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1 **TITLE PAGE**

2 **Title**

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

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21 **Contributorship Statement**

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

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

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

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

31

32 **What this study adds**

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

40

41 **ABSTRACT**

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

61 INTRODUCTION

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

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

87

88 **** Figure 1 here ****

89

90 The rugby scrum generates very high biomechanical demands on players' musculoskeletal
91 structures and thus exposes forwards, and front row forwards in particular, to the risk of both
92 acute and chronic (overuse) injuries. The epidemiological studies of rugby injury reviewed
93 later describe a moderate incidence/proportion of scrum-related injuries, but also the
94 potential seriousness of these occurrences. In fact, even though some recent data suggest a
95 relative decline in scrum-related serious injuries over recent decades, about 40% of all
96 catastrophic (typically spinal cord) injuries that occur in rugby are related to scrummaging.¹⁶
97 Furthermore, players may appear asymptomatic in the shorter-term, but may experience
98 repeated micro-trauma¹⁷ that contribute to the emergence of long-term degeneration and
99 pathologies of the spine, including physical abnormalities^{18,19}, reduced mobility²⁰, and
100 impaired proprioception.²¹

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

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

115

116 **METHODS**

117 **Search Strategy**

118 A literature search was conducted through Web of Knowledge and PubMed databases in
119 June 2011 and in March 2013. The search parameters were for years 1960-2011 and 2010-
120 2013 for the initial search and follow-up search, respectively. The search expressions were
121 'rugby and scrum', 'scrum and injury', 'rugby and spine', 'rugby and biomechanics', 'scrum
122 and biomechanics', 'rugby and injury prevention', and 'rugby and injury mechanism'. The
123 literature search was restricted to English and Italian language publications. The search
124 returned a total of 997 publications via Web of Knowledge and 1617 publications via
125 PubMed. The records returned were browsed for relevance via the title and abstracts, with
126 duplicate records being removed. The reference lists of included key studies, and relevant
127 "grey literature" (e.g. conferences proceedings) were manually searched to identify
128 additional articles.

129

130 **Selection Criteria**

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

134

135 **RESULTS AND DISCUSSION**

136 **Epidemiology of all-outcome scrummaging injuries**

137 The epidemiology of general rugby injury is well documented elsewhere.²⁷ Overall, elite
138 rugby union has comparatively high injury incidence²⁻⁵ in relation to other team sports, which
139 decreases as the playing level moves from the elite level to the community game²⁸⁻³⁰ and

140 youth levels.³¹⁻³⁴ Injury incidence also appears to be lower in women's compared with men's
141 rugby.^{35,36}

142 Approximately 6-8% of all rugby injuries result from scrummaging, which is moderate
143 compared with other injury-causing match events such as tackles.^{2-4,37} Brooks et al² found
144 that scrummaging accounted for 11% of injuries to forwards, and the incidence of
145 scrummaging injuries referenced to hours of exposure (10/1000 player match hours in elite
146 senior rugby^{2,38}; ~2/1000 player match hours in youth rugby³⁹) is correspondingly moderate
147 to low. However, when expressed as injury per event (propensity), scrum injuries are higher
148 than for any other contact event, reported at 8.1 injuries/1000 scrums in English Premiership
149 rugby.⁴⁰ Taking severity into account, the scrum has the highest injury risk per event of any
150 contact event, with 213 days lost per 1000 scrum events. This is nearly double the risk per
151 event of injuries from legal tackles. The risk of injury due to collapsed scrums versus
152 completed scrums has also been found to be significantly higher at professional (P=0.04)³⁸
153 and community (P<0.001) level.⁴¹

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

163 In comparing the injury profiles of each forward position versus all other forward playing
164 positions, Brooks & Kemp⁴³ found that player absence due to neck injuries for loose head
165 props and hookers was higher than other forward positions due mainly to cervical disc /
166 nerve root injuries. These injuries were sustained mainly during tackling (57% for loose

167 head, 38% for hooker) but also scrummaging (29% for loose head, 19% for hooker).
168 Possibly based on specificity of positional roles, the pattern of injury differed across the front
169 row. Loose head props had more absence than other forwards due to shoulder rotator cuff
170 injuries, primarily suffered to the right shoulder during scrummaging (66% of rotator cuff
171 injuries). Tight head props had a greater absence due to lumbar spine injuries (67% of
172 lumbar disc / nerve root injuries and 57% of lumbar soft tissue were attributed to
173 scrummaging) and also due to calf injuries which were suffered mainly (54%) during
174 scrummaging.

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

183

184 **Catastrophic Spinal Injuries in Rugby**

185 ***Magnitude***

186 In rare circumstances, a sports injury can result in permanent paralysis or a fatality. Spinal
187 cord injuries resulting in fatal or catastrophic consequences cause significant concern in
188 collision sports, such as American Football ⁴⁴ and Rugby Union. ¹⁶ There are difficulties in
189 the definition of “serious spinal cord injuries” or “catastrophic” injuries, and studies do not
190 always provide a definition of which injuries are covered. For the purposes of this review,
191 serious and catastrophic will be used synonymously and relate to an injury resulting in
192 neurological impairment without a return to full function, equivalent to ASIA classification of A

193 to D and therefore in line with the operational definition of catastrophic injury employed by
194 the International Rugby Board. ⁴⁵

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

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

211

212 **Match Event**

213 Understanding which phase of play is considered responsible for causing catastrophic spinal
214 injuries is a key step in prevention. For the period 1956-2004, the scrum was implicated as
215 the match event causing a catastrophic injury in 42% of cases, compared with the tackle
216 (34%), rucks/mauls (20%) and other phases (4%). ¹¹ A separate review of published data for
217 the period 1970-2001 offered similar findings, with scrums associated with approximately
218 40% of all serious cervical spine injuries in rugby union and the tackle associated with 36%
219 of injuries. ¹⁶ Bohu et al ⁵² stated that 19 out of 37 recorded acute spinal cord injuries (i.e.,

220 51%) occurred in the scrum, although it wasn't obvious which other game events were
221 associated with the remaining injuries.

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

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

241

242 ***Trend over Time***

243 It is difficult to ascertain whether the incidence of rugby-related serious cervical spine injuries
244 has changed over the last 30 years due to a lack of accurate exposure (player numbers)
245 data, ¹⁶ because the raw number of injuries is relatively low, and because there are
246 substantial differences in data collection methodologies. In Australia, there have been a

247 number of studies which overall suggest a tendency for a slight decrease in the incidence of
248 serious spinal injuries over time. Taylor et al reported that the incidence of serious spinal
249 cord injuries dropped from 4.6/100,000 players (1983-1989) to 3.0/100,000 players (1990-
250 1996),⁵⁰ and was at 3/100,000 players for all football codes in 1997-2002.⁵⁴ Between 1975-
251 1985 to 1986-1996 there was a 67% reduction in serious spinal cord injuries attributed to
252 scrum engagement, from 12 injuries to 4 injuries,⁵⁰ and there was a tendency for acute
253 spinal cord injuries to be less severe in the period 1997-2002 compared with 1986-1996.⁵⁴
254 Similar findings are reported by Berry et al⁵⁶ who tracked the incidence rates of severe
255 cervical spinal cord injury in rugby union and rugby league over 17 years (1986-2003) found
256 a non-significant decrease in the incidence rate of these severe injuries over time but with
257 wide confidence intervals.

258 In French rugby, Bohu et al⁵² suggested a reduction in serious cervical spine injury
259 incidence when comparing 1995-2001 (2.1/100,000 players) with 2001-2006 (1.4/100,000
260 players), and primarily attributed this to reduced incidence of injuries from scrummaging. The
261 authors considered these reductions to be due to a change in scrum laws (e.g. limited
262 engagement and pushing distances permitted at lower levels) and use of a 'front row forward
263 passport' as medical clearance to play in these positions.

264 In South Africa, there was an apparent 48% reduction in the incidence of serious spinal
265 injuries in schoolboys in the years 1990-1997 compared with previous datasets.⁵⁷ However,
266 there was a 22% increase in admissions to spinal units in adult players in the 1990-1997
267 period compared with the 1982-1989 period,⁵⁷ echoing the results of Scher.⁵⁸ A
268 retrospective pooled analysis, showed that the incidence of serious spinal cord injuries in
269 South African rugby (assuming relatively consistent player numbers) between 1980-2007
270 had neither increased nor decreased, consistently lying somewhere between 0.5-
271 1.0/100,000 players per year.⁵³

272 Overall, it is unclear whether there have been any changes over time in the rate of rugby-
273 related catastrophic injuries, perhaps due to cultural, medical resource and reporting

274 differences and the fact that the absolute numbers of injuries are low. However, pooling data
275 suggests there may have been slight reductions over the last 30 years.

276

277 ***Effect of Age and Playing Experience***

278 Reports on the relative risk of a serious spinal injury in young and adult players appear
279 contradictory, ¹⁶ with some studies reporting younger players to be at higher risk ^{59,60} and
280 others suggesting adult players are at relatively higher risk. ^{46,50,57,58,61} Noakes et al
281 conducted a retrospective analysis on schoolboy and adult players in South African rugby
282 and found that 80% of the 67 recorded serious spinal injuries occurred to adults and 20% to
283 schoolboys. ⁵⁷ No player numbers were reported but it was considered likely that there were
284 more schoolboy than adult players. These findings are supported by Scher ⁵⁸ who estimated
285 that adult players were at 10-12 times greater risk of a serious spinal injury than schoolboy
286 players, and Taylor et al ⁵⁰ who showed serious SCI incidence of 6.9/100,000 players in
287 adult players and 1.2/100,000 players in schoolboy rugby. Recent data from South Africa
288 which has used estimates of playing populations has confirmed that adult players
289 (5.3/100,000 players) are at increased risk of acute spinal cord injuries compared with junior
290 players (0.9/100,000 players), with the injuries to adult players also being more likely to
291 result in permanent impairments. ⁴⁶

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

299 A mismatch in skill, experience or strength has been suggested as a risk factor for injury in
300 the scrum, with the risk of injury being equal across the stronger and weaker team. Wetzler

301 et al ⁶⁴ found evidence of a mismatch of some type in 25% of all serious scrum injuries.
302 These sentiments are echoes of other research or opinion pieces (e.g. ^{65,66}). Also, a lack of
303 experience of playing in the front row has been highlighted previously as a risk factor for
304 injury (e.g attributed in 39% of scrum injuries ⁵⁰) although this practice should now be
305 impossible if IRB laws are enforced which state: “Each player in the front row and any
306 potential replacement(s) must be suitably trained and experienced”. What constitutes the
307 minimum standard for suitable training and experience and how this is monitored is likely to
308 vary between different national unions and playing levels.

309

310 ***Playing Position***

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

320

321 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

322 * Permanently disabling injuries included only

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

324

325

326 **Non-catastrophic Traumatic Spinal Injuries**

327 Most injuries to the spine from rugby are not catastrophic. ⁶⁷ Fuller et al ⁴⁷ conducted the
328 most comprehensive prospective cohort study on the nature of all spinal injuries with acute
329 presentation. The incidence of spine injuries during matches was approximately 11/1000
330 player match hours and 0.4/1000 player training hours. The nature of spinal injuries varied
331 between matches and training, with players more likely to sustain a cervical spine injury
332 during matches but a lumbar spine injury during training (primarily due to weight training or
333 running). During matches, the tackle was implicated in 37% of spinal injuries, compared with
334 19% in the scrum and 17% for the ruck/maul. Focussing specifically on cervical spine
335 injuries, the tackle was implicated in 52% of injuries compared with only 12% in the scrum,
336 highlighting the tackle as the major source of overall cervical spine injury. Player
337 characteristics (age and anthropometrics) were not found to influence injury risk but forwards
338 were twice as likely to sustain a spinal injury as backs. It should be noted that the scrum was
339 a likely source of spinal injury for front row forwards, with 58% of spinal injuries resulting
340 from the scrum and only 13% from the tackle. Thirty-three of the 35 injuries during
341 scrummaging were sustained by front row players and only 3 of these injuries were
342 attributed to scrum collapse.

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

352

353 **Chronic Degeneration Spinal Injuries**

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

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

377 Scher ⁷⁰ produced a case series comparison demonstrating greater cervical spondylosis
378 (premature degeneration) in 150 asymptomatic club rugby players compared with 150 age-
379 matched controls from the general population . Degeneration was particularly marked in front

380 row forwards and in the 30-35 year age group compared with 20-25 and 25-30 year groups.

381 ¹⁹ Using radiographic evidence of cervical spine degeneration combined with clinical
382 symptoms in a small group of professional rugby players, Hogan et al ⁶⁹ found that
383 experienced front row rugby players (average of 23 years of playing experience) exhibited
384 more visual evidence of general cervical spine degeneration, but that these were not
385 necessarily accompanied by clinical symptoms or disruption to activities of daily living over
386 and above age-matched controls. In considering these findings it is important to note that
387 clinical status and influence on daily living activities were obtained via questionnaire and
388 may be subject to bias due to the perceptions of what constitutes pain or symptoms.

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

399 In a series of studies focussing on cervical spine function in rugby players, Lark and
400 McCarthy have demonstrated that rugby forwards have impaired cervical function. This
401 impaired function includes: reduced cervical mobility but only some reduced proprioceptive
402 capacity (in extension) compared with rugby backs and active controls; ²⁰ reduced active
403 cervical range of motion after a single game ^{74,75} and over the course of a season; ⁷⁵ and an
404 inability for neck range of motion to substantially recover during an off-season despite active
405 rehabilitation being undertaken during this period. ⁷⁶ These findings are only partially
406 supported by a similar study ²¹ which assessed proprioceptive (head repositioning) function

407 in younger rugby players and found evidence of reduced repositioning ability in rugby
408 players compared with controls, but no difference between forwards and backs. The latter
409 point was taken to suggest that the tackle might be responsible for proprioceptive deficit
410 rather than the scrum since backs performed similarly in the test to forwards. Imoo et al ⁷⁷
411 further found that rugby players with previous cervical injuries had impaired static standing
412 balance when compared with rugby players without prior cervical spine injuries.

413

414 **Mechanisms of spinal injury relating to rugby scrummaging**

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

420 ***'Hyperflexion' mechanism for acute spinal injury during scrummaging***

421 Scher ⁵⁸ stated that the most common mistake was for players to engage the scrum with
422 slight flexion of the neck. This results in an elimination of the normal cervical lordosis ⁸⁰ so
423 that during a mistimed or misdirected scrum engagement or a collapsed scrum the load is
424 applied to the flexed cervical spine rather than across the shoulders. Under this paradigm,
425 the most common mechanism of cervical spine injury during scrummaging has been
426 identified as hyperflexion, with or without rotation leading to anterior dislocations and
427 unilateral or bilateral locking of facet joints. ⁷⁸ McIntosh ⁸¹ found the typical pattern of loading
428 relating to neck injury was axial loading accompanied by a bending moment, a loading type
429 that may occur during scrum engagement. The orientation of the applied load, the presence
430 of constrained motion and the amount of energy absorbed have been found to determine the
431 failure mode of the cervical spine, these factors all being relevant to the scrum situation.
432 Work from Milburn ¹⁴ with forward packs scrummaging against an instrumented machine has
433 confirmed that the forces measured on engagement could be sufficient to destabilise the

434 spine, and more recent research has demonstrated that contemporary scrummaging
435 produces even greater forces. ^{15,25,82} Milburn ⁸³ also highlighted that the bound rugby scrum
436 places the cervical spine at risk of injury. He identified that “charging in” or misalignment of
437 the head during engagement may result in injury, either via hyperextension (popping out) or
438 more commonly from compression and hyperflexion of the cervical spine.

439

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

442 Winkelstein et al ⁸⁴ suggested that an injury classification based on exceeding the range of
443 motion e.g. hyperflexion or hyperextension is not always applicable because injury often
444 occurs only a few milliseconds (2-20 ms) after impact when the known limits of movement of
445 the cervical spine are still far from being reached. The contention is that a hyperflexion
446 mechanism frequently does not explain the type of injury occurring in experimentally-induced
447 situations, for instance there may be compression-flexion type injuries without head flexion.

448 ⁸⁵ Several authors have described the concept of a “buckling” mechanism, first introduced by
449 Torg et al. ⁸⁶ Buckling describes the mechanical instability that occurs when a structure is
450 deformed primarily in compression, leading to changes in its deformation to a pattern of
451 bending in compression, like compressing a long flexible ruler. This type of deformation and
452 injury pattern has been reproduced in a number of experimental models ⁸⁵ and is said to
453 reproduce the types of injury seen in cervical spine injuries, with concurrent regions of
454 compression alone, compression with flexion and compression with extension.

455 A review ⁸⁵ of the biomechanics of acute cervical spine injury concluded that these
456 compression types of injury can occur at relatively low velocities (3.1 m/s) and with relatively
457 low loads or low percentages of total body weight (e.g. 16 kg) involved or acting on the
458 spine. ^{85,87} The risk of injury depends on a number of factors, including constraint of head-
459 neck complex motions which would normally allow escape from the torso, and the orientation
460 of the impact surface. The very low frequency of cervical spinal injury following head impact

461 has been explained by the remarkable flexibility of the neck. ⁸⁸ Constraints applied to
462 cervical motion such as “pocketing” in of the head (restricted motion of the head) are
463 therefore thought to increase the risk of injury by increasing stiffness of the system, and
464 preventing escape. ^{85,89} With respect to impact injuries Nightingale et al ⁸⁵ also showed that
465 additional constraint of the head by the impact surface, i.e. “pocketing”, may increase the
466 risk of injury but is not required for the injury to happen. They showed that the point of impact
467 and the characteristics of the impacting interface has an effect on injury risk and may explain
468 why apparently similar impacts can have dramatically different consequences. Impacts
469 perpendicular to the cervical spine placed it at increased risk for injury compared to those
470 where the spine's orientation was not perpendicular to the impact surface. In a neutral
471 position, the cervical spine has a flexion lordosis of approximately 25 degrees from
472 horizontal at T1 and it has been shown that impacts to the vertex of the head and up to 15
473 degrees anterior to that point have a higher frequency and severity of cervical spinal injuries
474 than impacts anterior to this or to the posterior portion of the head. ⁸⁷ This work informed the
475 "heads-up" campaign in American football and has been attributed with reducing cervical
476 injuries. ⁸⁰ The potential role of the neck muscles in providing some protection from injury
477 may be limited in this situation because load is mainly axial in compression and there are no
478 muscles that resist this movement.

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

484

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

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

500

501 ***Timing of acute spinal injury during scrummaging***

502 Earlier studies which considered at which time point in the scrum injuries were sustained
503 tended to conclude that cervical spine injuries were a result of scrum collapse. For instance,
504 Scher ⁹¹, reported that 16 out of 40 scrum-related cervical spine injuries studied were
505 sustained by front row forwards and reported to be due to scrum collapse. Similarly, Silver
506 ^{63,65} reported that the vast majority of scrum-related injuries were due to collapse as opposed
507 to engagement, and in Australian rugby between 1960 and 1996, seven scrum injuries were
508 attributed to collapse with four attributed to engagement. ⁵⁰ Contrary to this, Wetzler ⁶⁴
509 analysed injury data from 1970-1996 and found a statistical difference ($P < 0.002$) to
510 demonstrate that more scrum-related cervical spine injuries occurred during engagement
511 rather than collapse. When Quarrie et al ¹⁶ reviewed the available published data (in 2002) of

512 170 spinal injuries that occurred during scrummaging, an average of 47% (range 8-65%)
513 occurred during the engagement phase, with 46% (range 29-75%) attributed to collapse.
514 Similarly, Brown et al ⁴⁶ assimilated injury data in South Africa from 2008-2011 and reported
515 that 56% of the scrum injuries were considered due to scrum engagement, with 39% due to
516 scrum collapse. The differing findings across studies may reflect a changing profile of scrum-
517 related injuries from a historical tendency for injuries to be due to scrum collapse to an
518 increasing proportion of injuries to occur during engagement. This transition may be a
519 reflection on the more impulsive (dynamic) nature of scrum engagement used in
520 contemporary rugby union, which first appeared in the late 1990s.

521

522 **Biomechanics of rugby scrummaging**

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

534

535 ***Application of forward forces***

536 Milburn ¹⁴ investigated the forces applied by forward packs scrummaging on a rigid
537 instrumented scrum machine. The magnitude of summed forward forces during the

538 engagement phase ranged from 4430 N (high school) to 7982 N (international). The
539 observed impulsive forces were due to the large masses and 'high' speeds involved, and
540 therefore assumed to be due mainly to the momentum generated by speed of engagement
541 rather than active muscle action on impact. Considering primarily the forces produced by
542 individuals and entire forward packs during sustained scrummaging, Quarrie & Wilson ²³
543 reported the mean sustained force from seven Community/Elite packs to be 7170 N. The
544 sum of the force produced by each individual in each forward pack was also measured
545 during individual scrummaging and the force produced by teams was on average 65% of the
546 sum of these individual forces. Those packs that generated the largest scrum force were
547 those that managed to use individual scrummaging forces to the greatest extent, thus
548 emphasising the requirement for teams to develop technique and coordination as a unit in
549 order to maximise pushing force.

550 Preatoni et al ¹⁵ described the characteristic compression force curve (Figure 2) from scrum
551 machine trials on a range of playing levels, with the short-duration impact peak, a drop in
552 force to a minimum level, before a gradual rise to a relatively steady-state sustained push
553 force. The mean peak compression forces during engagement ranged from 8700 N
554 (Women) to 16500 N (Elite and International), whilst average sustained forces ranged from
555 4800 N (Women) to 8300 N (International). When forces were normalised by summed body
556 weight there was no differences in peak engagement force between Community, Academy,
557 Women and School playing levels, but International and Elite levels still produced more
558 force, indicative of an overall more dynamic style of scrummaging in these playing levels
559 even accounting for body mass.

560 Du Toit et al ⁹² employed a novel measurement approach for measuring forces during live
561 scrummaging via the use of pressure transducers attached to the shoulders of each player.
562 This study recorded a maximum engagement force of approximately 10 kN (10,000 N)
563 across an under 19 front row when they engaged with an opposition pack (so two packs
564 generating engagement speed rather than one pack against a static scrum machine). On

565 average, the forces applied by the front rows during sustained scrummaging were
566 significantly lower in magnitude than during engagement ($P<0.01$), although in one-off trials
567 these magnitudes were very similar. Similar to Milburn ¹⁴, this study found engagement
568 forces to be positively related to the combined mass of the opposing packs, although this
569 correlation was not present during sustained scrummaging, therefore suggesting that
570 technique plays more of a role during the sustained phase. Cazzola et al ²⁶ provided a recent
571 measurement of live scrummaging mechanics, recording mean peak engagement forces of
572 9.8 kN in a sample of professional senior players.

573

574 **** Figure 2 here ****

575

576 ***Application of vertical and lateral shear forces***

577 Given that the direction of movement towards the engagement is primarily horizontal and
578 after this the primary aim of scrummaging is to push the opposing pack backward, it would
579 be expected that the compression component of force would be the largest and the
580 magnitude of the shear forces relatively much smaller. Milburn ¹⁴ reported downward forces
581 (~1000 N, up to 20% of the compression force value magnitude) during the engagement
582 phase in all playing levels except for International level. It was suggested that the
583 destabilising moment caused by the downward force would be resisted by leg extension
584 actions of the front row players but that the presence of the downward forces would heighten
585 the risk of collapse. Retiere ⁸² reported a similar magnitude (~1500 N, approximately 12% of
586 the peak compression force magnitude) of downward forces in the engagement phase for
587 the French U19 team. Preatoni et al ¹⁵ however, reported downward forces of greater
588 magnitude during the engagement phase, ranging from -2000 N for School level to -3900 N
589 for International packs (24% of the peak compression force magnitude), with a gradual
590 transition to a slight upward force during the sustained phase. It seems plausible that the
591 magnitude of downward force observed from machine scrummaging is in part a function of

592 the design of the scrum machine and the amount of downward pressure players feel
593 confident exerting onto it.

594 The presence of lateral shear forces during both the engagement and sustained phases of
595 scrummaging were highlighted by Milburn as being inefficient and, over the long term, a
596 likely cause of premature degeneration of the cervical spine.⁷⁰ The proposed mechanism is
597 that shear forces introduce a moment of force which is not present during pure compression
598 and which induces undesirable rotation and/or bending of the spine. Preatoni et al¹⁵ found
599 the patterns of lateral forces during engagement to be lower in magnitude than compression
600 and vertical forces (approximately 10% of compression force magnitude) and inconsistent in
601 direction.

602 Given the values reported in the different studies it appears that the forces involved in rugby
603 scrummaging have increased considerably in the last twenty years, particularly during the
604 engagement phase. These changes may be due to a combination of increased player size
605 and a more dynamic engagement action, although differences in experimental
606 instrumentation (e.g. more rigid scrum machine structures used in older studies) should not
607 be ruled out as a contributing factor. In support of the suggestion that the engagement
608 process has become more dynamic, the speed of engagement of International-level packs in
609 Preatoni et al's study¹⁵ (~3.0 m/s, in 2013) was considerably greater than the engagement
610 speed observed in Milburn's 1990 study¹⁴ (~2.0 m/s, in 1990).

611 Table 2. Forces generated during rugby scrummaging

Study	Playing Level	Engagement			Sustained			Study Details
		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
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

per level; Lateral force during engagement is range of lateral force not peak.

612

613

614 ***Modifying the engagement process***

615 One potential route to modifying the forces generated in the rugby scrum, particularly during
616 the initial engagement phase, is to modify the engagement process through changes to
617 player actions or referee instructions. Previously this has been attempted by adjusting how
618 many players are involved in the engagement. Milburn & O'Shea⁹³ investigated a sequential
619 scrum formation whereby, each row of the scrum formed once the previous row were in
620 position (i.e., 3+2+3). Sequential engagement significantly reduced the total engagement
621 force (4833 N) experienced across the front row players compared with the standard scrum
622 (5882 N, $P<0.05$), primarily due to a reduction in force through the loose head prop.
623 However, sequential formation also reduced the stability of the scrum by increasing its
624 duration and increasing the variability of vertical and lateral forces acting on the front row
625 players as second rows and back row players were added asynchronously. Similarly, Du Toit
626 et al⁹² found that the peak engagement force of all players in the scrum was significantly
627 greater during a full scrum engagement (7526 N) as opposed to a sequential scrum
628 engagement (4596 N, $P<0.01$) in under 19 schoolboy teams, with no differences in the
629 forces achieved during sustained scrummaging. Retiere⁸² reported downward forces for the
630 French U19 team in the region of -1000 N for a normal engagement and -600 N for a
631 sequential 5+3 engagement, where the front and second row only were involved in the initial
632 engagement and the back row were added subsequently.

633 In machine-scrummaging trials, Preatoni et al²⁵ demonstrated that a 5+3 sequential
634 engagement significantly ($P<0.05$) reduced peak compression (12-20%) and downward (5-
635 32%) forces during the engagement phase for all playing levels but did not alter a 'Hazard
636 Index' combining measures of force and head-neck alignment. However, a 'fold-in'
637 engagement where all 8 forwards were involved but were instructed to de-emphasise the
638 engagement created larger reductions in peak compression forces (45-54%) and downward
639 forces (21-40%) as well as significantly reducing the Hazard Index measure ($P<0.05$). This

640 fold-in procedure also allowed forward packs to maintain forward force generation during the
641 sustained push phase.

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

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

659

660 **CONCLUSION**

661 This review has highlighted that, scrummaging accounts for up to, but probably no more
662 than, 10% of all rugby-related injuries. Most of these reported injuries are of moderate
663 severity and the incidence of catastrophic injuries from scrummaging is very low.
664 Approximately 40% of all rugby-related spinal cord injuries can be attributed to the scrum.
665 Conclusive statements regarding the true level and trends of catastrophic injuries in rugby
666 union have been hampered by a lack of consistency coherence in medical record keeping

667 and poor estimates of the size of the rugby-playing population. In recent years the
668 International Rugby Board has constituted a centralised database intended to capture all
669 catastrophic injuries occurring world-wide and so a clearer picture should become apparent.

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

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

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

686

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690

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693

694

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920 **FIGURE CAPTIONS**

921

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

931

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

935

Crouch Position



Touch Position

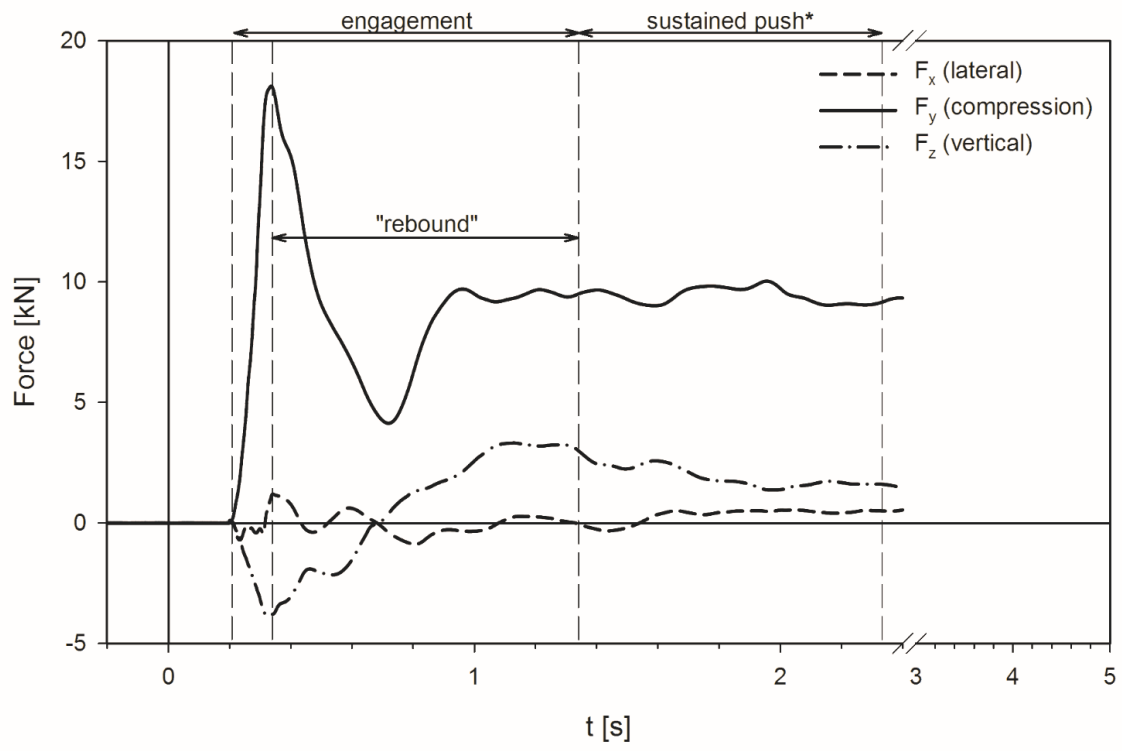


Set Position (post-engagement)



936 Figure 1

937



938 Figure 2