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Title

A modified pre-bind engagement process reduces biomechanical loading on front row players during scrummaging: a cross-sectional study of 11 elite teams.

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Contributorship Statement

Dario Cazzola: contributed to the validation of the data collection equipment; designed data collection software; contributed to data collection during the experimental campaign; designed data processing software; processed data; contributed to statistical analysis design; carried out statistical analysis; contributed to data analyses and interpretation; drafted the paper; contributed to revising the paper; approved the final version of the paper.

Ezio Preatoni: contributed to the definition of the experimental protocol and to its implementation; contributed to the design of the data collection equipment and to its validation; designed data collection software; contributed to data collection for the whole experimental campaign; designed data processing software; processed data; contributed to statistical analysis design; carried out statistical analysis; contributed to data analyses and interpretation; contributed to revising the paper; approved the final version of the paper.

Keith Stokes: initiated the project; contributed to the definition of the experimental protocol and to its implementation; contributed to data collection; contributed to statistical analysis design; contributed to data interpretation; contributed to revising the paper; approved the final version of the paper.

Mike England: contributed to the definition of the experimental protocol; contributed to data interpretation; contributed to revising the paper; approved the final version of the paper.

Grant Trewartha: is guarantor. Initiated the project and supervised all its phases; contributed to the definition of the experimental protocol and to its implementation; contributed to the design of the data collection equipment and to its validation; contributed to data collection for the whole experimental campaign; contributed to statistical analysis design; contributed to data analyses and interpretation; contributed to revising the paper; approved the final version of the paper.

Andreas Wallbaum: contributed to the design and implementation of all the technical devices used in the study; contributed to data collection for the whole experimental campaign.

What are the new findings

- A new scrum engagement technique which includes a pre-bind between the props of the two forward packs reduces the biomechanical stresses experienced by front row players during the engagement
- The ability to generate a sustained force after the initial engagement is not decreased using the new 'PreBind' technique
- Scrum stability measures show positive prospective results when using the PreBind technique with a potential minimisation of the number of scrum collapses
- The biomechanical stresses acting on front row professional players during live contested scrummaging have the potential to cause chronic injuries to the cervical and lumbar spine
- The engagement technique modification is a viable route to minimising potential injury risk during rugby scrummaging

How might it impact on clinical practice in the near future

- This study suggests that a new pre-bind scrum engagement technique may offer benefits in terms of reducing biomechanical loading experienced by front row rugby players
- This study provides an evidence base on which to inform discussions relating to the scrum laws of rugby union when seeking to improve player welfare

ABSTRACT

Aims: Biomechanical studies of the rugby union scrum have typically been conducted using instrumented scrum machines, but a large-scale biomechanical analysis of live contested scrummaging is lacking. We investigated whether the biomechanical loading experienced by professional front row players during the engagement phase of live contested rugby scrums could be reduced using a modified engagement procedure.

Methods: Eleven professional teams (22 forward packs) performed repeated scrum trials for each of three engagement techniques, outdoors, on natural turf. The engagement processes were the 2011/12 (referee calls crouch-touch-pause-engage; CTPE), 2012/13 (referee calls crouch-touch-set; CTS) and 2013/14 (props pre-bind with the opposition prior to the “Set” command; PreBind) variants. Forces were estimated by pressure sensors on the shoulders of the front row players of one forward pack. Inertial Measurement Units were placed on an upper spine cervical landmark (C7) of the six front row players to record accelerations. Players’ motion was captured by multiple video cameras from three viewing perspectives and analysed in transverse and sagittal planes of motion.

Results: The PreBind technique reduced biomechanical loading in comparison with the other engagement techniques, with engagement speed, peak forces and peak accelerations of upper spine landmarks reduced by approximately 20%. There were no significant differences between techniques in terms of body kinematics and average force during the sustained push phase.

Conclusion: Using a scrum engagement process which involves binding with the opposition prior to the engagement reduces the stresses acting on players and therefore may represent a possible improvement for players’ safety.

INTRODUCTION

Contemporary rugby union scrummaging involves a dynamic engagement phase and a period of sustained pushing [1,2]. Previous studies have alluded to the intense physical nature of the scrum [1-3], the moderate acute injury incidence arising from the scrum [4-8], the relatively high injury risk for front row forwards [9], the moderate association with catastrophic rugby injuries [10-12] and the potential effect scrummaging has on long-term degeneration of the spine [13-19].

The biomechanics of scrummaging has been described in terms of the forces produced [1-3,20,21] and motions observed [22], but most of these studies focus on scrummaging against a machine. Du Toit [23] measured forces at the front row interface during live scrummaging using pressure transducers, but this study only included school-age players. Consequently, there is still a gap between the understanding of machine scrummaging and the transfer of this knowledge to the contested scrummaging context, where forces and the motions might change because of the less controllable counteraction offered by the opposition pack [2]. In order to provide more insight into the level of loading experienced by rugby union forwards during scrummaging and whether this level of loading can be modified to potentially reduce injury risk, there is a need to measure the biomechanics of scrummaging under match-like conditions.

Therefore, the aim of this research was to determine whether modifying the engagement technique influences mechanical stresses that represent risk factors for injury during live contested scrummaging. The hypothesis was that an engagement process designed to de-emphasise the dynamics of the initial engagement would reduce the peak biomechanical loading metrics but maintain the forces observed during the sustained push phase.

METHODS

Study design

In a repeated measures design, rugby forward packs were analysed at one point in time during the 2012/13 season and each performed repetitions of trials under three different scrum engagement processes. Multiple force and motion measures were the dependent variables and the engagement technique was the within-group factor.

Engagement techniques

Three different engagement techniques, including the current technique at the initiation of the research programme and two modified processes were tested with each team (Table 1). The engagement processes were the 2011/12 variant (CTPE), the 2012/13 variant (CTS) and a process which modified the technique of props to incorporate a pre-bind with the opposition prior to the “Set” command, to be introduced globally as the 2013/14 variant (PreBind).

Table 1. The engagement processes tested. For all the techniques the coach/referee checked for reasonable distance between packs at set-up and all players simulated competitive scrummaging attempting to adhere to Law (IRB, Law 20). All scrums aimed for an “engage and sustained pressure” type scrum, involving initial engagement phase followed by a 4 s sustained push.

Full (Short) Name:	1. Crouch, Touch, Pause, Engage (CTPE)
Timing:	Crouch (t=-5.2 s) ; Touch (t=-2.9 s) ; Pause (t=-1.2 s) ; Engage (t=0.0 s)
Full Description:	The forward packs set up according to their normal current practice. Following an engagement call sequence of “crouch-touch-pause-engage” the forward packs engaged with each other and held a short-duration sustained shove. This technique was regarded as the baseline condition for data analysis as it best represented current scrummaging practice and law when the engagement techniques were defined (May 2012).
Full (Short) Name:	2. Crouch, Touch, Set (CTS)
Timing:	Crouch (t=-4.0 s) ; Touch (t=-1.7 s) ; Set (t=0.0 s)
Full Description:	Same as baseline CTPE except the vocal commands removed the “pause” so that this

	was non-verbal and the final command was changed from “engage” to “set” to reflect the scrum law amendment trials introduced globally by the IRB from September 2012.
Full (Short) Name:	3. CTS with Pre-Bind (PreBind)
Timing:	Crouch (t=-4.0 s) ; Touch (t=-1.70 s) ; Set (t=0.0 s)
Full Description:	The forward packs set up according to their normal current practice in terms of binding and body positions but the coach had previously instructed the two forward packs to reduce their spacing sufficient to allow the subsequent actions whilst maintaining balance. The scrum followed an engagement call sequence of “crouch-touch-set”. On the “crouch” players moved into their normal crouched posture. On “touch” all four props moved their outside arms forward to take a bind on their opposition’s body past the point of their shoulder, on their back or side. The loose head (LH) props moved their left arm inside the right arm of the tight head (TH) prop and gripped the TH prop’s jersey on the back or side. The TH props moved their right arm outside the left upper arm of the opposing LH prop and gripped the LH prop’s jersey with the right hand only on the back or side. The props were instructed not to grip the opponent’s chest, arm, sleeve, or collar. This loose bind was retained and the arm was not retracted. The “set” command was an instruction to allow the two front rows to engage and then commence a short-duration sustained shove.

Participants

Eleven rugby teams (22 forward packs, n=176 players) were recruited from the professional standard playing level, ranging from senior international forward packs to elite club forward packs (minimum Level 2 in the domestic club structure of Tier 1 Rugby Unions). The sample size was determined based on significant differences with 6 Elite teams evaluated during a machine scrummaging study [2], and expecting that in this study the engagement techniques evaluated would have smaller effect of size. For this reason a bigger sample (11) has been selected to have an adequate statistical power for evaluating differences between techniques. Mean pack mass was 853.9 ± 28.0 kg. Individual players provided individual written informed consent prior to participation and ethical approval for the study was granted by an institutional ethics committee at the University of Bath.

Data Collection

All testing sessions took place on natural turf, to mimic match conditions as closely as possible, and the measurement system was fully portable. Before testing, all players undertook a coach-directed warm-up, were provided with an additional verbal description of the different scrummaging techniques to be performed and had the chance of undertaking some practice trials to become familiar with the modified engagement processes. Each team (two forward packs) performed a complete scrum testing session that typically comprised a total of 12 scrums (4 repetitions per 3 techniques), up to a maximum of 16 scrums to account for mistiming of engagements or scrum collapses. Engagement techniques were presented in random order but all teams performed the trials in a blocked sequence. One forward pack was nominated as “Team A” who was the pack with the ball throwin; the opposing forward pack was nominated as “Team B” (Figure 1). Recovery intervals were included between repetitions (1-2 min) and between technique changes (~5 min).

Instrumentation and Data Processing

A bespoke control and acquisition system (cRIO- 9024, National Instruments, Austin, Texas, USA) was programmed (Labview 2010, National Instruments, Austin, Texas, USA) to synchronously simulate the referee’s call as during a real scrummage by delivering consistently timed audio commands and trigger the acquisition (inertial, pressure, video) hardware. Two versions of referee call sequences were used, the “crouch–touch–pause–engage” (duration of full sequence was 5.2 s with t=0.0 s the “engage” command) and “crouch–touch–set” (duration of full sequence was 4.0 s with t=0.0 s the “set” command).

Inertial measurement system

Each front raw player was equipped with an inertial measurement unit (IMU) (MTw, Xsens Technology B.V., NL) placed on the estimated C7 vertebra position. Raw acceleration signals were sampled at 1800 Hz and transmitted at 50 Hz using the proprietary strap-down integration method. To compare inertial loading across scrummaging techniques, acceleration data were expressed as the module of overall acceleration exerted on an anatomical segment during the trials.

Pressure measurement system

During each scrum session, three pairs of pressure sensors (Model #3005E VersaTek-XL size) were used to collect the pressure distribution between front rows at a sampling frequency of 500 Hz (F-Scan, Tekscan Inc, USA). Each pair of sensors was trimmed to fit into bespoke sleeves and attached on the left and right shoulder of "Team A" front row players (A1 – loose head prop, A2 - hooker, A3 – tight head prop). Pressure data were used to estimate contact forces. All the pressure sensors had been previously calibrated in the lab in comparison with force plate measures by using a method specially designed for force patterns typical of scrummaging [24]. The overall force ($F_{front\text{-}row}$) acting on the "Team A" front row was calculated as the sum of all the single player (A1, A2 and A3) estimated forces.

Video analysis

Four digital video cameras (2 side cameras and 2 top cameras) synchronously captured players' movements from three different views (top, left and right). Side cameras (HDR-HC9, Sony, Japan, 50 Hz) were placed to view the loose head and tight head props sagittal motion, whilst top cameras operated at 200 Hz (HVR-Z5, Sony, Japan) and 50 Hz (HVR-Z5, Sony, Japan), respectively, and were positioned to view transverse motion of the scrum (Figure 1). A rigid frame 3D calibration object was used for multiple 2D calibrations using 4-point projective scaling. Video sequences were later captured and digitised using Vicon Motus software (v.9, Vicon Motion Systems, USA) to allow the reconstruction of the position of selected body landmarks and for the estimation of kinematic variables (displacements, angles and their derivatives) (Figure 1).

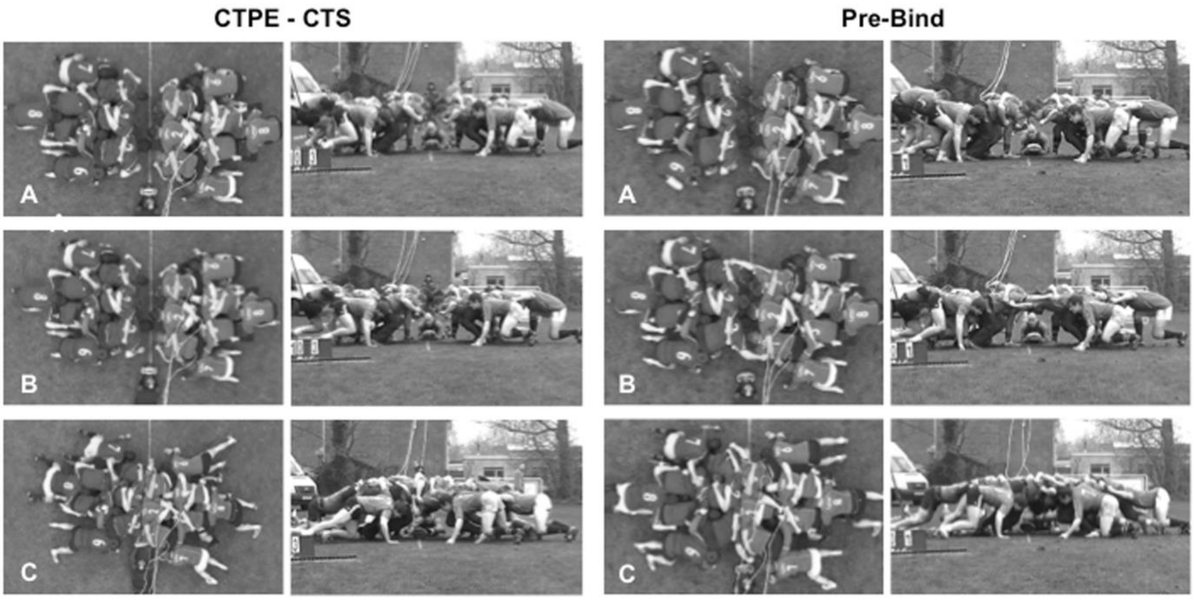

Figure 1. Images of 'key instants' of the CTPE (left) and Pre-Bind (right) techniques. A= "TOUCH" call; B= "ENGAGE" (CTPE) or "SET" (CTS and Pre-Bind) call; C= sustained push phase. CTS has not been reported because visually very similar to CTPE. The Pre-Bind technique evidently differs from CTPE (CTS) because of a lower distance between front rows at "TOUCH" (A), and of the bind maintained by the props on their opponent's trunk from "TOUCH" throughout the engagement phase (B).

Custom-written software (Matlab R2011b, MathWorks, Natick, Massachusetts, USA) was used to process acquired signals and to calculate a set of parameters for each scrum repetition. Parameters were selected with the aim of describing the kinematics (Figure 1) and kinetics of contested scrums across the phases of scrummaging (Figure 2) primarily in connection with potential injury factors The phases of the scrum were 'Approach', which incorporated initial set-up and lasted from onset of movement until the initial contact between the two teams; 'Engagement' was the interval between initial contact and 1 s after the instant of peak force ($F_{front\ row}$ max value); 'Sustained Push' extended from the end of 'Engagement' for an additional 1 s.

Statistics

One-way repeated measure ANOVA (with scrummaging technique as the within group factor) was applied to test for possible changes across engagement techniques, followed by Bonferroni post-hoc comparisons (P<0.05). Sphericity of datasets was checked by applying Mauchly's test. Differences were considered significant for P<0.05 and effect sizes (η^2) and observed power (OP) were reported. Pairwise effect sizes using Cohen's (d) values were also taken into account (Appendix 1-3).

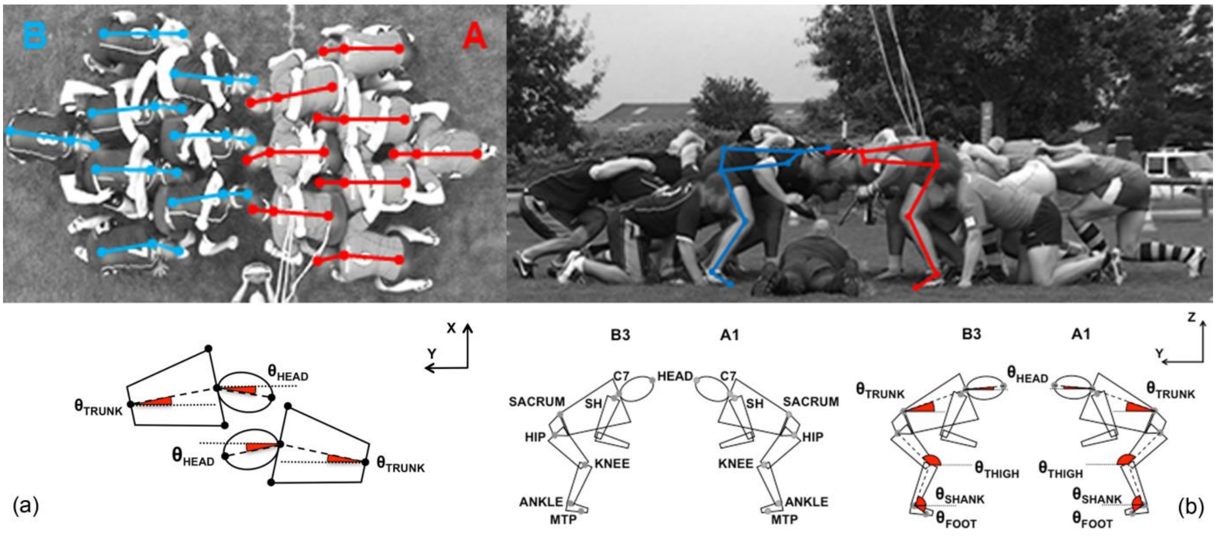

Figure 2. The camera views (side and top view) of a typical experimental set-up and their relative kinematics parameters. (a) Top view: the trunk centre of mass

position for each player was calculated using head, C7 and sacrum anatomical landmarks and referring weighting factors to De Leva anthropometric tables; (b) Side views: the props' centre of mass was calculated using hip and shoulder anatomical landmarks. Sagittal plane (Y horizontal axis – Z vertical axis) joint angles were calculated as the angle between the longitudinal axis of the head and the horizontal axis. In the sagittal plane, the whole scrum centre of mass motion was calculated as the combined centre of mass of player A1 and B3 (left side) and combined centre of mass of player A3 andB1 props.

RESULTS

Approach

PreBind (0.32 ± 0.07 m) reduced the distance between the two front rows at setup by about 0.12 m, compared with CTPE (0.44 ± 0.06 m) and CTS (0.45 ± 0.05 m). PreBind (2.12 ± 0.41 m/s) also significantly reduced the peak engagement speed (i.e. the maximum of the sum of the velocities of the two front rows coming together) by 18% compared with both CTPE (2.59 ± 0.41 m/s) and CTS (2.59 ± 0.44 m/s).

Props generally had a higher shoulder height and a more ‘shoulder above hips’ position (effect sizes, Table A1) prior to movement onset in the PreBind compared with the other two techniques.

Engagement

The PreBind technique resulted in a significant decrease in the biomechanical stresses acting on the front row players during the engagement compared with CTPE and CTS. The forces measured by the shoulder pressure sensors were approximately 35% (PreBind vs. CTPE) and 25% (PreBind vs. CTS) lower (Table 2 and Figure 2). In addition, the average peak accelerations of the sensor positioned on the cervical (C7) landmark decreased by about 16% (PreBind vs CTPE) and 14% (PreBind vs CTS), respectively (Table 2). Finally, the extent of vertical motion in the sagittal plane once the two forward packs had engaged showed a decreasing trend moving from CTPE to CTS and to PreBind with a moderate to large effect size between CTPE and PreBind for the amount of vertical excursion measured on both sides of the scrum (Table A2).

Table 2. Kinetic and kinematic measures of the front row players during the engagement phase, across the three different engagement techniques. All measures are reported as mean (standard deviation). Significant main effect (P<0.05) between engagement techniques (#) and pairwise comparisons are reported by the following convention: 1= different from CTPE; 2= different from CTS; 3= different from PreBind.

Variable\Category	CTPE	CTS	PreBind
Force [kN]			
Peak of total compression force (sum of front row players) [#]	9.8 (2.7) [3]	8.8 (2.2) [3]	6.3 (1.6) [1,2]
Loss of total compression force during the “rebound” [#]	6.1 (2.0) [3]	5.2 (1.6) [3]	3.3 (1.5) [1,2]
Peak acceleration at the cervical level [g]			
Average of the individual peaks of front row players [#]	6.01 (0.64) [3]	5.73 (0.69) [3]	4.90 (0.70) [1,2]
Maximum individual peaks of front row players	8.22 (0.89)	8.06 (1.44)	6.87 (1.37)
Hip angle range of motion in the sagittal plane [deg]			
Player A1 [#]	39 (17) [2]	26 (13) [1]	29 (13)
Player A3 [#]	45 (11) [3]	36 (15)	34 (13) [1]
Player B1	25 (12)	25 (8)	19 (9)
Player B3 [#]	47 (18) [3]	40 (17)	27 (14) [1]
Vertical scrum excursion in the sagittal plane [m]			
Left side of scrum (attacking team viewpoint)	0.14 (0.08)	0.11 (0.04)	0.09 (0.03)
Right side of scrum	0.12 (0.05)	0.11 (0.04)	0.10 (0.04)

Sustained Push

There were no significant differences between the three engagement techniques in the average force exerted during the sustained push phase (CTPE = 4.2 ± 1.4 kN; CTS = 3.8 ± 1.4 kN; PreBind = 3.8 ± 1.2 kN). The effect sizes for the differences between the three engagement techniques for the vertical offset between the props’ shoulder and hip, over the sustained push phase, were all small (Table A3).

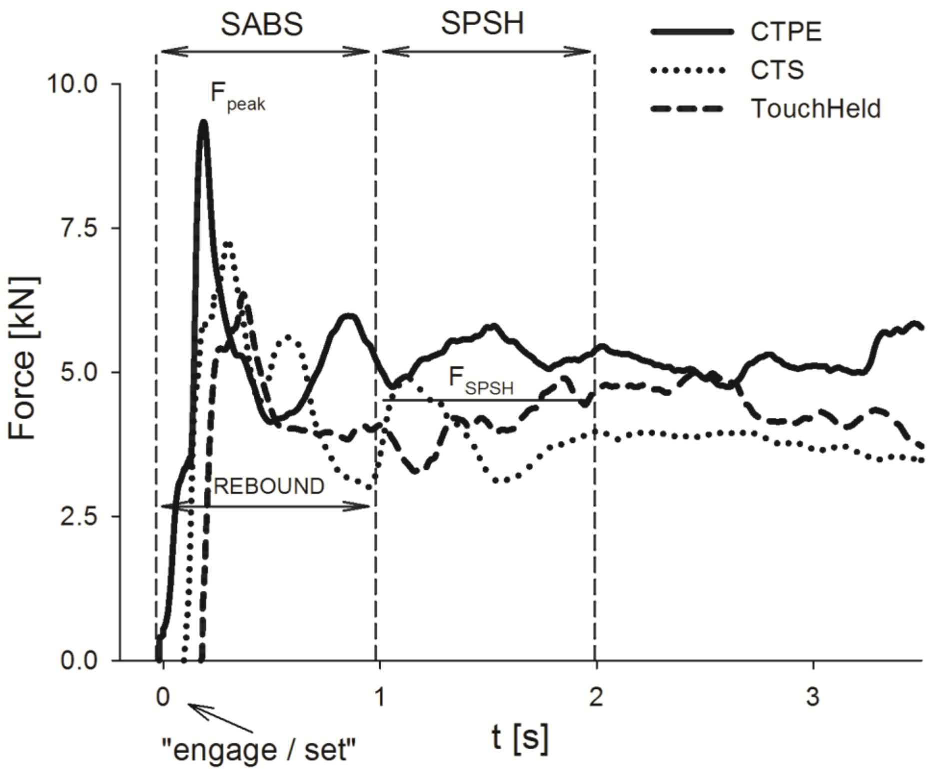

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Figure 3. . Characteristic summed force traces for each engagement technique for one Elite team, where t=0 represents the “engage” call for CTPE technique and “set” call for CTS and PreBind techniques. The force peak values of total compression force (sum of front row players) for each engagement technique are visible in the Engagement phase. The minimum values of the total compression force, used to calculate the “rebound” effect are detectable in the engagement phase. The average total compression force (sum of front row players) for each engagement technique is the average value calculated for each curve during the entire Sustained Push phase.

DISCUSSION

The aim of this study was to determine whether a modified engagement procedure could reduce the biomechanical loading experienced by front row players in live contested rugby scrums. Compared with the CTPE and CTS techniques, the PreBind technique (i) reduced the biomechanical load experienced by front row players during the initial engagement phase; (ii) maintained the overall ability to produce an effective sustained push; and, (iii) maintained scrum stability. Points (i) and (iii) are potentially important for injury prevention / player welfare, and point (ii) suggests the scrum can be maintained as a contest even with a modified engagement.

All the indicators of mechanical stresses (accelerations and peak forces) acting on the front row players were significantly lower in PreBind than in the CTPE and CTS engagement techniques, with the overall magnitude of this reduction being in the region of 20%. This was likely due to a lower front row distance at the initiation of the engagement and subsequent reduced engagement speed which will have decreased the momentum (since mass stayed constant) of the overall system at initial contact.

Repetitive loading/impacts on the spine [16], with magnitudes of force [25-29], speed [15,25] and/or accelerations [30] that are not dissimilar from the load absorbed by players during scrummaging, may induce chronic pain [13,14,16-19] to the cervical and lumbar spine. In general, the determinants of cervical injury mechanics include force characteristics (magnitude, vector direction and rate level) [31], head constraints, and trunk/neck orientation before impact [32]. High magnitude and eccentricity (off-centre application) of the compressive axial load causes bending moments in the cervical column segments leading to buckling mechanisms and consequent ligament disruptions and facet dislocations [31,33,34]. The described situation, with regards to constrained head movement and non-axial external loads, is exactly the one experienced by rugby forwards when scrummaging. For these reasons it is imperative to control the scrum engagement sufficiently to avoid impacts directly on the vertex of the head and to reduce the overall biomechanical load, in order to minimise the risk of both catastrophic injuries and chronic degeneration of the spine. Focusing on the effects of modifying the engagement technique from an injury prevention perspective, it could be speculated that a move to the PreBind technique could be a positive step for reducing chronic injury problems due to scrummaging. In fact, bearing in mind the high scrum rate undertaken by forward rugby players (estimated at up to 60 scrums per week including matches and training), then the approximately 20% reductions in loading parameters observed during the engagement phase with the PreBind technique should be viewed favourably when considering the repetitive nature of the task, since these reductions will exist for each scrum undertaken.

The PreBind technique provided a sustained push force magnitude as high as in the other techniques, even with a de-emphasised engagement and a reduced dynamics of the engagement phase compared to CTPE and CTS. In fact, during the PreBind technique, no decrease in the ability to generate force against the other pack was observed, and lower drops in force during the transition between the initial engagement and sustained push were observed (Table 2, Figure 2). This last result may indicate a better capability for the team to achieve a more consistent force production during PreBind, which is useful to either produce momentum or to counteract the drive of the opponents. This aspect may also be important from a scrum stability viewpoint where the ‘rebound’ effect in the PreBind was attenuated, and therefore in terms of force production the scrum did not pass through a passive phase where the two forward packs would have a transient phase of reduced congruence with each other. In analogous spring-like terms, the CTPE and CTS techniques are under-damped and the two forward packs continue to oscillate following engagement, whereas the PreBind technique is critically damped and the two forward packs converge quickly to a steady-state.

The extent of scrum stability was estimated by considering a number of kinematic variables whereby reduced excursions / range of motion was taken to mean more stability since players were making less postural adjustments. Generally, CTPE showed greater excursions and more instability than CTS and PreBind. These changes reflected scrum centre of mass movement during the engagement phase in the sagittal plane, and hip joint range of motion of the props, which we considered as indexes of stability. A moderate to large effect size (Table A2) indicated a tendency towards increasing stability moving from CTPE to CTS and to PreBind, but without showing a high consistency between variables. In any case, these results suggest that players were making more postural adjustments during the initial stages of the scrum in the CTPE technique compared with the PreBind and CTS technique. Regarding PreBind, this stability advantage may be due to the pre-bind action itself, where prop forwards take a legal bind on their opposite number before the engagement phase (before “set” call). Firstly, this means the PreBind technique may decrease the number of missed or slipped binds due to props having to establish a grip prior to the dynamic engagement phase. Secondly, the PreBind technique may help to establish a more controlled starting body position since props have to stretch out their arm and maintain the bind with the opponent, and therefore a horizontal or downward inclination of the trunk may be difficult and cause a loss of balance. A significantly higher props’ shoulder height measured in the PreBind technique provides support for this assertion. The apparent moderate improvement in stability of the CTS technique over CTPE is harder to explain. The only change was the move to the 3-stage call sequence, so possibly elimination of the “pause” command did indeed allow a more coordinated engagement between the two packs, which was one of the tenets of the introduction of this call sequence for the 2012/13 season.

Focusing on the trunk alignment and building on the ‘spine in line’ reference as the underpinning principle, no significant changes between engagement techniques emerged from the analysis of variables summarising the players’ movements over the engagement phase (Table 3): the average deviation from the direction of push (i.e. average absolute angle) in both the transverse (“left/right” rotation) and sagittal (“down/up” rotation) planes was similar in the three engagement techniques. This suggests that the PreBind technique did not positively or negatively influence players’ technique in terms of extremes of neck and trunk angles during the engagement phase.

CONCLUSION

Results on 11 elite rugby teams suggested that a scrum engagement technique which incorporated a pre-bind between the two forward packs produced the intended effect of reducing the loading experienced by front row players during the engagement process, whilst maintaining scrum stability and the ability to generate sustained pushing forces. The reduced loading with the PreBind technique was observed across all of the key outcome measures in a consistent manner, producing a reduction in the peak loading values of approximately 20%. The scrummaging forces during the sustained push phase were consistent across the engagement techniques and there were no apparent deleterious effects on players' technique from the PreBind technique, and some positive results in derived stability measures. For these reasons, the findings of this study are stimulating in terms of injury prevention and performance analysis, proposing biomechanical solutions to minimise potential injury risk and a novel method to evaluate different scrum techniques.

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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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APPENDIX

Table A1. Effect size statistics for horizontal plane kinematics of the front row players during the Approach, across the three different engagement techniques. *

Variable\EF	CTPE/CTS	CTPE/PreBind	CTS/PreBind
Timing [s]			
Time of onset of movement	-0.15	**-1.19**	**-1.03**
Distance at onset of movement [m]			
Between front rows	-0.41	**2.29**	**2.40**
Velocity of approach [m/s]			
Peak of engagement speed (sum of the front row velocities)	0.10	**1.60**	**1.60**
Linear measurements of body posture at set-up [m]			
Shoulder height player A1	**-0.89**	**-0.89**	-0.48
Shoulder height player A3	**-1.15**	**-2.69**	**-1.24**
Shoulder height player B1	-0.44	**-1.47**	**-0.97**
Shoulder height player B3	-0.31	**-1.89**	**-1.45**
Shoulder-hip height offset[‡] player A1	-0.06	-0.55	-0.50
Shoulder-hip height offset player A3	-0.27	**-1.42**	-**0.94**
Shoulder-hip height offset player B1	-0.12	**-1.02**	**-1.01**
Shoulder-hip height offset player B3	-0.17	-0.71	**-1.00**

EF= pairwise effect sizes (Cohen’s d). |d|>0.8 large effects; |d|>0.5moderate effects; |d|>0.2 small effects.

Table A2. Effect size statistics for the kinetic and kinematic measures of the front row players during 'Engagement' phase, across the three different engagement techniques. *

Variable\EF	CTPE/CTS	CTPE/PreBind	CTS/PreBind
Timing [s]			
Time of onset of force (= time of contact)	-0.40	**-2.18**	**-0.93**
Force [kN]			
Peak of total compression force (sum of front row players)	**1.02**	**1.88**	**1.49**
Loss of total compression force during the "rebound"	**0.96**	**1.93**	**1.41**
Peak acceleration at the cervical level [g]			
Average of the individual peaks of front row players	0.47	**2.19**	**2.00**
Maximum individual peaks of front row players	0.14	**1.15**	**1.36**
Trunk angle [deg]			
Average absolute angle across front 5 players in the transverse plane (top view)	0.50	0.43	-0.07
Hip angle in the sagittal plane (side view) [deg]			
Range of motion player A1	**0.94**	**0.83**	-0.26
Range of motion player A3	0.78	**1.01**	0.19
Range of motion player B1	0.02	0.58	0.70
Range of motion player B3	0.74	**1.33**	0.70
COM excursion in the transversal plane [m]			
Horizontal xCOM displacement	0.68	0.66	-0.12
Vertical yCOM displacement	0.41	0.42	0.09
COM excursion in the sagittal plane [m]			
Horizontal left $yCOM_{A1-B3}$ displacement	0.75	0.43	-0.19
Vertical left $zCOM_{A1-B3}$ displacement	0.53	**0.80**	0.59
Horizontal right $yCOM_{A3-B1}$ displacement	0.07	0.34	0.28
Vertical right $zCOM_{A3-B1}$ displacement	0.17	0.35	0.17

EF= pairwise effect sizes (Cohen's d). |d|>0.8 large effects; |d|>0.5moderate effects; |d|>0.2 small effects.

Table A3. Effect size statistics for the kinetic and kinematic measures of the front row players during the Sustained Push phase, across the three different engagement techniques. *

Variable\EF	CTPE/CTS	CTPE/PreBind	CTS/PreBind
Force [kN]			
Average total compression force (sum of front row players)	0.45	0.44	0.03
Linear measurements of body posture [m]			
Shoulder-hip height offset player A1	-0.08	-0.03	0.07
Shoulder-hip height offset player A3	0.28	-0.12	-0.37
Shoulder-hip height offset player B1	0.09	0.02	-0.07
Shoulder-hip height offset player B3	0.18	0.06	-0.11

EF= pairwise effect sizes (Cohen’s d). |d|>0.8 large effects; |d|>0.5moderate effects; |d|>0.2 small effects.

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