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Title

Injury and biomechanical perspectives on the rugby scrum: a review of the literature

Author list

Grant Trewartha(a,✉), Ezio Preatoni(a), Michael E. England(a,b) and Keith A. Stokes(a)

Affiliations

(a) Sport, Health and Exercise Science, Department for Health, University of Bath, UK

(b) Rugby Football Union, Twickenham, UK

✉ Corresponding author

Grant Trewartha

g.trewartha@bath.ac.uk

+44 (0)1225 383055

Sport, Health & Exercise Science – Department for Health, University of Bath

Applied Biomechanics Suite, 1.301

BA2 7AY - BATH (UK)

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Grant Trewartha: is guarantor. Initiated the overall project and supervised all its phases; performed the primary literature searches; drafted the paper; contributed to revising the paper; approved the final version of the paper.

Ezio Preatoni: contributed to the provision of grey literature; drafted the 'Mechanisms of injury' section; contributed to revising the paper; approved the final version of the paper.

Mike England: contributed to the provision of grey literature; contributed to revising the paper; approved the final version of the paper.

Keith Stokes: contributed to the provision of grey literature; contributed to revising the paper; approved the final version of the paper.

What this study adds

- Synthesises the recent research literature pertaining to the medical and biomechanical aspects of rugby union scrummaging
- Highlights the need to consider both acute catastrophic and chronic degenerative injury types when considering injuries occurring in the rugby scrum
- Highlights that the most contemporary literature available is collectively confirming that the forces involved in rugby scrummaging are high and multi-planar, but can be modified appropriately by alterations to the scrum engagement technique

ABSTRACT

As a collision sport, Rugby Union has a relatively high overall injury incidence, with most injuries being associated with contact events. Historically, the set scrum has been a focus of the sports medicine community due to the perceived risk of catastrophic spinal injury during scrummaging. The contemporary rugby union scrum is a highly dynamic activity but to this point has not been well characterised mechanically. In this review we synthesise the available research literature relating to the medical and biomechanical aspects of the rugby union scrum, in order to 1) review the injury epidemiology of rugby scrummaging; 2) consider the evidence for specific injury mechanisms existing to cause serious scrum injuries; and 3) synthesise the information available on the biomechanics of scrummaging, primarily with respect to force production. The review highlights that the incidence of acute injury associated with scrummaging is moderate but the risk per event is high. The review also suggests an emerging acknowledgement of the potential for scrummaging to lead to premature chronic degeneration injuries of the cervical spine and summarises the mechanisms by which these chronic injuries are thought to occur. More recent biomechanical studies of rugby scrummaging confirms that scrum engagement forces are high and multi-planar, but can be altered through modifications to the scrum engagement process which control the engagement velocity. Because the set scrum is a relatively “controlled” contact situation within Rugby Union it remains an important area for intervention with a long term goal of injury reduction.

INTRODUCTION

Rugby union (rugby) is a contact sport involving periods of submaximal activity such as walking and jogging interspersed with short bouts of high intensity activity such as sprinting, and game-specific events such as the tackle, maul, ruck and scrum. [1] Rugby union has comparatively high injury incidence, [2-5] albeit similar to other collision sports. [6-9] There has been a focus on the safety of specific contact elements of the game, with the scrum and the tackle at the forefront as the game events the International Rugby Board has targeted for injury prevention initiatives. The set scrum is of particular interest, since as a set piece phase there is a view that injury occurrence from the scrum should be to some extent "controllable". [10] Nevertheless, the scrum is perceived as a phase of play with considerable injury risk, particularly in the context of the risk of chronic or catastrophic spinal injury. This is principally because, although catastrophic injuries due to scrummaging are very rare, [11] they are exceptionally debilitating. Although some commentators have called for a radical alteration of the scrum or even its ban from certain levels of rugby to reduce this perceived injury risk, [12] these views have been equally strongly rebuffed. [11]

According to Law 20 of the International Rugby Board (IRB) Law Book which governs the rugby scrum, the purpose of the scrum is to "restart play quickly, safely and fairly, after a minor infringement or a stoppage". [13] A scrum involves a maximum of 8 players per team (the forward pack), who bind together in three rows (front, second and back), and then bind with an opposition forward pack to compete for possession of the ball by exerting a coordinated pushing action (Figure 1). Effective scrummaging requires a pack of forwards to produce forceful and coordinated actions to ensure dominance over the opposition, to provide a platform for launching attacks, and to disrupt opposition ball. Mechanically, contemporary scrummaging is broadly characterised by a high initial impact during the engagement of the opposing packs which is followed by the application of sustained opposing forces. [14,15]

**** Figure 1 here ****

The rugby scrum generates very high biomechanical demands on players' musculoskeletal structures and thus exposes forwards, and front row forwards in particular, to the risk of both acute and chronic (overuse) injuries. The epidemiological studies of rugby injury reviewed later describe a moderate incidence/proportion of scrum-related injuries, but also the potential seriousness of these occurrences. In fact, even though some recent data suggest a relative decline in scrum-related serious injuries over recent decades, about 40% of all catastrophic (typically spinal cord) injuries that occur in rugby are related to scrummaging. [16] Furthermore, players may appear asymptomatic in the shorter-term, but may experience repeated micro-trauma [17] that contribute to the emergence of long-term degeneration and pathologies of the spine, including physical abnormalities [18,19], reduced mobility [20], and impaired proprioception. [21]

While rugby scrums may be associated with a number of potential injury risk factors, there is currently very little quantitative data to identify and describe these risk factors. There is a lack of information about the forces and motions involved in live contested scrummaging, and, consequently, little objective knowledge about how performance could be optimised and injuries prevented. Quantitative research on the rugby scrum has been occasional [14,22-24] and has demonstrated that high forces can be generated, particularly during the engagement phase. [14] Recent research has increased the scale and scope of the biomechanical investigation of the scrum, [15,25] and has moved the investigation into live contested scrummaging to improve the ecological validity of the data. [26]

The aim of this review is to synthesise the available literature relating to injury and biomechanical aspects of the rugby union scrum, and to 1) review the injury epidemiology of rugby scrummaging; 2) consider the evidence for specific injury mechanisms existing to cause serious scrum injuries; and 3) synthesise the information available on the biomechanics of scrummaging, primarily with respect to force production.

METHODS

Search Strategy

A literature search was conducted through Web of Knowledge and PubMed databases in June 2011 and in March 2013. The search parameters were for years 1960-2011 and 2010-2013 for the initial search and follow-up search, respectively. The search expressions were ‘rugby and scrum’, ‘scrum and injury’, ‘rugby and spine’, ‘rugby and biomechanics’, ‘scrum and biomechanics’, ‘rugby and injury prevention’, and ‘rugby and injury mechanism’. The literature search was restricted to English and Italian language publications. The search returned a total of 997 publications via Web of Knowledge and 1617 publications via PubMed. The records returned were browsed for relevance via the title and abstracts, with duplicate records being removed. The reference lists of included key studies, and relevant “grey literature” (e.g. conferences proceedings) were manually searched to identify additional articles.

Selection Criteria

Studies were selected for further review based on focus of study and population studied, with case reports being given low priority. 137 studies were initially fully critiqued and considered for inclusion in the manuscript.

RESULTS AND DISCUSSION

Epidemiology of all-outcome scrummaging injuries

The epidemiology of general rugby injury is well documented elsewhere. [27] Overall, elite rugby union has comparatively high injury incidence [2-5] in relation to other team sports, which decreases as the playing level moves from the elite level to the community game [28-30] and youth levels.[31-34] Injury incidence also appears to be lower in women's compared with men's rugby.[35,36].

Approximately 6-8% of all rugby injuries result from scrummaging, which is moderate compared with other injury-causing match events such as tackles.[2-4,37] Brooks et al[2] found that scrummaging accounted for 11% of injuries to forwards, and the incidence of scrummaging injuries referenced to hours of exposure (10/1000 player match hours in elite senior rugby[2,38]; ~2/1000 player match hours in youth rugby[39]) is correspondingly moderate to low. However, when expressed as injury per event (propensity), scrum injuries are higher than for any other contact event, reported at 8.1 injuries/1000 scrums in English Premiership rugby.[40] Taking severity into account, the scrum has the highest injury risk per event of any contact event, with 213 days lost per 1000 scrum events. This is nearly double the risk per event of injuries from legal tackles. The risk of injury due to collapsed scrums versus completed scrums has also been found to be significantly higher at professional ($P=0.04$)[38] and community ($P<0.001$) level.[41]

It is important to note that a wide range of injuries are associated with scrummaging. In a cohort of professional rugby union players, calf muscle injuries were the most common scrummaging injury followed by lumbar spine injury, with calf muscle injuries and shoulder injuries causing the greatest number of days absence due to scrummaging.[42] Neck injuries made up only 15% of the scrummaging injury burden. Front row forwards sustained 91% of all scrummaging injuries. Furthermore, the scrum was responsible for a high proportion of front row spinal injuries (41% of cervical; 56% of thoracic; 71% of lumbar).[42] The reason for front row players' susceptibility to spinal injuries has been suggested to be the repeated high forces experienced by these players,[23] particularly during scrum engagement.

In comparing the injury profiles of each forward position versus all other forward playing positions, Brooks & Kemp[43] found that player absence due to neck injuries for loose head props and hookers was higher than other forward positions due mainly to cervical disc / nerve root injuries. These injuries were sustained mainly during tackling (57% for loose head, 38% for hooker) but also scrummaging (29% for loose head, 19% for hooker). Possibly based on specificity of positional roles, the pattern of injury differed across the front row. Loose head props had more absence than other forwards due to shoulder rotator cuff injuries, primarily suffered to the right shoulder during scrummaging (66% of rotator cuff injuries). Tight head props had a greater absence due to lumbar spine injuries (67% of lumbar disc / nerve root injuries and 57% of lumbar soft tissue were attributed to scrummaging) and also due to calf injuries which were suffered mainly (54%) during scrummaging.

In summary, scrummaging accounts for a moderate proportion of the overall injury burden within rugby union, but scrummaging can be considered a high risk event in comparison with other game activities, particularly if the scrum collapses. Front row players are particularly susceptible to scrummaging injury and the scrum is responsible for a considerable proportion of the spinal and shoulder injuries sustained by front row forwards. In the context of the scrum being a relatively “controllable” event when compared with other match events such as the tackle, it is reasonable to suggest that there should be further efforts to reduce the injury burden of scrummaging.

Catastrophic Spinal Injuries in Rugby

Magnitude

In rare circumstances, a sports injury can result in permanent paralysis or a fatality. Spinal cord injuries resulting in fatal or catastrophic consequences cause significant concern in collision sports, such as American Football [44] and Rugby Union. [16] There are difficulties in the definition of “serious spinal cord injuries” or “catastrophic” injuries, and studies do not always provide a definition of which injuries are covered. For the purposes of this review, serious and catastrophic will be used synonymously and relate to an injury resulting in neurological impairment without a return to full function, equivalent to ASIA classification of A to D and therefore in line with the operational definition of catastrophic injury employed by the International Rugby Board. [45]

Estimates suggest that the incidence of catastrophic spinal injury from rugby union may lie anywhere from 1-2/100,000 players per year to 10/100,000 players per year. [16,46-50] This reflects a small number of injuries in the context of the playing population, but preventative strategies must be prioritised towards injuries causing permanent disability or death due to the devastating consequences of such injuries. [51]

Fuller [11] performed a risk analysis for sustaining a catastrophic spinal cord injury in rugby union and compared this with other collision sports and other common activities. The overall risk of catastrophic injury from rugby union ranged from 'acceptable' to 'tolerable' (as defined by the UK's Health and Safety Executive) depending on the country analysed. The risks in rugby union were described as *similar* or *less than* other sports such as American Football, rugby league and ice hockey, comparable to work-based risks and less than risks for motorcyclists and pedestrians. While acknowledging the subjective nature of perceiving risk in terms of the activity context, this study concluded that the risk of sustaining a catastrophic injury from rugby union was acceptable and the laws of the game adequately managed this risk, although all reasonably practicable measures should be taken to further reduce the risk in accordance with accepted risk management principles.

Match Event

Understanding which phase of play is considered responsible for causing catastrophic spinal injuries is a key step in prevention. For the period 1956-2004, the scrum was implicated as the match event causing a catastrophic injury in 42% of cases, compared with the tackle (34%), rucks/mauls (20%) and other phases (4%). [11] A separate review of published data for the period 1970-2001 offered similar findings, with scrums associated with approximately 40% of all serious cervical spine injuries in rugby union and the tackle associated with 36% of injuries. [16] Bohu et al [52] stated that 19 out of 37 recorded acute spinal cord injuries (i.e., 51%) occurred in the scrum, although it wasn't obvious which other game events were associated with the remaining injuries.

There is some evidence to suggest that the tackle phase is becoming the game event most implicated in serious spinal cord injury. [16] In South Africa during the period 1980-2007, 45% of 126 serious acute spinal cord injuries were attributed to the tackle phase, and 37% to the scrum. [53] In Australian rugby during the 1997-2002 period, 9 of 23 injuries occurred as a result of the tackle, 7 as a result of the scrum and 6 the ruck/maul. [54]

A recent study by Brown and colleagues [46] updated the rugby-related catastrophic injury landscape in South Africa. In the period 2008-2011 45 acute spinal cord injuries were recorded, including near-miss events, resulting in an estimated annual incidence of 1.73 injuries per 100,000 players. The scrum accounted for 42% of these injuries (19 of 45) and the tackle 38% of injuries. There was a greater preponderance for scrum injury to occur to senior players and for the injuries caused by scrummaging to result in permanent disability. Information has recently been collected regarding admissions of under 19 rugby players to spinal units in Great Britain and Ireland between 1996 and 2010. [55] Thirty six injuries were recorded, 13 of which were associated with injuries in the scrum, compared with 17 associated with the tackle. The proportion of cases with complete neurological deficit following an injury in the scrum (61%) was significantly greater than in injuries following the tackle (29%, $P<0.001$). Overall, these findings suggest that acute spinal cord injuries occur at a similar frequency in the scrum and tackle, but that neck injuries sustained in the scrum are more likely to be more serious.

Trend over Time

It is difficult to ascertain whether the incidence of rugby-related serious cervical spine injuries has changed over the last 30 years due to a lack of accurate exposure (player numbers) data, [16] because the raw number of injuries is relatively low, and because there are substantial differences in data collection methodologies. In Australia, there have been a number of studies which overall suggest a tendency for a slight decrease in the incidence of serious spinal injuries over time. Taylor et al reported that the incidence of serious spinal cord injuries dropped from 4.6/100,000 players (1983-1989) to 3.0/100,000 players (1990-1996), [50] and was at 3/100,000 players for all football codes in 1997-2002. [54] Between 1975-1985 to 1986-1996 there was a 67% reduction in serious spinal cord injuries attributed to scrum engagement, from 12 injuries to 4 injuries, [50] and there was a tendency for acute spinal cord injuries to be less severe in the period 1997-2002 compared with 1986-1996. [54] Similar findings are reported by Berry et al [56] who tracked the incidence rates of severe cervical spinal cord injury in rugby union and rugby league over 17 years (1986-2003) found a non-significant decrease in the incidence rate of these severe injuries over time but with wide confidence intervals.

In French rugby, Bohu et al [52] suggested a reduction in serious cervical spine injury incidence when comparing 1995-2001 (2.1/100,000 players) with 2001-2006 (1.4/100,000 players), and primarily attributed this to reduced incidence of injuries from scrummaging. The authors considered these reductions to be due to a change in scrum laws (e.g. limited engagement and pushing distances permitted at lower levels) and use of a ‘front row forward passport’ as medical clearance to play in these positions.

In South Africa, there was an apparent 48% reduction in the incidence of serious spinal injuries in schoolboys in the years 1990-1997 compared with previous datasets. [57] However, there was a 22% increase in admissions to spinal units in adult players in the 1990-1997 period compared with the 1982-1989 period, [57] echoing the results of Scher. [58] A retrospective pooled analysis, showed that the incidence of serious spinal cord injuries in South African rugby (assuming relatively consistent player numbers) between 1980-2007 had neither increased nor decreased, consistently lying somewhere between 0.5-1.0/100,000 players per year. [53]

Overall, it is unclear whether there have been any changes over time in the rate of rugby-related catastrophic injuries, perhaps due to cultural, medical resource and reporting differences and the fact that the absolute numbers of injuries are low. However, pooling data suggests there may have been slight reductions over the last 30 years.

Effect of Age and Playing Experience

Reports on the relative risk of a serious spinal injury in young and adult players appear contradictory, [16] with some studies reporting younger players to be at higher risk [59,60] and others suggesting adult players are at relatively higher risk. [46,50,57,58,61] Noakes et al conducted a retrospective analysis on schoolboy and adult players in South African rugby and found that 80% of the 67 recorded serious spinal injuries occurred to adults and 20% to schoolboys. [57] No player numbers were reported but it was considered likely that there were more schoolboy than adult players. These findings are supported by Scher [58] who estimated that adult players were at 10-12 times greater risk of a serious spinal injury than schoolboy players, and Taylor et al [50] who showed serious SCI incidence of 6.9/100,000 players in adult players and 1.2/100,000 players in schoolboy rugby. Recent data from South Africa which has used estimates of playing populations has confirmed that adult players (5.3/100,000 players) are at increased risk of acute spinal cord injuries compared with junior players (0.9/100,000 players), with the injuries to adult players also being more likely to result in permanent impairments. [46]

In older adult players, degenerative arthritis of the spine may be an additional risk factor for acute injury, [17,19,62] although it can be argued that a lack of maturity in skeletal and ligamentous structures is a potential additional risk factor for younger players. [63] In terms of physical conditioning characteristics, there is no compelling evidence to suggest that body anthropometrics or training status is a major risk factor for spinal injury but most recommendations continue to advocate the need for suitable physical build and specific training for those players involved in scrummaging, particularly in the front row.

A mismatch in skill, experience or strength has been suggested as a risk factor for injury in the scrum, with the risk of injury being equal across the stronger and weaker team. Wetzler et al [64] found evidence of a mismatch of some type in 25% of all serious scrum injuries. These sentiments are echoes of other research or opinion pieces (e.g. [65,66]). Also, a lack of experience of playing in the front row has been highlighted previously as a risk factor for injury (e.g attributed in 39% of scrum injuries [50]) although this practice should now be impossible if IRB laws are enforced which state: “Each player in the front row and any potential replacement(s) must be suitably trained and experienced”. What constitutes the minimum standard for suitable training and experience and how this is monitored is likely to vary between different national unions and playing levels.

Playing Position

There is consistent evidence to show that front row forwards, and particularly hookers, are at highest risk for serious spinal cord injuries (Table 1). Hookers represent 7% of the players in a team, yet in South Africa, [46] hookers account for 46% (12 of 26 injuries) of all the permanent outcome acute spinal cord injuries, with 83% (10 injuries) of these injuries occurring in the scrum. The vulnerability of the hooker in the scrum has been attributed to a number of factors, including the wrapping of their arms around props in the scrum with the effect that he or she cannot control or dissipate forces of engagement, the reliance on the props for support during engagement and formation, and the inability to adjust upper body position to react to improper engagement.

Table 1. Playing positions sustaining acute spinal cord injuries.

Study	Number of injuries	Percentage of injuries sustained by playing groups (%)		Percentage of injuries sustained by specific playing positions (%)			
		Forwards	Backs	Prop	Hooker	Other Forwards	Backs
Silver [63]	19	79	21				
Hermanus [53]	139	76	24	16	30	30	24
Bohu [52]	37	89	11	19	38		
Quarrie [16] **	341	76	24	18	33	25	24
Brown [46]	40	86	14	13	38	35	14
Brown [46] *	26	100	0	12	46	42	0

* Permanently disabling injuries included only

** Only including injuries in the sample with known playing positions

Non-catastrophic Traumatic Spinal Injuries

Most injuries to the spine from rugby are not catastrophic.[67] Fuller et al[47] conducted the most comprehensive prospective cohort study on the nature of all spinal injuries with acute presentation. The incidence of spine injuries during matches was approximately 11/1000 player match hours and 0.4/1000 player training hours. The nature of spinal injuries varied between matches and training, with players more likely to sustain a cervical spine injury during matches but a lumbar spine injury during training (primarily due to weight training or running). During matches, the tackle was implicated in 37% of spinal injuries, compared with 19% in the scrum and 17% for the ruck/maul. Focussing specifically on cervical spine injuries, the tackle was implicated in 52% of injuries compared with only 12% in the scrum, highlighting the tackle as the major source of overall cervical spine injury. Player characteristics (age and anthropometrics) were not found to influence injury risk but forwards were twice as likely to sustain a spinal injury as backs. It should be noted that the scrum was a likely source of spinal injury for front row forwards, with 58% of spinal injuries resulting from the scrum and only 13% from the tackle. Thirty-three of the 35 injuries during scrummaging were sustained by front row players and only 3 of these injuries were attributed to scrum collapse.

A prospective cohort study of neck injuries (not all spine injuries) in two Australian amateur-level rugby clubs was carried out over two seasons (2006 and 2007).[68] Neck injury incidence was 6/1000 player match hours and 0.7/1000 player training hours. Forwards suffered 79% of all neck injuries, with the front row particularly susceptible, sustaining 38% of all neck injuries for only 20% of the overall player numbers and sustaining the majority of severe injuries (>3 weeks absence). Overall, the tackle was the phase of play producing most neck injuries (42%), followed by the ruck/maul (30%) and then the scrum (25%). The most common injuries were cervical facet injury (42%), followed by brachial/plexus cervical nerve root injury (stingers / burners).

Chronic Degeneration Spinal Injuries

Acute injuries are the most evident and quantifiable type of injury in sports/rugby injury surveillance. However, repeated exposure to mechanical stresses on musculo-skeletal structures may also induce sub-critical damage, and therefore the potential for long-term damage to the spine due to rugby participation is an important consideration. The effects of repeated exposure to scrummaging and the associated loading of the spine are very difficult to detect in the short term, but likely contribute to chronic conditions. For example, front row forwards are particularly prone to premature degeneration of the cervical spine, [17-19,69,70] which may result in osteoarthritis and functional impairment, [19] with the repeated microtrauma experienced during scrummaging a likely contributory cause. [17]

Unfortunately, longitudinal data of players following retirement from the game is not currently available. It has been suggested that chronic degenerative abnormalities due to repeated subfailure injuries from the repeated trauma of collisions in scrummaging and tackling may be underestimated and may be frequent, particularly for front row forwards, representing an under-acknowledged injury issue for rugby. [71] Quinn & Winkelstein [72] and Panjabi [73] have shown that sub-catastrophic injuries to soft tissues of the spine may happen well before failure limit and result in chronic pain. Repetitive (micro) traumas may generate a detrimental loop in which subfailure stresses cause degeneration of intervertebral ligaments and receptors, which leads to altered functioning and feedback to corrupt muscle performance. This in turn produces distorted stresses in ligaments and applies abnormal loads on the facet joints, accelerating degeneration and causing pain. Cervical spine degeneration may be a risk factor for traumatic spinal cord injury, [19] but there is no definitive data to support this presently. However, cervical spine degeneration is likely to impact upon the wellbeing of players after the end of their careers.

Scher [70] produced a case series comparison demonstrating greater cervical spondylosis (premature degeneration) in 150 asymptomatic club rugby players compared with 150 age-matched controls from the general population . Degeneration was particularly marked in front row forwards and in the 30-35 year age group compared with 20-25 and 25-30 year groups.[19] Using radiographic evidence of cervical spine degeneration combined with clinical symptoms in a small group of professional rugby players, Hogan et al [69] found that experienced front row rugby players (average of 23 years of playing experience) exhibited more visual evidence of general cervical spine degeneration, but that these were not necessarily accompanied by clinical symptoms or disruption to activities of daily living over and above age-matched controls. In considering these findings it is important to note that clinical status and influence on daily living activities were obtained via questionnaire and may be subject to bias due to the perceptions of what constitutes pain or symptoms.

Other studies have demonstrated narrowing of the cervical spinal canal in rugby players compared with control (non-collision) athletes, which worsens with age. [17] All asymptomatic French professional front row rugby players were assessed using static MRI imaging of the cervical spine region in seasons 2002/03 and 2003/04 and both static and dynamic MRI in seasons 2004/05 and 2005/06. [18] There was no clear difference in the medulla to canal ratio between younger and older front row players, but older players (>21 years) had a 3-fold increase in abnormalities, mainly relating to degenerative lesions. Approximately half of the sample (56 out of 127 players) presented with an anatomical abnormality and players who exhibited an abnormal medulla-to-canal ratio were also much more likely (3-fold) to exhibit anatomical abnormalities.

In a series of studies focussing on cervical spine function in rugby players, Lark and McCarthy have demonstrated that rugby forwards have impaired cervical function. This impaired function includes: reduced cervical mobility but only some reduced proprioceptive capacity (in extension) compared with rugby backs and active controls; [20] reduced active cervical range of motion after a single game [74,75] and over the course of a season; [75] and an inability for neck range of motion to substantially recover during an off-season despite active rehabilitation being undertaken during this period. [76] These findings are only partially supported by a similar study [21] which assessed proprioceptive (head repositioning) function in younger rugby players and found evidence of reduced repositioning ability in rugby players compared with controls, but no difference between forwards and backs. The latter point was taken to suggest that the tackle might be responsible for proprioceptive deficit rather than the scrum since backs performed similarly in the test to forwards. Imoo et al [77] further found that rugby players with previous cervical injuries had impaired static standing balance when compared with rugby players without prior cervical spine injuries.

Mechanisms of spinal injury relating to rugby scrummaging

A number of injury mechanisms which may contribute to cervical spine injury in scrummaging have been suggested. The commonly accepted notion which has guided research and opinion is that acute injuries during scrummaging normally occur through 'hyperflexion' mechanisms. [78] Increasingly, this assertion is being challenged by research suggesting that a 'buckling' mechanism is more likely. [79]

'Hyperflexion' mechanism for acute spinal injury during scrummaging

Scher [58] stated that the most common mistake was for players to engage the scrum with slight flexion of the neck. This results in an elimination of the normal cervical lordosis [80] so that during a mistimed or misdirected scrum engagement or a collapsed scrum the load is applied to the flexed cervical spine rather than across the shoulders. Under this paradigm, the most common mechanism of cervical spine injury during scrummaging has been identified as hyperflexion, with or without rotation leading to anterior dislocations and unilateral or bilateral locking of facet joints. [78] McIntosh [81] found the typical pattern of loading relating to neck injury was axial loading accompanied by a bending moment, a loading type that may occur during scrum engagement. The orientation of the applied load, the presence of constrained motion and the amount of energy absorbed have been found to determine the failure mode of the cervical spine, these factors all being relevant to the scrum situation. Work from Milburn [14] with forward packs scrummaging against an instrumented machine has confirmed that the forces measured on engagement could be sufficient to destabilise the spine, and more recent research has demonstrated that contemporary scrummaging produces even greater forces. [15,25,82] Milburn [83] also highlighted that the bound rugby scrum places the cervical spine at risk of injury. He identified that “charging in” or misalignment of the head during engagement may result in injury, either via hyperextension (popping out) or more commonly from compression and hyperflexion of the cervical spine.

‘Buckling’ Mechanism for acute / chronic spinal injury during scrummaging

Winkelstein et al [84] suggested that an injury classification based on exceeding the range of motion e.g. hyperflexion or hyperextension is not always applicable because injury often occurs only a few milliseconds (2-20 ms) after impact when the known limits of movement of the cervical spine are still far from being reached. The contention is that a hyperflexion mechanism frequently does not explain the type of injury occurring in experimentally-induced situations, for instance there may be compression-flexion type injuries without head flexion. [85] Several authors have described the concept of a “buckling” mechanism, first introduced by Torg et al. [86] Buckling describes the mechanical instability that occurs when a structure is deformed primarily in compression, leading to changes in its deformation to a pattern of bending in compression, like compressing a long flexible ruler. This type of deformation and injury pattern has been reproduced in a number of experimental models [85] and is said to reproduce the types of injury seen in cervical spine injuries, with concurrent regions of compression alone, compression with flexion and compression with extension.

A review [85] of the biomechanics of acute cervical spine injury concluded that these compression types of injury can occur at relatively low velocities (3.1 m/s) and with relatively low loads or low percentages of total body weight (e.g. 16 kg) involved or acting on the spine. [85,87] The risk of injury depends on a number of factors, including constraint of head-neck complex motions which would normally allow escape from the torso, and the orientation of the impact surface. The very low frequency of cervical spinal injury following head impact has been explained by the remarkable flexibility of the neck. [88] Constraints applied to cervical motion such as “pocketing” in of the head (restricted motion of the head) are therefore thought to increase the risk of injury by increasing stiffness of the system, and preventing escape. [85,89] With respect to impact injuries Nightingale et al [85] also showed that additional constraint of the head by the impact surface, i.e. “pocketing”, may increase the risk of injury but is not required for the injury to happen. They showed that the point of impact and the characteristics of the impacting interface has an effect on injury risk and may explain why apparently similar impacts can have dramatically different consequences. Impacts perpendicular to the cervical spine placed it at increased risk for injury compared to those where the spine's orientation was not perpendicular to the impact surface. In a neutral position, the cervical spine has a flexion lordosis of approximately 25 degrees from horizontal at T1 and it has been shown that impacts to the vertex of the head and up to 15 degrees anterior to that point have a higher frequency and severity of cervical spinal injuries than impacts anterior to this or to the posterior portion of the head. [87] This work informed the "heads-up" campaign in American football and has been attributed with reducing cervical injuries. [80] The potential role of the neck muscles in providing some protection from injury may be limited in this situation because load is mainly axial in compression and there are no muscles that resist this movement.

Despite disagreement regarding mechanism, there is general consensus that situations should be avoided where 1) spinal elements are subjected to simultaneous compression and bending loads, and 2) sudden loads are applied, since it reduces the influence of the visco-elastic elements to dampen the forces and doesn’t provide time for active muscular responses.

'Hyperflexion' or 'Buckling' Mechanism for acute / chronic spinal injury during scrummaging

Kuster and colleagues [79] conducted a systematic review of studies which considered rugby union-related cervical spine injury mechanisms and concluded that it was unlikely that the traditionally quoted hyperflexion mechanism was the true mechanism for acute injuries involving spinal cord impairment. Their interpretation was that the weight of evidence suggests the primary mechanism for the commonly observed bilateral facet joint dislocation (normally C5-C7) injury to be buckling. In opposition, Dennison et al, [90] stated that it is too early to conclude that buckling is the predominant mechanisms of injury within the rugby union context. This opposition was partly based on the limitations associated with the *ex vivo* cadeveric testing upon which some of Kuster's evidence was based and the fact that the same injuries produced via buckling mechanisms in cadavers have not been recreated *in vivo*, possibly due to active involvement of the musculature in protecting from injury. Therefore, there is consensus that the C4-C6 region is the most common area of injury, but the precise mechanisms for acute spinal cord injuries during scrummaging are still not clear.

Timing of acute spinal injury during scrummaging

Earlier studies which considered at which time point in the scrum injuries were sustained tended to conclude that cervical spine injuries were a result of scrum collapse. For instance, Scher [91], reported that 16 out of 40 scrum-related cervical spine injuries studied were sustained by front row forwards and reported to be due to scrum collapse. Similarly, Silver [63,65] reported that the vast majority of scrum-related injuries were due to collapse as opposed to engagement, and in Australian rugby between 1960 and 1996, seven scrum injuries were attributed to collapse with four attributed to engagement. [50] Contrary to this, Wetzler [64] analysed injury data from 1970-1996 and found a statistical difference ($P<0.002$) to demonstrate that more scrum-related cervical spine injuries occurred during engagement rather than collapse. When Quarrie et al [16] reviewed the available published data (in 2002) of

170 spinal injuries that occurred during scrummaging, an average of 47% (range 8-65%) occurred during the engagement phase, with 46% (range 29-75%) attributed to collapse. Similarly, Brown et al [46] assimilated injury data in South Africa from 2008-2011 and reported that 56% of the scrum injuries were considered due to scrum engagement, with 39% due to scrum collapse. The differing findings across studies may reflect a changing profile of scrum-related injuries from a historical tendency for injuries to be due to scrum collapse to an increasing proportion of injuries to occur during engagement. This transition may be a reflection on the more impulsive (dynamic) nature of scrum engagement used in contemporary rugby union, which first appeared in the late 1990s.

Biomechanics of rugby scrummaging

The biomechanics of rugby scrummaging has been investigated for injury reduction/prevention (e.g. [14]) and performance profiling (e.g. [23]) purposes. Most studies have employed an experimental model of one forward pack scrummaging against an instrumented scrum machine, allowing good experimental control and better repeatability than live scrummaging, but not replicating the conditions of live scrummaging. Generally, the literature indicates that rugby scrummaging involves an initial impact-like engagement phase followed by a more steady-state sustained push phase. The majority of force is produced in a forward (compression) direction but the magnitude of shear forces in the vertical direction can be considerable and lateral forces also exist. The forces produced in scrummaging have been sporadically measured over the last 25 years with a general trend for more recent studies to demonstrate greater magnitudes of force production (Table 2).

Application of forward forces

Milburn [14] investigated the forces applied by forward packs scrummaging on a rigid instrumented scrum machine. The magnitude of summed forward forces during the engagement phase ranged from 4430 N (high school) to 7982 N (international). The observed impulsive forces were due to the large masses and ‘high’ speeds involved, and therefore assumed to be due mainly to the momentum generated by speed of engagement rather than active muscle action on impact. Considering primarily the forces produced by individuals and entire forward packs during sustained scrummaging, Quarrie & Wilson [23] reported the mean sustained force from seven Community/Elite packs to be 7170 N. The sum of the force produced by each individual in each forward pack was also measured during individual scrummaging and the force produced by teams was on average 65% of the sum of these individual forces. Those packs that generated the largest scrum force were those that managed to use individual scrummaging forces to the greatest extent, thus emphasising the requirement for teams to develop technique and coordination as a unit in order to maximise pushing force.

Preatoni et al [15] described the characteristic compression force curve (Figure 2) from scrum machine trials on a range of playing levels, with the short-duration impact peak, a drop in force to a minimum level, before a gradual rise to a relatively steady-state sustained push force. The mean peak compression forces during engagement ranged from 8700 N (Women) to 16500 N (Elite and International), whilst average sustained forces ranged from 4800 N (Women) to 8300 N (International). When forces were normalised by summed body weight there was no differences in peak engagement force between Community, Academy, Women and School playing levels, but International and Elite levels still produced more force, indicative of an overall more dynamic style of scrummaging in these playing levels even accounting for body mass.

Du Toit et al [92] employed a novel measurement approach for measuring forces during live scrummaging via the use of pressure transducers attached to the shoulders of each player. This study recorded a maximum engagement force of approximately 10 kN (10,000 N) across an under 19 front row when they engaged with an opposition pack (so two packs generating engagement speed rather than one pack against a static scrum machine). On average, the forces applied by the front rows during sustained scrummaging were significantly lower in magnitude than during engagement ($P<0.01$), although in one-off trials these magnitudes were very similar. Similar to Milburn [14], this study found engagement forces to be positively related to the combined mass of the opposing packs, although this correlation was not present during sustained scrummaging, therefore suggesting that technique plays more of a role during the sustained phase. Cazzola et al [26] provided a recent measurement of live scrummaging mechanics, recording mean peak engagement forces of 9.8 kN in a sample of professional senior players.

**** Figure 2 here ****

Application of vertical and lateral shear forces

Given that the direction of movement towards the engagement is primarily horizontal and after this the primary aim of scrummaging is to push the opposing pack backward, it would be expected that the compression component of force would be the largest and the magnitude of the shear forces relatively much smaller. Milburn [14] reported downward forces (~1000 N, up to 20% of the compression force value magnitude) during the engagement phase in all playing levels except for International level. It was suggested that the destabilising moment caused by the downward force would be resisted by leg extension actions of the front row players but that the presence of the downward forces would heighten the risk of collapse. Retiere [82] reported a similar magnitude (~1500 N, approximately 12% of the peak compression force magnitude) of downward forces in the engagement phase for the French U19 team. Preatoni et al [15] however, reported downward forces of greater magnitude during the engagement phase, ranging from -2000 N for School level to -3900 N for International packs (24% of the peak compression force magnitude), with a gradual transition to a slight upward force during the sustained phase. It seems plausible that the magnitude of downward force observed from machine scrummaging is in part a function of the design of the scrum machine and the amount of downward pressure players feel confident exerting onto it.

The presence of lateral shear forces during both the engagement and sustained phases of scrummaging were highlighted by Milburn as being inefficient and, over the long term, a likely cause of premature degeneration of the cervical spine. [70] The proposed mechanism is that shear forces introduce a moment of force which is not present during pure compression and which induces undesirable rotation and/or bending of the spine. Preatoni et al [15] found the patterns of lateral forces during engagement to be lower in magnitude than compression and vertical forces (approximately 10% of compression force magnitude) and inconsistent in direction.

Given the values reported in the different studies it appears that the forces involved in rugby scrummaging have increased considerably in the last twenty years, particularly during the engagement phase. These changes may be due to a combination of increased player size and a more dynamic engagement action, although differences in experimental instrumentation (e.g. more rigid scrum machine structures used in older studies) should not be ruled out as a contributing factor. In support of the suggestion that the engagement process has become more dynamic, the speed of engagement of International-level packs in Preatoni et al's study [15](~3.0 m/s, in 2013) was considerably greater than the engagement speed observed in Milburn's 1990 study [14] (~2.0 m/s, in 1990).

Table 2. Forces generated during rugby scrummaging

		Engagement			Sustained			Study Details
Study	Playing Level	Peak Forward / Compression (N)	Peak Vertical (N)	Peak Lateral (N)	Average Forward / Compression (N)	Average Vertical (N)	Average Lateral (N)	
Milburn [14]	School	4430	-940	-150	3370	190	-3040	Scrum Machine; Rigid frame; 500 Hz sampling; 1 team per level
	University	6540	-160	-730	4610	610	-1510	
	Community	5630	-868	-2413	4300	-151	-3093	
	International	7982	2268	-85	5761	1305	-340	
Rodano & Tosoni [24]	International U19	~11400	~4400	~400				Rigid frame; 500 Hz sampling; Single players and simulated pack reconstruction
Quarrie & Wilson [23]	Community	11000			7170			Scrum machine; 20 Hz sampling; Forces represent absolute (modulus) of force
Du Toit [92]	School	7526			6145			Live scrum; Pressure transducers; Force derived from summed pressures Mean of 13 teams
Retiere [82]	International U19	~ 12000	~ -1500		~ 7000	~ -200		Scrum machine; 500 Hz sampling; Damping in machine pads; 1 team
Preatoni [15]	School	9100	-2000	1100	4880	100	110	Scrum machine; 500 Hz sampling; Damping in machine pads; 4-6 teams

University	11700	-2900	1300	5940	96	130	per level; Lateral force during engagement is range of lateral force not peak.
Women	8700	-2400	1000	4790	7	-90	
Community	12000	-2300	1400	5780	-28	110	
Elite Club	16500	-3900	1900	8300	720	620	
International	16500	-3600	1900	8300	1084	600	

Modifying the engagement process

One potential route to modifying the forces generated in the rugby scrum, particularly during the initial engagement phase, is to modify the engagement process through changes to player actions or referee instructions. Previously this has been attempted by adjusting how many players are involved in the engagement. Milburn & O'Shea [93] investigated a sequential scrum formation whereby, each row of the scrum formed once the previous row were in position (i.e., 3+2+3). Sequential engagement significantly reduced the total engagement force (4833 N) experienced across the front row players compared with the standard scrum (5882 N, $P<0.05$), primarily due to a reduction in force through the loose head prop. However, sequential formation also reduced the stability of the scrum by increasing its duration and increasing the variability of vertical and lateral forces acting on the front row players as second rows and back row players were added asynchronously. Similarly, Du Toit et al [92] found that the peak engagement force of all players in the scrum was significantly greater during a full scrum engagement (7526 N) as opposed to a sequential scrum engagement (4596 N, $P<0.01$) in under 19 schoolboy teams, with no differences in the forces achieved during sustained scrummaging. Retiere [82] reported downward forces for the French U19 team in the region of -1000 N for a normal engagement and -600 N for a sequential 5+3 engagement, where the front and second row only were involved in the initial engagement and the back row were added subsequently.

In machine-scrummaging trials, Preatoni et al [25] demonstrated that a 5+3 sequential engagement significantly ($P<0.05$) reduced peak compression (12-20%) and downward (5-32%) forces during the engagement phase for all playing levels but did not alter a 'Hazard Index' combining measures of force and head-neck alignment. However, a 'fold-in' engagement where all 8 forwards were involved but were instructed to de-emphasise the engagement created larger reductions in peak compression forces (45-54%) and downward forces (21-40%) as well as significantly reducing the Hazard Index measure ($P<0.05$). This fold-in procedure also allowed forward packs to maintain forward force generation during the sustained push phase.

Measuring player loading variables in the more realistic setting of contested live scrummaging, Cazzola et al [26] performed an initial study in a group of elite professional teams, demonstrating an approximate reduction of peak forces across the front row during engagement of approximately 25% when using a pre-bind engagement process (~6300 N) compared with the 2012-13 full scrum engagement process (~8800 N). This pre-bind engagement process did not impair force generation in the sustained phase of scrummaging and also did not negatively influence scrum stability measures.

In summary, a number of studies have shown that a sequential engagement process for the scrum, by progressively adding players following the initial engagement of the two forward packs in some way, reduces peak forces experienced by front row players but upsets the stability of the scrum in terms of creation of shear forces, spinal misalignments, or overall duration of the scrum. Therefore, the principle of sequential scrum engagement has not been recommended by any of the published studies. On the other hand, engagement processes which involve the full scrum configuration (all 16 players) in the initial engagement phase but which de-emphasises the momentum generated during this phase appear to produce more encouraging results in terms of force reduction alongside maintenance of scrum stability.

CONCLUSION

This review has highlighted that, scrummaging accounts for up to, but probably no more than, 10% of all rugby-related injuries. Most of these reported injuries are of moderate severity and the incidence of catastrophic injuries from scrummaging is very low. Approximately 40% of all rugby-related spinal cord injuries can be attributed to the scrum. Conclusive statements regarding the true level and trends of catastrophic injuries in rugby union have been hampered by a lack of consistency coherence in medical record keeping and poor estimates of the size of the rugby-playing population. In recent years the International Rugby Board has constituted a centralised database intended to capture all catastrophic injuries occurring world-wide and so a clearer picture should become apparent.

There is also emerging evidence regarding the issue of chronic degeneration in rugby players, with the suggestion that scrummaging may play a role in the deleterious anatomical and functional effects displayed by rugby forwards. Again, a lack of longitudinal clinical datasets on cohorts of rugby players and matched controls makes definitive statements around the influence of rugby, and scrummaging in particular, on degeneration of the spine difficult to make and this is a key area for future research.

During the engagement phase, the forces generated at the interface between the two front rows during scrummaging are considerable and include forces in multiple directions, mainly forward but also downward. The forces acting during engagement can be modified but negative consequences in terms of stability have been reported when sequential scrum engagement processes have been attempted; limitations apparently not observed when fold-in/pre-bind engagement processes are employed.

The relatively “controlled” environment of the scrum is a phase of play in which it should be possible to intervene to reduce injury occurrence, either through modifications to player technique, coaching practices or laws. [10] The scrum therefore remains high priority for research with a long term goal of injury reduction.

COMPETING INTERESTS

None of the authors has competing financial, professional or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

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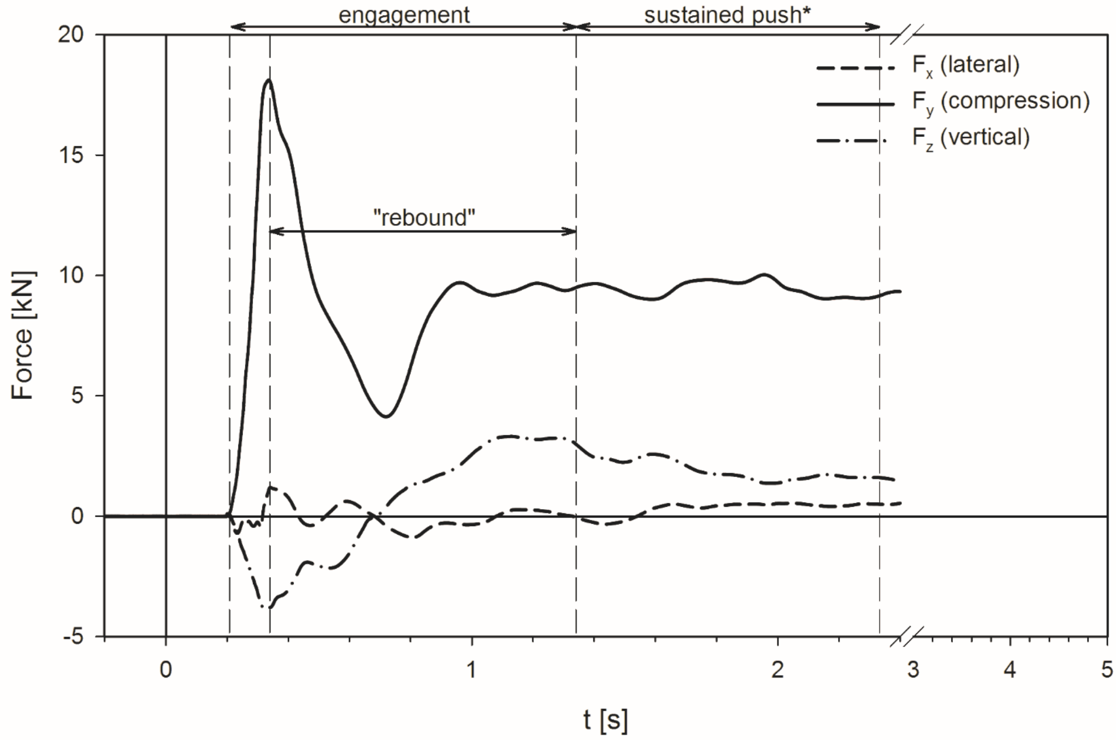
FIGURE CAPTIONS

Figure 1. Key events and body postures during rugby scrum engagement. Following a referee call of “crouch” then “touch” the front rows crouch so that when they meet, each player’s head and shoulders are no lower than the hips and props touch the shoulder of the opposing prop before withdrawing their arm. The referee then calls “set” (as of August 2012), which is an indication that the front rows may come together when ready. The front rows of each team’s scrum pack engage with their heads interlocked, with contact between the front row players taking place through the backs of their necks and shoulders. As a result of this a tunnel is created into which the scrum-half throws in the ball and the forward packs compete for possession by aiming to push the opposing pack backwards.

Figure 2. Characteristic force traces typical of those obtained from studies involving one forward pack scrummaging against an instrumented scrum machine, adapted from Preatoni et al [15]


Crouch Position
02 02
Touch Position
02 02
Set Position (post-engagement)
02 02

Figure 1


engagement
sustained push*
"rebound"
F_x (lateral)
F_y (compression)
F_z (vertical)
Force [kN]
20
15
10
5
0
-5
0
1
2
3
4
5
t [s]

938 Figure 2