,[65] in game measurements,[20, 24, 32, 53, 76, 90, 91, 94, 96, 112, 119] numerical methods[5, 38, 97, 120] and reconstructions using anthropometric test devices[41, 78, 87, 88, 109, 110, 113] in helmeted sports such as American football[20, 24, 91, 119] and ice hockey[90, 112] and in un-helmeted sports such as soccer[45] and rugby union.[53]

The on-field assessment of head impacts has been captured with a head impact telemetry system (HITS) (Simbex, LLC, Lebanon, NH) using helmet mounted accelerometers enabling determination of the head linear and rotational accelerations in American football,[23, 24, 26, 32, 80, 119] ice hockey[90, 112] and in a headband in youth soccer.[45] The data collected through the HITS has enabled analytical risk functions,[88, 92-94] concussion risk curves,[94] and risk weighted exposure metrics[107] to be developed further assisting in the identification of sports participants at risk of concussive injuries. More recently, a publication utilized an instrumented mouthguard known as the XGuard (X2biosystems, Inc., Seattle, WA, USA) in rugby union.[53].

The immediate and long term effects of multiple and repeated blows to the head that athletes receive in contact sporting environments are a growing concern in clinical practice.[4, 40] In particular, concern has been growing about the effects of subconcussive impacts to the head and how these impacts may adversely affect cerebral functions.[4, 40, 44] Subconcussive events are those impacts that occur where there is an apparent brain insult with insufficient force to result in the hallmark signs and symptoms of a concussion.[40, 111, 114] Studies[3, 28] have reported that although subconcussive events do not result in observable signs and apparent behavioural alterations, they can cause damage to the central nervous system and have the potential to transfer a high degree of linear and rotational acceleration forces to the brain.[16] Proposed decades previously,[104, 105] it was posited that exposure to repetitive subconcussive blows to the head may result in similar, if not greater damage than a single concussive event[111] and may be cumulative.[99]

As subconcussive impacts do not result in observable concussion related signs and symptoms, these are often undiagnosed and not medically assessed. As a result, participants can be exposed to a high number of impacts per season[44] and this can result in exacerbating the cognitive aging process at an accelerated rate that may not be observable until later in life. It has been suggested[100, 103] that brain injuries not only come from concussive events but also from the accrual of subconcussive impacts that can result in pathophysiological changes in the brain. There are numerous studies[2, 4, 35, 40, 67, 89, 103] published that have demonstrated that the accumulation of subconcussive blows can result in neurophysiological changes. However, similar to the literature focused on concussion and mild traumatic brain injury (mTBI), the literature on subconcussive head trauma is limited.[95]

Although there is an increasing amount of published literature reporting impact accelerations to the head in the sporting environment, there is less attention focussed on identifying what is a subconcussive impact and where this occurs. Studies[1, 48, 80] have been conducted reporting the impacts absorbed by the head during activities undertaken daily. Although impacts to the head and body under 10*g* have been reported[80], these activities such as walking, jumping, running and sitting are considered to be non-contact events.[24, 69] However, impacts greater than 10*g* occurring from contact events that do not result in acute signs or symptoms of concussion, are identified as subconcussive impacts.[2] What remains unknown is the level of impact greater than 10*g* that these subconcussive impacts occur where there is a cumulative effect. Several studies have undertaken to report impacts to the head in sports such as American football,[7, 8, 14-17, 24-26, 32, 45, 46, 69, 75, 91, 94, 96, 107, 115] ice hockey,[71, 72, 90] soccer[45] and rugby union[53] but these have all utilised different data impact thresholds (see Table 1) and reported different results (see Table 2).

Head impact data are essential to help understand the biomechanics of head injury to develop potential injury prevention strategies. There is currently no standard for reporting head impact data to enable comparison between studies. Currently the use of accelerometers may not necessarily provide the meaningful inter-study comparisons that are sought due to data collection, processing and methodologies not being standardized.[86] Studies utilising different impact thresholds have proposed varying conclusions based on the methodological and reporting approaches undertaken. Therefore the aim of this study was to outline the influence of head impact thresholds used in reporting head impact data in contact and collision sport, using examples for impact data obtained from senior amateur rugby union during matches in New Zealand.[53]

2. Methods

The guideline for the reporting of observational studies (MOOSE: Meta-analysis Of Observational Studies in Epidemiology)[102] was followed for the empirical evidence included in this study. The MOOSE checklist contains specifications and guidelines for the conduct and review of the studies. To enable a comparison with the studies identified, the percentage differences obtained from analysis of data from one study[53] were used to determine impact counts using different linear impact thresholds (10*g* to 30*g*).

2.1 Search strategy for identification of publications

A total of 52,813 studies available online from Jan 1990 to Dec 2014 identified through databases were screened for eligibility (see Fig. 1). The keywords utilized for the search of relevant research studies included combinations of ‘head impact telemetry system*’, ‘HITS’, ‘concussion’, ‘impact*’, ‘traumatic brain injury’, ‘chronic traumatic encephalopathy', 'angular', 'linear', 'rotational', 'acceleration', 'biomechanics', 'head acceleration' and 'risk'. All identified studies were screened and those meeting the inclusion criteria were downloaded and reviewed.

To establish some control over heterogeneity of the studies,[102] inclusion criteria were established. Any published study or book that did not meet the inclusion criteria was excluded from the study. Publications were included if they reported on head impact biomechanics and met the following inclusion criteria:

(i) The study was published in a peer reviewed journal or book; and

(ii) The study reported the biomechanics of impacts to the head in a sporting environment; and

(iii) The study specifically addressed areas relating to this study.

Reviewed studies were excluded from this review if it was identified that the publication:

(i) Was unavailable in English; or

(ii) Did not provide additional information; or

(iii) Reported a previously included head impact dataset; or

(iv) Had not been referred to by other included publications.

2.2 Assessment of publication quality

All studies[6-9, 12-17, 20, 23-27, 31-33, 38, 39, 42-46, 53, 61, 62, 66, 69, 71-73, 75, 81, 88, 90, 91, 93, 94, 96, 103, 107, 115, 119, 120] that met the inclusion criteria were assessed for quality by two of the authors (DK and CG) on the basis of the MOOSE[102] published checklist. Heterogeneity of the studies included in the literature review was expected as there might be differences in the study design, population and outcomes.[102] For this review, quality was described as confidence that the study design, conduct and analysis minimized bias in estimation of the effect of the risk factor on the outcome measures.[60] As a result of the MOOSE[102] checklist, the studies included had a median score of 4.8/6.0 with a range of 4.0-5.0.

2.3 Statistical analysis

The impact variables obtained for comparisons in this study has been previously reported.[53] The impact variables were not normally distributed (Sharpo-Wilk test; $p<0.001$). Therefore data were expressed using descriptive statistics of mean ±standard deviation (SD), median [25th to 75th interquartile range] and 95th percentile. The impact variables were analysed using a Krusal-Wallis one-way ANOVA with a Dunn's post-hoc test for all pairwise comparisons. All significant differences are $p<0.001$ unless stated. The estimated number of impacts were calculated by multiplying the number of reported impacts by the percentage of impacts removed at the different thresholds. The total number of reported impacts were subtracted from the calculated number of total impacts identifying the possible number of impacts removed from the data set.

3. Results and Discussion

A total of 47 publications were identified that reported on head impact biomechanics and met the inclusion criteria. The differences between the studies are reported and discussed.

3.1 Impact threshold

A third (39%) of the studies[6, 17, 24-26, 32, 39, 45, 46, 53, 69, 71-73, 75, 81, 90, 91, 96] reported the impact threshold at 10*g* (see Table 1). Ten (22%) studies[7, 8, 13, 20, 23, 27, 94, 103, 107, 119] reported the impact threshold at 14.4*g* while six[12, 14-16, 33, 61] (13%) reported the impact threshold at 15*g*. Only one study[115] used a 30*g* impact threshold. Four studies[38, 66, 88, 120] (9%) were reconstruction studies from video analysis but were included as they reported impact biomechanics. Five studies[9, 31, 42, 43, 93] (11%) did not report the impact threshold but did report head impact biomechanics. Two[44, 62] studies (4%) reported impact data within 10*g* to 60*g* and greater than 90*g*.

By utilising data from a previously published study[53] (included in this study) that used the 10*g* impact threshold, data was re-extracted at differing impact thresholds from 10*g* to 30*g*. By adjusting the impact threshold (see Fig. 2) the number of impacts decreased as the impact threshold increased (see Table 3). Based on the differences observed in this study, at the 14.4*g* threshold there could have been as many as 42% of the impacts recorded not being reported. As a result, studies[7, 8, 12-15, 20, 27, 33, 94, 107, 115, 119] using impact thresholds above 10*g* may have removed 2,100 to 206,573 impacts (see Table 2). At the 30*g* impact threshold it can be estimated that 80 to 85% of impacts were not reported.[115] Again, based on the differences observed in this study it is possible that each player in the Pop Warner study[115] may have experienced a cumulative total of 1,885 impacts above 10*g*. Although the impacts may not have been recorded, the players may well have been exposed to this number of impacts between 10*g* and 30*g*. The differences between impacts reported and the possible number of impacts (480 vs. 2,365) may result in an underestimation of the exposure risk to these players of subconcussive impacts.

The equipment utilised to record and report head impacts vary in the sensitivity and the types of algorithms they employ for the identification of impacts.[117] These differences may invariably influence the results of the published studies as, although some studies report the linear threshold as 14.4*g*, they may actually be recording from 10*g* and, if the researcher is unaware that this threshold is the default then the data may be included (personal correspondence S. Broglio; Sept 2015). In the recording of data for the HITS, the data is based on the triggering of one accelerometer, and the unfiltered / unprocessed data only loosely relates to the final measurement of interest at the heads centre of gravity.

The discussion surrounding subconcussive impacts has become popular. [2, 11, 30, 44, 61, 100] Initially the term subconcussive impact described an impact that did not result in severe, noticeable symptoms especially loss of consciousness,[30] but more recently it is utilised to describe an asymptomatic non-concussive impact to the head.[2, 11, 44, 61, 100] The issue relating to the effects of subconcussive impacts is controversial as researchers and clinicians are divided on the true effects.[4, 40, 44, 67, 74, 103] Some research[74] has reported that these impacts have minimal effect on cognitive functions, while others[4, 40, 67, 89, 103] have reported these to be detrimental to cerebral and cognitive functions. To date, there is a paucity of evidence to identify the impact acceleration that is adequate to produce a non-structural brain injury associated with the neuronal changes of concussion.[4]

Although animal models do show that there are metabolic changes associated with concussion, it is likely that this may be similar in subconcussive impacts.[36] To research subconcussive impacts in isolation is challenging and there are, to date, no reports on animal models or other reliable methodologies that have been successful at identifying these impacts[36] The concept that brain injury does not only occur from concussive events, but can also be from an accumulation of the subconcussive impacts.[100] The effects of concussive events and multiple subconcussive impacts have been associated with long term progressive neuropathologies and cognitive deficits.[2, 68, 84, 101] To be able to identify what may be occurring then longitudinal impact monitoring at the level where these subconcussive events are beginning to occur is important, but the identified threshold still needs to be established.

Impacts <10*g* of linear acceleration have been considered negligible in regards to impact biomechanical features. The 10*g* impact threshold was utilised to eliminate head accelerations from non-impact events such as jumping and running.[24, 69, 80] The inclusion of these non-impact events to head trauma make it difficult to distinguish between head impacts and voluntary head movement[70] and eliminating these will help identify the true extent of the number of impacts that do occur from sports participation. As there is no established criterion for reporting head impact biomechanics in sport, and the most frequently reported limit is >10*g,* reporting all impacts above the 10*g* resultant linear acceleration threshold would assist in establishing the full extent of impacts to sports participants. Consensus for this threshold will need to be established, and should be based on validation studies to determine the best impact threshold for various sports and injury outcomes.

3.2 Head impact results

Most studies (91%) reported resultant linear accelerations while slightly less (76%) reported resultant rotational accelerations. Nearly three-quarters (74%) of the studies[6-9, 12-16, 20, 24, 26, 27, 31, 33, 42, 45, 46, 53, 61, 66, 71-73, 75, 81, 88, 90, 91, 93, 107, 119, 120] reported both resultant linear and rotational accelerations. A quarter (26%) of the studies[12, 13, 16, 24, 33, 42, 46, 61, 71, 72, 75, 81] reported the Head Impact Telemetry severity profile (HITsp). Ten (22%) of the studies reported the Head Impact Criterion (HIC) for 15ms (HIC$_{15}$).[7, 8, 32, 38, 39, 42, 45, 88, 90, 120] Three (7%) of the studies[7, 32, 45] reported the Gadd Severity Index (GSI). Only two (4%) of the studies reported the HIC for 15ms (HIC$_{15}$) and 36ms (HIC$_{36}$).[8, 90] No study reviewed reported the Generalised Acceleration Model for Brain Injury Threshold (GAMBIT)[77, 78] or the Head Impact Power (HIP)[79] in their assessment of head impact biomechanics.

The HIC and GSI are the most commonly utilised head injury assessment functions, particularly in safety standards[120] but this was not reflected in the studies reviewed. Based on the Wayne State University tolerance curve,[108] the HIC and GSI criteria do not account for the complex motion of the brain, or the contribution of resultant rotational acceleration to the head.[78, 79, 120] The inclusion of these parameters may be more historical and provide the ability for inter-study comparisons with previous studies but, as they are not commonly reported, the inclusion of these parameters in future studies needs to be standardised and consensus is needed to clarify this.

The most commonly reported head impact biomechanics were the resultant linear and rotational accelerations, although not all studies reviewed reported both. Some studies reported only resultant linear accelerations[17, 32, 39, 43, 44, 62, 69, 96, 115] or resultant rotational accelerations[38, 94] which may limit their inter-study comparison usability. It has been suggested that both resultant linear and rotational accelerations should be reported with head impact metrics.[83] By reporting both linear and rotational accelerations there is an improved correlation between impact biomechanics and the occurrence of a concussion, than when linear accelerations are reported alone.[120] Research[19, 56, 58, 98, 110] suggests that the brain is more sensitive to rotational than linear accelerations. Rotational accelerations are reported[106, 120] to be correlated to the strain response of the brain and the primary mechanism for diffuse brain injury including concussion, contusion, axonal injuries and loss of consciousness.[51, 55, 56, 58] Whereas linear accelerations are reported[57, 106] to be the intracranial pressure response of the brain and the primary mechanism for skull fractures and epidural haematomas. Reporting both linear and rotational accelerations should assist with identification of possible brain injury.

More recently[93, 107] resultant linear and rotational acceleration results have been combined into a risk weighted exposure (RWE) metric. This metric can be beneficial for fully capturing the linear ($\mathrm{RWE}_{\mathrm{Linear}}$), rotational ($\mathrm{RWE}_{\mathrm{Rotational}}$) and combined probability (from linear and rotational) ($\mathrm{RWE}_{\mathrm{CP}}$) of the risk of a concussion as it accounts for the frequency and severity of each player's impacts. Consensus is required on the incorporation of these, and other biomechanical reporting metrics into future research.

3.3 Data reporting

All of the studies reviewed identified the number of impacts that were recorded. These did however vary for studies reporting impacts that occurred during matches only, those that were recorded for both match and training activities and those that combined both match and training activity impacts. More than half (52%) of the studies[6, 7, 14, 16, 17, 32, 33, 38, 43, 46, 53, 61, 62, 69, 71-73, 75, 81, 88, 91, 107, 115, 119, 120] reported the impact biomechanics data as mean ± standard deviation (±SD). Some studies[7, 33, 75, 107, 119] (10%) also reported the head impacts as median, but not all[75, 119] (4%) included the interquartile ranges (IQR) for this data. Of the studies that reported the impact biomechanics by the median only 7% reported the IQR. Most of the studies reporting the median also reported the 95th percentile of the impacts. Other data reporting methodologies utilised within the data sets reviewed were the median of 95th percentile,[24] the 98th,,[33, 42] 99th,[33, 42] and 99.5th[33] percentiles. Some studies also included lower and upper limits[69, 71, 72, 81] for the range of impacts,[31, 90] and the mean range[115] of the impacts. A few studies reported their impacts as x, y, z axis data,[91] +1SD,[96] Cumulative Distribution Functions (CDF),[26, 107] percentage of impacts,[23, 24] and the impact duration (ms).[7, 8, 12, 15, 88]

In addition to the impact biomechanics being presented by various methodologies, some studies[14, 16, 43, 46, 53, 81, 120] also incorporated impact tolerances and impact severity levels. The use of this data may be important if a risk assessment is undertaken for possible long term implications from repetitive head impacts (RHI). Recently it was reported[6] in a small sample of collegiate players with no reported concussions after a season of American football that there were white matter changes that correlated with multiple head impact measures. Participants with more that 30-40 RHI's with peak rotational accelerations >4,500 radians per second per second (rad/s^2) per season (r=0.91; p<0.001) and when more than 10-15 RHI's were >6,000 rad/s^2 (r=0.81; p<0.001) were significantly correlated with post-season white matter changes.[6] These changes post season imply a relationship between the number of RHI's that occur over a season of American football and white matter injury, despite no clinically evident concussion being recorded.[6]

The inclusion of impact tolerances and impact severity levels may also assist with the identification of players at risk of possible long term injuries. This may also act as an indicator of when to rest players if they are exposed to RHI's above these impact tolerances (>4,500 rad/s^2 and >6,000 rad/s^2). This information will assist in formulating a detailed understanding of the exposure and mechanism of injury.[10, 23] Other possible benefits that can occur reporting this information may be: (1) The evaluation of the injury tolerance of concussive type injuries, (2) Future development of interventions to reduce the likelihood of any concussive type injuries, and (3) Development of exposure durations and stand down periods to establish a broader understanding of the potential role of subconcussive events and long term health.[23] Further research and consensus is warranted to assist in the development of this knowledge.

3.4 Collaboration to stimulate comparability

The use of accelerometers to record and assess movement is not new to the scientific community.[21, 116] Accelerometers have been utilised to record physical activity and there have been some inter-study and international comparability limitations.[86] These identified limitations may be identical to areas now being faced by studies reporting the biomechanics of impacts to the head. To date, there is an increasing number of studies reporting head impact biomechanics, and this will increase further as more systems become available. The majority of these studies have utilised HITS,[6-9, 12-17, 20, 23-27, 31-33, 39, 42-44, 46, 61, 62, 69, 71-73, 75, 81, 90, 91, 93, 94, 96, 103, 107, 115, 119] or a variant[45] and, more recently, an electronic mouthguard has been used to assess head impacts in rugby union.[53]

The issues identified with the use of accelerometers for physical activity may be similar for head impact biomechanics. It was identified[86] that these limitations were (a) Affordability of the accelerometers:[86] the associated costs with the purchase of these instruments may limit the use of these to researchers, and research facilities, that can afford to provide the funding for this sort of research activity; (b) Administration burden[86] to the researcher(s) and participants and post data collection analysis; (c) Choice of accelerator brand,[85] generation[18] and firmware version;[47] (d) Wearing position[118] based on the sports code requirements (i.e. helmet mounted vs. headband mounted vs. mouthguard embedded vs. patch); and (e) Specifics of the research being undertaken such as the epoch length[34, 82] (match vs. training vs. combined), data imputation methods,[59] dealing with spurious data[37] and the reintegration of smaller epochs into larger epochs.[50] In addition to the limitations identified, there is always the issue of constant technological developments, emerging methodological questions and a lack of academic consensus that may also hinder the development of uniformity in the utilisation of accelerometers[86] for recording head impact biomechanics.

4. Conclusion

This study undertook to identify the methodological differences in the threshold limits of biomechanical impacts to the head as a result of participation in contact sports. A third (39%) of the studies reported impact biomechanics at the 10*g* impact threshold while 22% (n=10) of studies used the 14.4*g* impact threshold. The majority of studies (91%) reported resultant linear accelerations while slightly less (76%) reported resultant rotational accelerations. Nearly three-quarters (74%) of studies reported both resultant linear and rotational accelerations. Over half (52%) of studies reported impact data as mean ± standard deviation (±SD). Some (10%) studies also reported the head impact data as median, but not all (4%) included the interquartile ranges (IQR) for these data. Consensus is required to identify the reporting modalities (e.g. linear threshold, biomechanical calculations and reporting modalities), utilised in future biomechanical impact studies to enable collaborative analysis.

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TABLES

Table 1: Head impacts by impact threshold utilised, biomechanical aspects reported and how data were reported.

Table 2: Studies of head impacts reported at the 14,4*g*, 15*g* and 30*g* impact thresholds, predicted total number of impacts recorded and predicted number of impacts not included in the dataset.

Table 3: Differences observed in the resultant linear (PLA(*g*)) and rotational (PRA(rad/s^2)) accelerations, head impact criterion (15ms) (HIC_{15}) and Gadd severity index (GSI) at different impact thresholds by the mean and standard deviation (±SD), median [25th to 75th percentile] and 95th percentile of senior amateur rugby union players.

FIGURES:

Figure 1: Flow of identification, screening, eligibility and study inclusion of previously published studies.

Figure 2: Percentage of number of impacts removed with different impact thresholds compared with 10*g* for senior amateur rugby union players.

Table 1: Head impacts by impact threshold level utilised, biomechanical aspects reported and how data were reported.

Study	Data acquisition impact threshold	PLA(*g*)	PRA(rad/s^2)	HIC$_{15}$	HIC$_{36}$	GSI	HITsp	Mean (SD)	Median	IQR	95%	Other
Brolinson et al.[17]	10*g*	Y						Y				
Bazarian et al.[6]	10*g*	Y	Y					Y				
Crisco et al.[24]	10*g*	Y	Y				Y		Y		Y	Y
Crisco et al.[25]	10*g*	Y	Y								Y	
Daniel et al.[26]	10*g*	Y	Y						Y		Y	Y
Duma et al.[32]	10*g*	Y		Y		Y		Y				
Funk et al.[39]	10*g*	Y		Y								
Hanlon et al.[45]	10*g*	Y	Y	Y		Y						
Harpham et al.[46]	10*g*	Y	Y				Y	Y				
King et al.[53]	10*g*	Y	Y					Y				
Mihalik et al.[69]	10*g*	Y						Y				Y
Mihalik et al.[73]	10*g*	Y	Y					Y				Y
Mihalik et al.[72]	10*g*	Y	Y				Y	Y			Y	Y
Mihalik et al. [71]	10*g*	Y	Y				Y	Y				Y
Munce et al.[75]	10*g*	Y	Y				Y	Y	Y		Y	
Ocwieja et al.[81]	10*g*	Y	Y				Y	Y				Y
Reed et al.[90]	10*g*	Y	Y	Y	Y							Y
Rowson et al.[91]	10*g*	Y	Y					Y				Y
Schnebel et al.[96]	10*g*	Y										Y
Beckwith et al.[8]	14.4*g*	Y	Y	Y	Y							Y
Beckwith et al.[7]	14.4*g*	Y	Y	Y		Y		Y	Y	Y		
Broglio et al.[13]	14.4*g*	Y	Y				Y					
Cobb et al.[20]	14.4*g*	Y	Y						Y		Y	Y
Crisco et al.[23]	14.4*g*											Y
Daniel et al.[27]	14.4*g*	Y	Y						Y		Y	Y
Rowson et al.[94]	14.4*g*		Y									
Talavage et al.[103]	14.4*g*											
Urban et al.[107]	14.4*g*	Y	Y					Y	Y	Y	Y	
Young et al.[119]	14.4*g*	Y	Y					Y	Y		Y	Y
Broglio et al.[14]	15*g*	Y	Y					Y				Y
Broglio et al.[15]	15*g*	Y	Y									Y
Broglio et al.[12]	15*g*	Y	Y				Y					Y
Broglio et al.[16]	15*g*	Y	Y				Y	Y				
Eckner et al.[33]	15*g*	Y	Y				Y	Y	Y	Y	Y	Y
Martini et al.[61]	15*g*	Y	Y				Y	Y				
Wong et al.[115]	30*g*	Y						Y				
Gysland et al.[44]	<60 *g* >90*g*	Y										Y
McCaffrey et al.[62]	<60 *g* >90*g*	Y						Y				Y
Fréchède et al.[38]	Reconstruction		Y	Y				Y				Y
McIntosh et al.[66]	Reconstruction	Y	Y									Y
Pellman et al.[88]	Reconstruction	Y	Y	Y				Y				
Zhang et al.[120]	Reconstruction	Y	Y	Y				Y				Y
Breedlove et al.[9]	N/S	Y	Y						Y			Y
Duhaime et al.[31]	N/S	Y	Y									
Greenwald et al.[42]	N/S	Y	Y	Y			Y				Y	
Guskiewicz et al.[43]	N/S	Y						Y				
Rowson et al.[93]	N/S	Y	Y									Y
Percentage of studies		90.7	74.4	23.3	2.3	9.3	25.6	48.8	23.3	7.0	23.3	60.5

N/S = not stated.

Table 2: Studies of head impacts reported at the 14,4*g*, 15*g* and 30*g* impact thresholds, predicted total number of impacts recorded and predicted number of impacts not included in the dataset.

Author	Data acquisition limit	No impacts reported	Possible total number of impacts at 10*g*	Possible number of impacts not included compared with 10*g*
Beckwith et al.[8]	14.4*g*	161,732	272,735	111,003
Beckwith et al.[7]	14.4*g*	161,732	272,735	111,003
Broglio et al.[13]	14.4*g*	32,510	54,823	22,313
Cobb et al.[20]	14.4*g*	11,978	20,199	8,221
Daniel et al.[27]	14.4*g*	4,678	7,889	3,211
Rowson et al.[94]	14.4*g*	300,977	507,550	206,573
Urban et al.[107]	14.4*g*	15,264	25,740	10,476
Urban et al.[107]	14.4*g*	3,059	5,159	2,100
Young et al.[119]	15*g*	54,247	95,843	41,596
Broglio et al.[14]	15*g*	19,224	33,965	14,741
Broglio et al.[15]	15*g*	101,994	180,201	78,207
Broglio et al.[12]	15*g*	101,994	180,201	78,207
Eckner et al.[33]	15*g*	35,620	62,933	27,313
Wong et al.[115]	30*g*	480	2,365	1,885

Total number of impacts and impacts not included for published studies based on the percentage of impacts removed compared with a10*g* impact threshold using data analysis of New Zealand senior rugby players.

Table 27: Differences observed in the resultant linear (PLA(*g*)) and rotational (PRA(rad/s^2)) accelerations, head impact criterion (15ms) (HIC_{15}) and Gadd severity index (GSI) at different impact threshold limits by the mean and standard deviation (±SD), median [25th to 75th percentile] and 95th percentile of senior amateur rugby union players.

Data acquisition impact threshold (*g*)	Resultant Linear Accelerations (PLA(*g*))				Resultant Rotational Accelerations (PRA(rad/s^2))			Head Impact Criterion 15ms (HIC_{15})			Gadd Severity Index (GSI)		
	No of impacts	Mean ±SD	Median [25th-75th]	95%	Mean ±SD	Median [25th-75th]	95%	Mean ±SD	Median [25th-75th]	95%	Mean ±SD	Median [25th-75th]	95%
10	20,687	22.2 ±16.2	16.3 [12.0-26.3]	52.9	3,902.9 ±3,948.8	2,625.2 [1,323.9-4,934.0]	12,204.2	32.3 ±98.5	8.7 [4.5-24.7]	127.7	48.3 ±117.9	15.2 [7.7-38.8]	192.3
11	17,747[a]	24.1 ±16.7[a]	18.3 [13.4-28.5]	56.3	4,254.7 ±4,096.3[a]	2,897.7 [1,548.6-5,389.4]	12,945.1	37.1 ±105.5[a]	11.3 [5.7-30.0]	145.0	55.2 ±125.9[a]	18.9 [9.5-46.8]	217.9
12	15,454[a]	26.0 ±17.1[a]	20.4 [14.9-30.6]	59.3	4,602.9 ±4,214.0[a]	3,181.0 [1,781.4-5,860.3]	13,580.8	42.0 ±112.3[a]	14.1 [7.0-35.1]	160.1	62.3 ±133.5[a]	23.0 [11.8-55.1]	241.0
13	13,825[a]	27.6 ±17.4[a]	22.0 [16.2-32.3]	61.5	4,858.1 ±4,293.4[a]	3,423.4 [1,966.5-6,262.5]	13,948.3	46.4 ±117.9[a]	16.7 [8.5-39.7]	175.5	68.6 ±139.8[a]	26.9 [[14.1-62.4]	261.5
14	12,531[a]	29.1 ±17.7[a]	23.5 [17.5-33.8]	63.5	5,079.2 ±4,368.0[a]	3,589.4 [2,122.8-6,595.5]	14,324.6	50.6 ±123.1[a]	19.1 [10.1-44.1]	187.5	74.6 ±145.5[a]	30.5 [16.5-69.4]	278.4
15	11,459[a]	30.5 ±17.9[a]	24.8 [18.8-35.1]	65.4	5,285.7 ±4,438.2[a]	3,773.7 [2,262.6-6,907.6]	14,647.2	54.7 ±128.0[a]	21.6 [11.8-48.6]	205.1	80.4 ±150.8[a]	34.0 [18.9-76.1]	296.7
16	10,570[a]	31.7 ±18.1[a]	26.0 [20.0-36.3]	66.9	5,477.9 ±4,510.3[a]	3,936.3 [2,400.1-7,180.4]	14,994.4	58.6 ±132.5[a]	24.0 [13.5-53.0]	215.4	86.1 ±155.7[a]	37.8 [21.3-81.7]	317.8
17	9,784[a]	32.9 ±18.2[a]	27.1 [21.2-37.5]	68.1	5,655.3 ±4,564.5[a]	4,082.2 [2,538.0-7,394.2]	15,234.7	62.6 ±137.0[a]	26.6 [15.0-57.1]	227.7	91.8 ±160.5[a]	41.4 [23.6-88.4]	330.7
18	9,095[a]	34.1 ±18.4[a]	28.3 [22.2-38.8]	69.7	5,799.4 ±4,609.6[a]	4,173.1 [2,643.5-7,566.8]	15,486.3	66.5 ±141.3[a]	29.2 [16.8-61.6]	241.4	97.4 ±165.1[a]	45.4 [26.5-94.9]	348.1
19	8,500[a]	35.2 ±18.5[a]	29.1 [23.2-39.9]	71.4	5,938.9 ±4,662.2[a]	4,265.1 [2,730.5-7,743.6]	15,822.7	70.3 ±145.4[a]	31.5 [18.3-65.6]	252.9	102.9 ±169.4[a]	49.2 [28.8-101.5]	363.9
20	7,934[a]	36.3 ±18.7[a]	30.2 [24.3-40.9]	73.5	6,071.5 ±4,716.0[a]	4,357.1 [2,810.1-7,931.3]	16,256.4	74.4 ±149.6[a]	34.2 [20.1-69.9]	263.1	108.7 ±173.9[a]	53.1 [31.4-108.5]	374.2
21	7,430[a]	37.4 ±18.8[a]	31.2 [25.2-42.1]	75.5	6,206.3 ±4,756.7[a]	4,483.2 [2,896.4-8,157.5]	16,469.5	78.5 ±153.8[a]	36.8 [21.9-75.1]	275.3	114.5 ±178.2[a]	57.4 [33.9-114.1]	390.9
22	6,938[a]	38.5 ±19.0[a]	32.2 [26.2-43.5]	77.3	6,362.5 ±4,800.7[a]	4,594.8 [2,991.6-8,426.3]	16,806.4	82.9 ±158.2[a]	39.5 [23.8-80.4]	291.2	120.7 ±182.8[a]	62.0 [37.0-120.9]	414.8
23	6,463[a]	39.7 ±19.2[a]	33.3 [27.3-44.5]	79.6	6,518.5 ±4,858.8[a]	4,721.5 [3,096.4-8,628.3]	17,073.4	87.6 ±162.9[a]	42.7 [26.1-84.7]	302.3	127.3 ±187.7[a]	66.9 [40.0-129.2]	444.4
24	6,060[a]	40.8 ±19.3[a]	34.3 [28.3-45.7]	81.5	6,656.1 ±4,905.9[a]	4,834.7 [3,200.7-8,797.6]	17,282.3	92.1 ±167.2[a]	45.9 [28.2-89.6]	318.3	133.7 ±192.1[a]	71.1 [43.0-135.4]	466.2
25	5,666[a]	41.9 ±19.5[a]	35.2 [29.1-47.0]	82.8	6,818.5 ±4,951.8[a]	4,965.1 [3,305.1-9,011.9]	17,435.2	97.0 ±171.9[a]	49.0 [30.6-94.9]	336.7	140.6 ±196.8[a]	76.3 [46.7-143.6]	484.6
26	5,275[a]	43.1 ±19.6[a]	36.3 [30.2-48.1]	84.4	6,977.0 ±4,986.4[a]	5,101.1 [3,428.4-9,296.6]	17,622.4	102.4 ±176.9[a]	53.1 [33.0-101.0]	357.3	148.2 ±201.8[a]	81.3 [50.2-152.3]	512
27	4,955[a]	44.2 ±19.8[a]	37.3 [31.2-49.4]	86.9	7,107.0 ±5,036.1[a]	5,209.8 [3,494.6-9,459.3]	17,843.8	107.3 ±181.4[a]	56.5 [35.2-106.6]	389.0	155.1 ±206.3[a]	86.2 [53.9-162.0]	535.8
28	4,642[a]	45.3 ±20.0[a]	38.5 [32.1-50.7]	88.1	7,260.6 ±5,078.9[a]	5,338.9 [3,607.3-9,703.8]	18,130.8	112.7 ±186.2[a]	60.4 [37.9-113.7]	396.0	162.6 ±211.0[a]	92.7 [58.3-172.8]	557.4
29	4,305[a]	46.6 ±20.1[a]	39.6 [33.3-52.2]	90.5	7,448.1 ±5,129.8[a]	5,492.1 [3,777.7-9,916.8]	18,220.5	119.2 ±191.8[a]	64.9 [41.3-123.2]	407.3	171.6 ±216.5[a]	99.4 [63.9-185.9]	583.2
30	4,024[a]	47.8 ±20.3[a]	40.7 [34.4-53.5]	91.9	7,597.4 ±5,186.8[a]	5,623.7 [3,874.8-10,129.3]	18,435.5	125.2 ±197.0[a]	68.8 [44.3-131.2]	419.9	180.0±221.4[a]	106.1 [68.3-195.6]	606.0

PLA (g) = peak linear acceleration; PRA (rad/s^2) = peak rotational acceleration in radians/second/second (rad/s^2); Significant difference ($p<0.05$) than: (a) = 10*g*

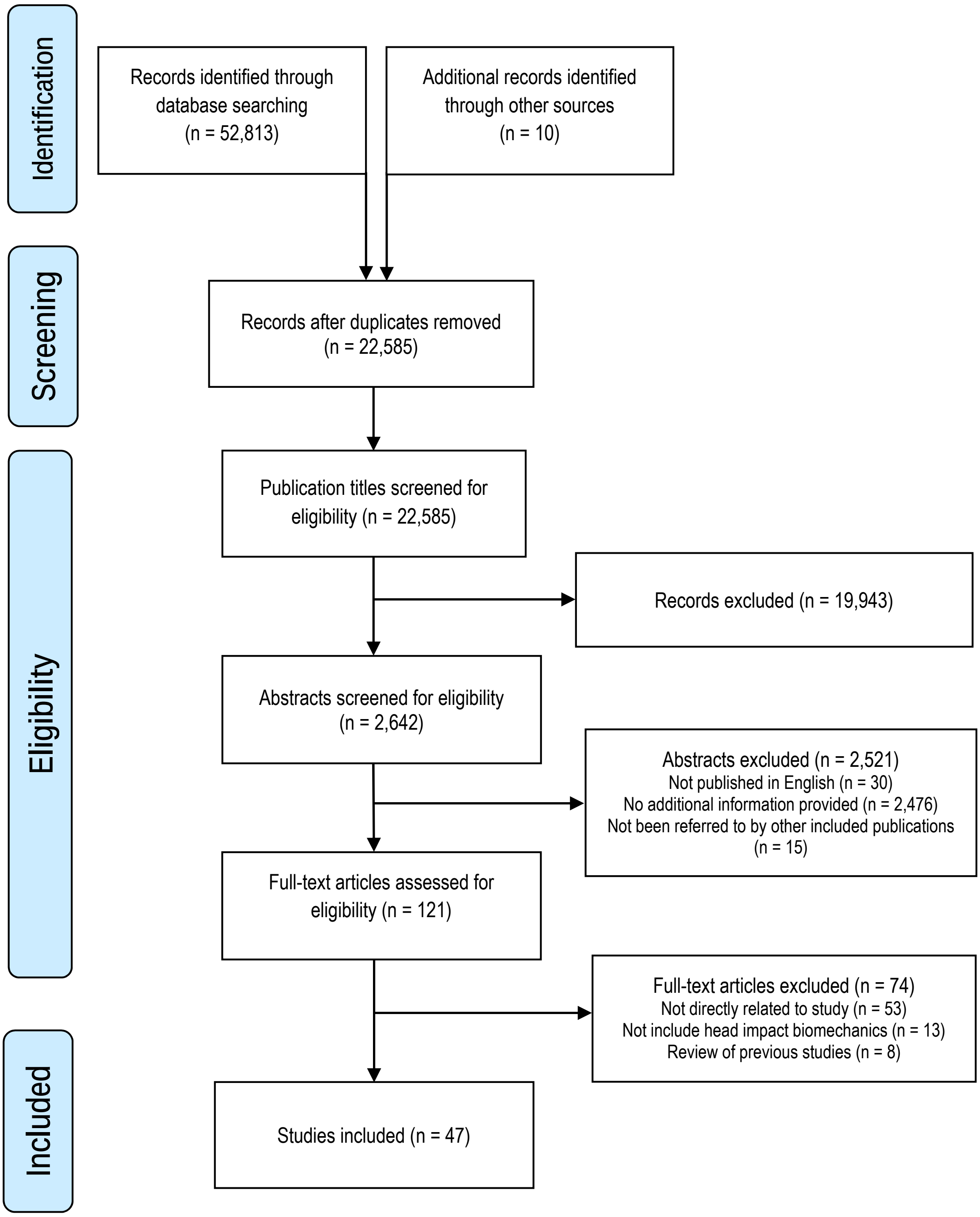

Figure 1: Flow of identification, screening, eligibility and study inclusion of previously published studies.

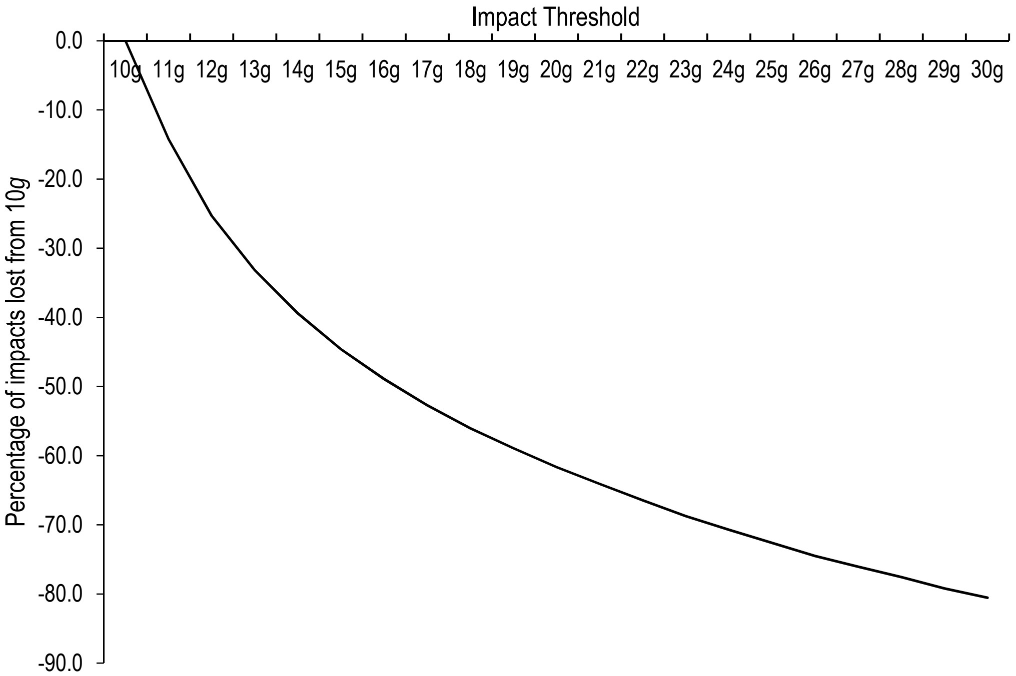

Figure 2: Percentage of number of impacts removed with different data impact threshold limits compared with 10*g* for senior amateur rugby union players.