Development and application of a measurement method to investigate spinal kinematics during rugby union scrummaging

Adrien Cerrito

Bachelor of Science in Physiotherapy, Master of Science in Physiotherapy

A thesis submitted in fulfilment of the requirements of the degree of Doctor of Philosophy

Menzies Health Institute Queensland and School of Allied Health Sciences
Griffith University, Gold Coast, Australia
September 2018
Abstract

Scrummaging in a game of rugby union occurs after a minor infringement and involves up to eight players from each team pushing against each other to compete for ball possession. The scrum has the greatest propensity for injury compared to all other events in rugby. Injuries affecting the spine of front-row players are of particular concern because these injuries occur frequently and can result in significant pain and functional impairment and, in rare instances, catastrophic consequences. Therefore, identifying potential mechanisms for scrum-related spine injuries is a priority.

To develop optimal injury-prevention strategies, it is essential to better understand the biomechanics of the scrum. Kinematic investigations of the spine in front-row players during contested scrummaging could provide important information but these measurements are technically challenging, particularly because of the number of participants involved in the scrum. Given that current methods are not able to measure spinal kinematics during field-based competitive scrums, the aim of this thesis was to develop a method to measure spinal kinematics in front-row players during scrummaging under ecologically valid conditions and begin to investigate the influence of player interactions on spinal kinematics.

The novel measurement method was designed using a combination of an electromagnetic motion tracking system and close-range photogrammetry system. To be viable, the measurement method had to (1) require no bulky markers or sensors; (2) be portable to allow field-based measurements; (3) be versatile to allow measurements in any scrum formation and (4) be as reliable and as accurate as traditional measurement methods.
The first study evaluated reliability of an electromagnetic motion tracking system for the measurement of cervical spine kinematics during one-man scrums. The second study involved the development of a photogrammetry system, which consisted of five DSLR cameras, to measure thoracic and lumbar spine kinematics and also evaluated reliability and accuracy of this method. The results of the first study indicated reliability of the electromagnetic tracking system was comparable to that of an optoelectronic motion capture system. The second study showed that the photogrammetric system was sufficiently accurate and reliable for the measurement of spinal kinematics during scrums in both laboratory and field environments. Therefore, the findings of these two studies supported the use of the innovative method developed for measuring spinal kinematics during scrummaging.

Subsequently, the influence of player interactions during scrummaging was investigated. A series of investigations started with the most simple scrum formation - the one-man scrum. The one-man scrum consists of only one player scrummaging against a static scrum machine and this formation is often used in training sessions to practice the scrum technique. The third study investigated spinal kinematics during one-man scrums to determine basic kinematic patterns, as well as movement variability during the task. The results indicated front-row-players performed the basic scrum technique in a consistent manner, although large within-subject movement variability was found in the sagittal plane for the cervical spine. The difference between cervical spine kinematics during scrums against a scrum machine and against opponents was then investigated in the fourth study. The results revealed that the cervical spine was much more flexed when scrummaging against opponents than when scrummaging against a scrum machine. The fifth study further investigated these cervical spine kinematics during scrums against opponents to determine how different scrum phases
affect kinematics. The results showed that impact was the most likely phase to result in traumatic injuries because the cervical spine is considerably flexed, a posture likely to increase the risk of injury. Finally, the sixth study investigated the effect of second-row players on lumbar spine kinematics in front-row players during scrums. The results showed that interactions with second-row players resulted in a substantial decrease of the neutral lumbar lordosis which may result in low back injuries. This series of studies are the first to investigate player interactions on scrub kinematics and collectively the findings suggest that machine-based scrummaging practice should be kept to a minimum given this type of practice has limited potential to prepare players for competitive scrummaging. Moreover, scrum formation should be selected carefully in training and rehabilitation programs to best foster safe and effective scrub technique given interactions between players have significant influence on front-row players’ spinal kinematics.

This thesis provides an innovative method to facilitate the measurement of spinal kinematics during field-based contested scrums. The findings extend the understanding of kinematics of the cervical and lumbar spine in front-row players during scrums and provides practical information that could be implemented by coaches and those involved in the rehabilitation of players regarding scrummaging technique.
Statement of originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Adrien Cerrito
## Contents

Abstract  
Statement of originality  
List of figures and tables  
List of abbreviations  
Acknowledgements  
Acknowledgement of published or submitted papers  

<table>
<thead>
<tr>
<th>Chapter 1</th>
<th>General introduction</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Overview of the research topic</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>General purpose of the research</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>Specific aims of the research</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 2</th>
<th>Literature review</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Rugby and the scrum</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Injuries in rugby</td>
<td>10</td>
</tr>
<tr>
<td>2.3</td>
<td>Spinal injuries in rugby</td>
<td>12</td>
</tr>
<tr>
<td>2.4</td>
<td>Mechanisms of scrum-related spine injuries</td>
<td>15</td>
</tr>
<tr>
<td>2.5</td>
<td>Biomechanics of the scrum</td>
<td>20</td>
</tr>
<tr>
<td>2.6</td>
<td>Investigating scrum kinematics</td>
<td>26</td>
</tr>
<tr>
<td>2.7</td>
<td>Gaps in the literature</td>
<td>29</td>
</tr>
<tr>
<td>2.8</td>
<td>Conclusion</td>
<td>33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 3</th>
<th>General methods</th>
<th>46</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>46</td>
</tr>
<tr>
<td>3.2</td>
<td>General approach and experimental progression</td>
<td>46</td>
</tr>
<tr>
<td>3.3</td>
<td>Requirements for novel measurement methods</td>
<td>47</td>
</tr>
</tbody>
</table>
Chapter 7  Cervical spine kinematics during machine-based and opposed scrummaging  121

6.5 Conclusion  117

Chapter 8  Cervical spine kinematics during opposed scrummaging  145

Chapter 9  Second-row players’ influence on the lumbar spine kinematics of front-row players during rugby union scrummaging.  170

Chapter 10  Discussion and Conclusion  194
10.3 Future research directions 203
10.4 Conclusion 206

Appendices 207
Appendix 1 208
Appendix 2 209
Appendix 3 215
Appendix 4 216
Appendix 5 217
List of figures and tables

Figures

Figure 2.1. Schematic representation of a scrum including all player positions. 10

Figure 2.2. Schematic representation of the scrum position recommended by coaching manuals. The left part (a) shows the initial crouched position and the right part (b) represents the position adopted during the pushing phase with a knee flexion angle of 105 – 125°. Note the low body position adopted with a 'straight, flat back'.

Figure 2.3 Phase separation based on forward force output (compression) measured from instrumented scrum machine. Reproduced from 'Injury and biomechanical perspectives on the rugby scrum: a review of the literature', Trewartha et al., Vol. 49, 425-433, 2015 with permission from BMJ Publishing Group Ltd.

Figure 3.1 Custom-built scrum machine used for machine-based scrums. 52

Figure 3.2 (a) Mouthpiece that was used to attach a sensor to track head motion. (b) The sensor was attached to the mouthpiece's tongue, which extended out of the mouth when worn.

Figure 3.3 Final jersey design 54

Figure 3.4 Custom-designed camera-mount with the PVC control frame 55

Figure 4.1 Sensors and reflective markers placement 64

Figure 4.2 Representative curves of one participant’s movements in flexion/extension, lateral-flexion, and axial rotation (mean ±2 standard deviations) 72

Figure 5.1 Imaging system and laboratory-based experimental set-up: a) wooden frame supporting five DSLR cameras and the control frame. The figure illustrates
the experimental set-up used for laboratory-based measurements with the Vicon cameras, the shutter remote control, the board with four retro-reflective targets, and the weighted collision-targets. The red dot indicates the location of the LED-based timing system; b) the five DSLR cameras in a convergent set-up

**Figure 5.2** Custom-designed LED-based timing system used to determine consistency of camera frame rate, and to synchronise frames during data processing. Each LED light represented a specific time unit. For example, the figure illustrates an elapsed time of 4 tenth of a second (ds), 7 hundredth of a second (cs), and 5 thousandth of a second (ms)

**Figure 5.3** Illustration of frames used to test tracking accuracy in a) laboratory, and b) rugby field environment. The cranio-caudal (CC) and medio-lateral (ML) distances between the two pairs of retro-reflective targets are illustrated. The elapsed time indicated on the LED-based timing system was used to synchronise data during data processing

**Figure 5.4** Bland-Altman plots illustrating the mean measurement errors (solid lines) and 95% limits of agreement (dotted lines) between both measurement systems (tested system vs. Vicon) in measuring orientation angles: a) yaw, b) pitch, and c) roll

**Figure 6.1** Mean (solid line) ± SD (dashed lines) kinematic curve representing flexion/extension (FE) of the head relative to the thorax in a representative participant.

**Figure 7.1** Illustration of the sensor placement (white dots) and digitised anatomical landmarks (red dots). X- and Z-axes of the two local coordinate systems (LCSH and LCST) are represented by the green and blue arrows, respectively.
**Figure 7.2** Scrum trial examples showing the two conditions: machine-based (a) and live (b) scrums.

**Figure 7.3** Analysis of head orientation (a and b) and head location (c and d) relative to the thorax as an indicator of cervical spine kinematics.

**Figure 7.4** Example of T1 ('bind' prior to engagement) and T2 (instant of impact) identification in a machine-based scrummaging trial. The marker on C7 was tracked to identify T1 and T2 and the elapsed time read on the timer was transferred to the EMT data.

**Figure 7.5** Posterior distributions for FE, LF, and ROT at both time points (T1 and T2) and for both conditions (machine-based and opposed) in head orientation data.

**Figure 7.6** Posterior distribution for FE and LF at both time points (T1 and T2) and for both conditions (machine-based and opposed) in head location data.

**Figure 7.7** FE and LF values for both kinematic analyses (head orientation and head location). ‘Head Orientation’ represents an analysis of the total movement occurring in the cervical spine. ‘Head Location’ refers to an analysis estimating the movement occurring in the lower cervical spine.

**Figure 8.1** a) Sensor placement on the thorax and head (black dots) and digitised anatomical landmarks (red dots). b) Definition of rotation axes for calculation of head orientation relative to the thorax. c) Definition of α and β angles

**Figure 8.2** Illustration of the time points (T1-T3). The three time points are indicated as red lines in the graph representing FE kinematics in a representative participant. The grey shaded area illustrates the ~0.4 s time window between Pre_T2 and Post_T2

**Figure 8.3** a) Mean (solid line) ± SD (dashed lines) kinematic curve for FE. The
red line indicates T2 (impact). b) Detailed illustration of the mean (solid line) ± SD (dashed lines) kinematic curve for FE during the ~0.4 s time window between Pre_T2 and Post_T2. c) Graphical representation of the calculation of the slopes before (green arrow) and after T2 (blue arrow)

**Figure 9.1** a) Measurement set-up with the camera mount holding the five cameras above the scrum. The oval indicates the placement of the cameras. The hanging photogrammetric control frame and the scrum machine are also illustrated. b) Field-of-view of one camera. The circle indicates the location of the LED-based timer placed on the control frame

**Figure 9.2** a) Anatomical landmarks used to generate two local coordinate systems (i.e. pelvis and thorax). b) Movement in FE and LF was calculated relative to the sagittal plane of the pelvis. Movement in ROT was calculated as rotation around the Z-axis of LCSP. ROT was calculated from the rotation matrix describing thorax orientation relative to the pelvis

**Figure 9.3** Illustration of posterior distributions of all movement directions and at all three time points (T1 = the 'bind', T2 = impact, T3 = sustained push). The black lines represent one-man scrummaging and the grey lines represent the supported scrummaging

**Tables**

**Table 4.1** Generation of local coordinate systems for the head (LCS_H) and thorax (LCS_T)

**Table 4.2** Descriptive statistics (mean ± SD) of cervical spine kinematics [°] for each movement direction (FE, LF and ROT) at each time point (T1, T2, and T3) for both measurement systems (Vicon and Polhemus)
Table 4.3 Overall reliability results for discrete time points (T1-T3) 69

Table 4.4 Reliability results for discrete time points (T1-T3) in non-player participants 70

Table 4.5 Reliability results for discrete time points (T1-T3) in non-player participants 71

Table 4.6 Reliability results for kinematic curves 71

Table 5.1 Accuracy and reliability of the camera calibration process. Accuracy is expressed as Trueness (T), and reliability as Precision (P) and Uncertainty (U) 94

Table 5.2 Reliability indices for the measurement of control frame targets 94

Table 5.3 ‘Excessive’ recorded frames summed over five trials for each 1s-interval 95

Table 5.4 Tracking accuracy in laboratory simulations. Accuracy and reliability are expressed as absolute and relative Trueness (T and %T), and Precision (P) and Uncertainty (U and %U), respectively 96

Table 5.5 Tracking accuracy of on-field measurements. Accuracy and reliability are expressed as absolute and relative Trueness (T and %T), and Precision (P) and Uncertainty (U and %U), respectively 98

Table 6.1 Joint kinematic repeatability at discrete time points (T1-T3) for flexion/extension (FE), lateral-flexion (LF) and axial rotation (ROT) 114

Table 7.1 Number of participants and their playing position, anthropometrics and playing experience 133

Table 7.2 Kinematic analysis of head orientation relative to the thorax at the 'bind' (T1) and impact (T2) 134

Table 7.3 Kinematic analysis of head location relative to the thorax 134

Table 8.1 Kinematic analysis of head orientation relative to the thorax at the 161
‘bind’ (T1), impact (T2) and sustained push (T3)

**Table 8.2** Kinematic analysis of ‘neck line’ inclination at the ‘bind’ (T1), impact (T2) and sustained push (T3)

**Table 9.1** Outcomes of the linear mixed-effects model presented as summary of posterior distributions
List of abbreviations

ANOVA: Analysis of variance

CI: Confidence interval

CMC: Coefficient of multiple correlations

CBS: ‘Crouch, bind, set’

CTPE: 'Crouch, touch, pause, engage'

CTS: 'Crouch, touch, set'

C1 to C7: First to seventh cervical vertebrae

EMG: Electromyography

EMT: Electromagnetic motion tracking

FE: Flexion/extension

ICC: Intraclass correlation coefficient

IQR: Interquartile range

IVD: Intervertebral disc

LCS: Local coordinate system

LF: Lateral-flexion

L3 and L5: First and fifth lumbar vertebrae

MDC: Minimal detectable change

PVC: Polyvinyl chloride

QCA: Queensland College of Art

ROM: Range of motion
ROT: Axial rotation

SD: Standard deviation

SEM: Standard error of the measurement

T7 and T12: Seventh and twelfth thoracic vertebrae

T1: Beginning of scrum trial

T2: Instant of impact

T3: Sustained push phase

T4: End of scrum trial

2D: Two-dimensional

3D: Three-dimensional

95% CrI: 95% Credible interval
Acknowledgements

Foremost, I would like to express my sincere gratitude to my supervisors Prof. Peter Milburn and Dr. Kerrie Evans for their continuous support throughout my PhD candidature and to Prof. Rod Barrett for his support more recently. Their motivation, guidance and vast knowledge have helped me in all stages of the project including the development of the research questions, research procedure, as well as writing of publications and thesis. I will forever be indebted for everything my supervisors taught me!

A particular anecdote that I would like to mention here and that I will never forget, is that Prof. Milburn and Dr. Evans did not hesitate to ‘get their hands dirty’ when helping me with field-based data collection. This was not only an immense help, but also a particular moment that I loved sharing with them and I am very grateful for that. I look forward to many years of friendship that are still to come.

I would also like to thank my unofficial external supervisor Dr. Albert Chong at the University of Southern Queensland in Toowoomba. His expertise has allowed me to better understand photogrammetry and to develop the methodology used in this thesis. I would also like to mention his enthusiasm about research and his energy which were both very inspiring.

My sincere thanks also go to engineers who helped me develop the measurement methods used in this research project: Mr. Guillermo Jacuinde from Griffith University and Mr. Terry Byrne from University of Southern Queensland. Moreover, I had two unofficial supervisors who always helped me when I faced biomechanics-related problems and to whom I would also like to express my most sincere gratitude: Dr. Claudio Pizzolato and Dr. David Saxby. I would also like to thank Dr. Clair Alston-Knox for her continuous support regarding questions about statistical procedures.

To all participating rugby teams, coaches and players, as well as to BodyScience™, I extend my sincere gratitude and appreciation for your commitment, efforts and support. This research project would not have been possible without their help.
The candidature with its countless emotional ups and downs was made possible through the support of the fellow students I had the chance to meet and with whom I had the chance to work. Not only sharing emotionally loaded moments, but also having the famous coffee breaks where we had discussions ranging from light and comic to ones relating to world problems, made the journey truly exceptional. I am very grateful for having built close friendships with these fellow students.

And of course, last but not the least, I would like to thank my family and my partner, Melissa Vallant, for their immense support. While my family members are in Europe, their continuous encouragements via Skype calls, emails or text messages have helped not giving up. Special thanks go to Melissa Vallant who came with me to Australia and who always shared the thrill of the ups and downs with me throughout the candidature. Thank you!
Acknowledgement of published or submitted papers

Included in this thesis are papers in Chapters 4, 5, 6, 7, 8 and 9, which are co-authored with other researchers. My contribution to each co-authored paper is outlined at the front of the relevant chapter. The bibliographic details for published or accepted papers as well as the status for papers under review are:

Chapter 4: Cerrito A., Milburn P., Adams R., Evans K. (2018). Cervical spine kinematics measured during rugby union scrums: Reliability of optoelectronic and electromagnetic tracking systems. This paper has been accepted for publication in the journal *Cogent Medicine* on July 23 2018.

Chapter 5: Cerrito A., Milburn P., Chong A. (2018). Close-range photogrammetry for the measurement of spinal kinematics in rugby union scrums. This paper has been submitted for publication in the journal *Sports Engineering* and is currently under review.


Chapter 7: Cerrito A., Milburn P., Alston-Knox C., Evans K. (2019). Cervical spine kinematics during machine-based and opposed scrumming. This paper has been accepted for publication in the *Journal of Sport Sciences* on January 03 2019.

Chapter 8: Cerrito A., Milburn P., Alston-Knox C., Evans K. (2018). Cervical spine kinematics during opposed scrumming. This paper has been submitted for publication in the *Scandinavian Journal of Medicine & Science in Sports* and is currently under review.
Chapter 9: Cerrito A., Milburn P., Alston-Knox C., Evans K. (2018). The influence of second-row players on lumbar spine kinematics of front-row players during rugby union scrummaging. This paper has been submitted for publication in the European Journal of Sport Science and is currently under review.

Appropriate acknowledgements of those who contributed to the research but did not qualify as authors are included in each paper.

_________________________________   18 September 2018
Mr. Adrien Cerrito

_________________________________   18 September 2018
Professor Peter Milburn, principal supervisor

_________________________________   18 September 2018
Dr. Kerrie Evans, associate supervisor

_________________________________   17 September 2018
Professor Rod Barrett, associate supervisor
CHAPTER 1

General introduction

1.1 Overview of the research topic

In the sport of rugby union (rugby), injuries occur more frequently than in many other team sports (Williams, Trewartha, Kemp, & Stokes, 2013) and spinal injuries are of particular concern (Quarrie, Cantu, & Chalmers, 2002). While injuries to the spine with catastrophic consequences are relatively rare, less severe spinal injuries occur frequently and can lead to pain, reduced mobility, and degeneration of the intervertebral disc (IVD) as well as early osteoarthritis (Hogan, Hogan, Vos, Eustace, & Kenny, 2010). In rugby, spinal injuries are often attributed to the forces involved in scrummaging (Cazzola, Preatoni, Stokes, England, & Trewartha, 2015; Preatoni, Stokes, England, & Trewartha, 2013) and often occur in those players who are in the first line of the scrum (i.e. front-row players) (Fuller, Brooks, & Kemp, 2007). For this reason, over the past few decades, scrummaging rules have been modified in an effort to reduce the forces transmitted between players in the scrum. There is some evidence that these modifications may be effective in preventing spinal injuries. For example, recent biomechanical studies have shown that the new rules adopted in 2014 resulted in an approximately 20% decrease of generated forces (Cazzola et al., 2015), but there remains a need to further investigate biomechanics of the scrum to better understand how injuries occur and how these can be prevented (Trewartha, Preatoni, England, & Stokes, 2015).
For scrum-related injuries affecting the cervical spine, two mechanisms of injury have been described: hyperflexion and 'buckling' of the cervical spine. However, it remains unclear which mechanism predominates (Dennison, Macri, & Cripton, 2012; Trewartha et al., 2015). Thus, to better understand scrum-related injury mechanisms of the cervical spine, detailed kinematic and kinetic investigations of the scrum are required. For injuries affecting other regions of the spine, there is even less literature such that no typical injury mechanism has been described to explain, for example, the occurrence of lumbar spine injuries. Kinematic investigations of the spine in front-row players during scrummaging could help better understand the occurrence of spinal injuries by revealing potential injurious motion patterns, but these investigations are rare. One of the reasons for the lack of such kinematic investigations is that tracking spinal motion in three dimensions (3D) during scrums is technically challenging. The dynamic nature of the scrum, the large number of players involved and the fact that rugby is played outdoors make it difficult to use traditional measurement systems, such as optoelectronic motion capture. Although inertial sensors could be used for this task, these sensors do not measure position in space which can be a major limitation, particularly when investigating the cervical spine. Therefore, an alternative measurement procedure should be developed and then tested for accuracy and reliability to ensure measurement quality. For example, the use of simple ‘off the shelf’ cameras appears to be an attractive alternative, given this method has been successfully used in other medical and sports-related scientific studies (Bernardina, Cerveri, Barros, Marins, & Silvatti, 2016; Chong, 2011). However, given the way front-row players are interlocked during scrummaging, the head and neck are obscured such that a non-optical system must be used to record cervical spine kinematics. Electromagnetic motion tracking (EMT) appears to be an interesting solution to this problem as this method allows more degrees-of-freedom.
compared to, for example, inertial sensors, and has been used to record cervical spine kinematics previously (Koerhuis, Winters, van der Helm, & Hof, 2003).

Other than finding methodological solutions, consideration must also be given to factors that can influence spinal kinematics and thereby the risk of spinal injuries. One possible way to evaluate spinal kinematics is to use the neutral spinal posture as a starting point. Spinal posture has a significant influence on distribution and magnitude of internal loads applied to spinal structures (Benzel, 2012; Gunning, Callaghan, & McGill, 2001; Newell et al., 2017; Oktenoğlu et al., 2001; Shirazi-Adl & Parnianpour, 1999) and it is believed that spinal posture should be kept neutral during scrummaging (Posthumus & Viljoen, 2008). However, it has been shown that front-row players utilise a large proportion of their spinal movement capacity during scrums (Swaminathan, Williams, Jones, & Theobald, 2016a, 2016b), although it remains unclear what factors influence players' ability to maintain a given spinal posture. One factor that may have significant influence on front-row players' spinal kinematics is the large number of players involved in the scrum resulting in many interactions between players. Since this factor cannot be modified, unless the laws of the scrum are fundamentally changed, it is important to understand the influence of other players on spinal kinematics in order to better prepare or rehabilitate players. That is, it is important to investigate spinal kinematics in front-row players during scrummaging in different scrum formations to better understand the influence of other players on their spinal kinematics.

1.2 General purpose of the research

This thesis aimed to investigate spinal kinematics during scrums and to determine the effect of the complexity of the scrum formation on spinal kinematics. For this purpose,
an alternative method was developed for the measurement of 3D spinal kinematics in front-row players during scrummaging. Given that in front-row players the head and neck region is hidden by other players, a combination of optical and non-optical measurement methods had to be employed. Spinal kinematics were investigated during scrummaging in different environments and in different formations. Investigations began with the simplest scrum formation involving only one player scrummaging against a scrum machine (i.e. one-man scrum) to explore spinal kinematics in individual players when no external perturbation was applied. Then, spinal kinematics were further investigated during one-man scrums and other formations performed in the field.

1.3 Specific aims of the research

1) Examine reliability of cervical spine kinematic measures during one-man scrums to determine the viability of electromagnetic motion tracking as an alternative for optoelectronic motion capture.

2) Analyse accuracy and reliability of a photogrammetric method for the measurement of spinal kinematics during scrummaging.

3) Evaluate repeatability (or movement variability) of kinematics of the axial skeleton (i.e. pelvis, spine, thorax and head) during one-man scrums performed in a laboratory.

4) Explore and compare cervical spine kinematics during field-based one-man scrums and scrums against two opponents.

5) Evaluate cervical spine kinematics during field-based scrums against two opponents with particular focus on posture at specific time points and risk of injury.
6) Explore and compare lumbar spine kinematics during field-based one-man scrums and scrums with the support of two players from the second row.
References


Swaminathan, R., Williams, J. M., Jones, M. D., & Theobald, P. S. (2016b). Does the new rugby union scrum sequence positively influence the hooker’s in situ spinal kinematics? *BMJ Open Sport & Exercise Medicine, 2*(1), e000064.


CHAPTER 2

Literature review

2.1 Rugby and the scrum

Rugby union (rugby) is a popular sport worldwide with, according to the governing body 'World Rugby', more than 8 million registered and non-registered players from over 120 countries participating each year (World Rugby, 2016). For example, in Australia, there are approximately 700,000 players participating in rugby, with the largest proportion playing at school and amateur levels (Australian Rugby Union, 2015; World Rugby, 2016).

A rugby match is usually played outdoors on turf where two opposing teams, each composed of 15 players, compete for 80 minutes to achieve the higher score. Points are awarded by scoring tries (i.e. carrying the ball and placing it in the opposition's in-goal area), conversions or penalty kicks (i.e. kicking the ball between the two goal posts from a fixed location after scoring a try or after a major infringement committed by the opposition, respectively), or through drop goals (i.e. kicking the ball between the two goal posts during an offensive playing phase). To create a fair contest throughout all game phases, strict rules apply in rugby matches, such that infringements often lead to stoppages with restarts favouring the non-offending team. While major offences can lead to direct scoring opportunities (i.e. penalty kicks), minor infringements (e.g. when the ball is played forward) may result in a contested event called the scrum.

In the scrum, eight players from both teams, in a structured formation, compete for ball possession by dynamically engaging and pushing against each other (World Rugby,
In each scrum formation, the three foremost players (the loose-head prop, the tight-head prop, and the hooker) form the front-row and are in direct contact with the opposing pack. The three front-row players are supported by the second-row, consisting of two players (the locks), themselves laterally supported by two flank forwards and from behind by the number eight (Figure 2.1). The compact formation is maintained by each player firmly grasping their team mates' jerseys and shorts. This iconic phase of a rugby match represents a tactical advantage for the team that possesses the ball, but is known to be physically demanding and to impart high biomechanical loads, especially to the front-row players (Cazzola, Preatoni, Stokes, England, & Trewartha, 2015).

![Figure 2.1](image)

Schematic representation of a scrum including all player positions.

### 2.2 Injuries in rugby

Rugby is a full contact collision team sport and injuries sustained during training or matches are common, although the incidence of injuries appears to be dependent on factors such as age and the level of play. For example, in Australian school level rugby,
an incidence of 23.7 injuries per 1000 player hours (95% confidence interval (CI) 21.2 – 26.3) has been reported (Leung et al., 2017), compared with 46.8 injuries per 1000 player hours (95% CI 34.4 – 59.2) in senior, amateur rugby (Yeomans et al., 2018). The highest incidence of injuries occurs in senior men’s professional rugby with 81 injuries per 1000 player hours (Williams, Trewartha, Kemp, & Stokes, 2013). Despite the heterogeneity of the reported data, it is generally accepted that rugby has a higher overall incidence rate of injuries than many other team sports (Trewartha, Preatoni, England, & Stokes, 2015; Whitehouse, Orr, Fitzgerald, Harries, & McLellan, 2016; Williams et al., 2013). For example, Whitehouse et al. (2016) reported the risk of injury is twice as high in rugby compared to soccer (66.1 versus 32.8 injuries per 1000 hours).

A number of risk factors for rugby-related injuries have been proposed, such as the time elapsed in a match, with injuries occurring more frequently during the later stages (Williams et al., 2013). Fatigue or a rushed warm-up session after the half-time break have been proposed for this time-dependent risk factor (Williams et al., 2013). Interestingly, it has often been observed that playing position was a factor influencing risk of injury, with players involved in the scrum (i.e. forwards) being at higher risk of sustaining an injury than other players (i.e. backs) (Bathgate, Best, Craig, Jamieson, & Wiley, 2002; Best, McIntosh, & Savage, 2005; Targett, 1998; Yeomans et al., 2018). However, it has also been reported that the tackle caused most rugby-related injuries and thus, it is still debated whether forwards have a higher risk of injury than backs (Williams et al., 2013). In order to obtain a better representation of the relative risk of individual events and playing positions, Fuller, Brooks, Cancea, Hall, and Kemp (2007) replaced incidence of injuries, defined as the number of injuries per 1000 player hours, by propensity, defined as the number of injuries per 1000 events (e.g. scrummaging) to investigate risk of injury. Using the propensity analysis, the authors demonstrated that
forwards were exposed to higher risk events than backs given 8.1 injuries occur in 1000 scrums, while only 6.1 injuries occur in 1000 tackles (Fuller, Brooks, Cancea, et al., 2007). Regardless of how risk of injury is calculated, playing position has consistently been shown to influence injury profile in terms of injury location (Brooks & Kemp, 2011) and injury severity (Fuller, Brooks, & Kemp, 2007). For example, with 213 days lost due to injuries per 1000 scrums, which is nearly double the amount of days lost due to tackling, it appears that forward players have a higher risk of severe injuries than backs (Fuller, Brooks, Cancea, et al., 2007).

Fortunately, severe injuries with catastrophic consequences, such as spinal injuries with neurological damage, do not occur frequently in rugby. In English, Irish, and Argentinean rugby, the risk of sustaining a catastrophic injury has been categorised as 'acceptable' with a rate of 0.1 – 2 catastrophic injuries per 100,000 players per year (Fuller, 2008). In Australian and New Zealand rugby the risk has been found to be higher (4.4 and 4.2/100,000 players per year respectively) but was still classified as 'tolerable' (Fuller, 2008). It should also be noted that these epidemiological studies on the relative risk of rugby-related injuries were published between the years 2007 and 2011. It is conceivable that the relative risk is different nowadays because several injury prevention programs, such as 'BokSmart' in South Africa (Posthumus & Viljoen, 2008), have been implemented since publication of these epidemiological studies. However, despite the lack of more recent epidemiological data and the fact that catastrophic injuries rarely occur, it has been highlighted that research should focus on developing strategies to prevent injuries resulting in irreversible impairment or death (Fuller, 2008, Trewartha et al., 2015).
2.3 Spinal injuries in rugby

Injuries to the spine can be divided into two broad categories: traumatic and overuse injuries. According to the definition by Fuller (2006), a traumatic injury results from a specific injurious event, whereas overuse injuries have an insidious onset and are caused by repetitive micro-trauma. Traumatic spinal injuries can range from musculoligamentous damage with short-term symptoms to vertebral fractures and/or dislocations. Severe traumatic injuries are generally of greater concern, since a loss of integrity of the bones and/or ligaments that stabilise and protect the spinal cord increase the risk of catastrophic consequences, such as paraplegia or quadriplegia, or even death (Boden & Jarvis, 2009). In addition to significant physical impairments, spinal cord injuries can have serious psychological consequences with 20-40% of patients reporting symptoms of depression or anxiety (Kennedy, Duff, Evans, & Beedie, 2003).

In contrast, although overuse injuries affecting the spine do not have catastrophic consequences, these injuries can still lead to significant symptoms such as pain and/or transient neurological deficits and absence from play (Fuller, Brooks, & Kemp, 2007). In addition, overuse injuries can lead to degenerative changes (Trewartha et al., 2015), which in turn triggers a series of phenomena that increase the risk of further tissue degeneration. For example, degenerative articular surfaces and soft-tissue structures such as hypertrophied ligaments, may lead to poor proprioception (Freppel et al., 2013; Trewartha et al., 2015). Decreased proprioception can then result in altered muscular control and abnormally high loads on the facet joints, which accelerates the degenerative process (Armstrong, McNair, & Taylor, 2008; Trewartha et al., 2015). Another factor that contributes to the detrimental loop of degenerative changes is the distortion of load distribution among spinal structures when degeneration occurs (Gellhorn, Katz, & Suri, 2013). For example, in absence of degenerative changes, the
facet joints in the lumbar spine bear up to 33% of compressive forces (Dunlop, Adams, & Hutton, 1984). However, degeneration of the IVD increases the compressive forces on the facet joints to up to 70% (Adams & Hutton, 1983), which is likely to result in joint overload and degeneration (Gellhorn et al., 2013). Similar trends have been found by Pollintine, Dolan, Tobias and Adams (2004) where 8% of compressive forces were found to be borne by the neuronal arch in healthy lumbar spines, as opposed to 40% in the presence of IVD degeneration.

In rugby, both traumatic and overuse injuries occur and often affect forwards who have a 2.2 times higher risk of sustaining spinal injuries during matches than backs, and a 1.8 times higher risk of sustaining an injury during training (Fuller, Brooks, & Kemp, 2007). Brooks and Kemp (2011) calculated risk ratio, defined as the risk of missing matches due to injuries when exposed to the scrum divided by the risk of missing matches when not exposed to the scrum, to evaluate the risk of injuries in forwards and backs. The results demonstrated that front-row players are particularly likely to miss matches due to cervical spine injuries. Loose-head props and hookers (Figure 2.1) have been shown to have the highest risk of missing matches due to cervical spine injuries with a risk ratio of 2.33 (95% CI 1.1 – 5.1) and 1.99 (95% CI 1.1 – 3.5) respectively, compared to other forwards (Brooks & Kemp, 2011). Furthermore, front-row players are more likely to sustain serious spinal cord injuries than other players (Bohu et al., 2009; Brown et al., 2013; Hermanus, Draper, & Noakes, 2010), likely due to the physical nature of the scrum (Brooks & Kemp, 2011). Indeed, it has been reported that scrum-related injuries are generally of greater severity compared to injuries related to other events (Quarrie, Cantu, & Chalmers, 2002) and that the scrum accounts for 41% of all cervical injuries, 56% of thoracic injuries and 71% of lumbar spine injuries in professional front-row players (Brooks, Fuller, & Kemp, 2005). Moreover, for players
affiliated to the French Rugby Union, it has been shown that approximately 40% of all catastrophic cervical spine injuries are sustained during scrumming (Reboursiere et al., 2018).

However, these severe traumatic injuries to the spine occur rarely (Fuller, 2008) whereas the micro-traumas induced by repeated scrums appear to affect a larger number of players (Castinel et al., 2010; Hogan, Hogan, Vos, Eustace, & Kenny, 2010; Watson, Hodge, & Gekis, 2014). Several cross-sectional studies assessing cervical spine abnormalities based on medical images (radiography or magnetic resonance imaging) consistently revealed that adult rugby players had increased prevalence of degenerative changes compared to age-matched healthy controls, particularly in front-row players (Castinel et al., 2010; Hogan et al., 2010; Scher, 1990). Moreover, it is thought that degenerative changes may increase the risk of traumatic injury (Scher, 1990), but this remains unclear (Trewartha et al., 2015). Therefore, it is crucial to develop strategies to prevent traumatic and overuse injuries to the spine in rugby players involved in the scrum. For this purpose, however, it is critical to have a better understanding of the mechanisms of injury.

2.4 Mechanisms of scrum-related spinal injuries

The vast majority of research investigating mechanisms of spine injuries in scrums has focussed on catastrophic spinal injuries. Early investigations, often based on case reports (i.e. observation of incidents and self-reports) and cadaveric studies, have proposed two different injury mechanisms each with distinct patterns of motion of the head and neck. First, it has been suggested that injuries to the cervical spine result from hyperflexion where the head and neck are forced into supraphysiological flexion with or
without an axial rotation component (Trewartha et al., 2015). The hyperflexion injury mechanism was first suggested by Scher (1982) who reported two cases of amateur male players injured during scrummaging through forceful flexion of the neck. The author concluded that scrum-related cervical spine injuries were generally due to hyperflexion. Cadaveric studies have confirmed that injuries due to hyperflexion can result in dislocations of the facet joints (Ivancic et al., 2007, 2008; Panjabi et al., 2007), which are lesions commonly found in scrum-related cervical spine injuries. The second injury mechanism has been described as ‘buckling’ of the cervical spine under axial compression and has initially been proposed to explain cervical spine injuries occurring in head-first impacts, such as during the spear-tackle in American Football (Torg, Vegso, O’Neill, & Sennett, 1990). Under the ‘buckling’ paradigm, it is believed that injuries occur when the axially directed compressive load is applied to the cervical spine, such that the force is transmitted axially from one vertebra to the next (Torg et al., 1990). The cervical spine is caught between the head generally transmitting the axial compression force, and the static trunk, such that high compressive loads are generated within the cervical spine. Under these conditions, the cervical spine bows or deforms in a more serpentine profile (i.e. second order buckling) and vertebrae fail, resulting in fractures and/or facet joint dislocations (Chao, Pacella, & Torg, 2010). It has been highlighted that buckling injuries were especially likely to occur when the cervical lordosis is attenuated, such as in an approximately 30° neck flexion (Chao et al., 2010; Swartz, Floyd, & Cendoma, 2005) or during a simultaneous flexion and extension of the upper and lower cervical spine regions respectively (Kapandji, 2007; Mayoux-Benhamou et al., 1994; Vitti, Fujiwara, Basmanjian, & Iida, 1973). Moreover, the location and orientation of the impact were found to be important factors influencing the severity of the injury (Trewartha et al., 2015). For example, it has been shown that when
the impact surface is perpendicular to the cervical spine, the risk of injury is higher than when the surface is non-perpendicular (Nightingale, Richardson, & Myers, 1997). Impacts applied close the vertex of the cranium also have a higher risk to result in a severe injury (Nightingale et al., 1997). 'Buckling' of the cervical spine has been confirmed as a possible injury mechanism for scrum-related injuries by cadaveric studies showing axial compression of the cervical spine can result in facet joint dislocations (Nightingale, McElhaney, Richardson, Best, & Myers, 1996; Yoganandan et al., 1986).

It is still debated whether hyperflexion or 'buckling' of the cervical spine is the predominant injury mechanism. For example, Kuster, Gibson, Abboud and Drew (2012) concluded in their systematic review that ‘buckling’ must be the most likely injury mechanism in rugby-related cervical spine injuries. However, Dennison, Macri and Cripton (2012) criticised this systematic review, arguing that the conclusion was mainly based on cadaveric studies, which may not necessarily reflect in vivo scenarios. In addition, Dennison et al. (2012) highlighted the fact that Kuster et al. (2012) failed to include cadaveric studies that reproduced facet joint dislocations via hyperflexion in their systematic review. Therefore, the authors suggested it was too early to abandon hyperflexion as the main mechanism underpinning rugby-related cervical spine injuries. Overall, Trewartha et al. (2015) concluded that the primary injury mechanism remains largely unclear. One of the main reasons why mechanisms of injury are still debated is that measuring scrum biomechanics is technically challenging due the involvement of so many players. For example, investigating spinal kinematics during scrums could provide key information on how injuries occur given the two proposed injury mechanisms imply different motion patterns. Although studies that investigated 3D spinal kinematics during scrums exist (Swaminathan, Williams, Jones, & Theobald,
2016a, 2016b), they are rare due to that difficulty of measuring cervical spine kinematics during scrums. Therefore, it is important to develop alternative measurement methods to further investigate spinal, and particularly cervical, kinematics.

Mechanisms underpinning scrum-related overuse injuries of the cervical spine have been less well documented, but it is believed that the exposure to repetitive micro-traumas sustained by front-row players during scrums is an important contributing factor (Trewartha et al., 2015). However, although supporting literature provides evidence that large compressive and shear forces are generated during scrums (Cazzola et al., 2015; Milburn, 1990; Preatoni, Stokes, England, & Trewartha, 2013), many questions remain unanswered. For example, it is known that the scrum applies high biomechanical loads to front-row players’ cervical spine, but because position and orientation of the head and neck have not been reported in the scientific literature it remains unclear what spinal structures are most stressed and how they are stressed. Nevertheless, 3D kinematics of the cervical spine have been measured during contested scrumming in two studies (Swaminathan et al., 2016a, 2016b). The authors reported that the amplitude of movement of the cervical spine is only moderate during scrums, with 63% of the total range of motion (ROM) utilised by front-row players (Swaminathan et al., 2016b). It could be argued that larger movement amplitudes would increase the risk of injuries because spinal structures experience highest stresses in extreme movement amplitudes (Cholewicki et al., 2005; Chosa, Totoribe, & Tajima, 2004; Goel, Kong, Han, Weinstein, & Gilbertson, 1993), but the authors acknowledged that the causal relationship between movement amplitude and risk of injury is not clear (Swaminathan et al., 2016b). Indeed, it could also be argued that more constrained head and neck movements may imply more repetitive stresses on the same structures and therefore result in faster degeneration (Swaminathan et al., 2016a). For example, such
repetitive stresses have also been proposed as a contributing factor for overuse injuries in running (Hamill, Palmer, & Van Emmerik, 2012). Moreover, it is thought that constrained movements of the head and neck during scrummaging may result from substantial muscle activation, such as in the upper trapezius and sternocleidomastoideus, which are acting as stabilising agents (Cazzola, Stone, Holsgrove, Trewartha, & Preatoni, 2016; Silvestros & Cazzola, 2017). Although stabilising the cervical spine is important to avoid extreme movement amplitudes, these large muscle activations may also have the negative effect of increasing compressive loads experienced by spinal structures and accelerating their degeneration (Cazzola et al., 2016; Silvestros & Cazzola, 2017; Swaminathan et al., 2016b). In summary, it is conceivable that a balance between a certain degree of variability in cervical spine posture and large movement excursions could help prevent overuse injuries of the cervical spine, however, this remains unclear.

Compared to the number of studies investigating cervical spine injuries, epidemiological and biomechanical studies investigating lumbar spine injuries are even more rare. Of the studies that have been conducted, it has been shown that the lumbar spine is often injured during scrums, with the IVD frequently affected (Fuller, Brooks, & Kemp, 2007). It has also been reported that conditioning training, especially weight training, can result in a large number of lumbar spine injuries in both senior (Fuller, Brooks, & Kemp, 2007) and school level rugby players (Palmer-Green et al., 2015). Factors such as poor preparation of the abdominal and dorsal musculature, or poor weight-lifting technique might be causes for lumbar spine injuries in rugby players (Palmer-Green et al., 2015). In the present context, the squatting technique appears to be particularly important as its biomechanical characteristics are similar to those of the scrums, especially when the athlete is in the half-squat position. This position is very
similar to the position adopted by front-row players when they start pushing forward (see section 2.5). From a crouched position, the squatting athlete pushes the mass upwards by extending hips and knees. Although the acting muscles are mainly gluteal, hamstrings and quadriceps (Schellenberg, Taylor, & Lorenzetti, 2017), the force transmitted through the upper body results in considerable stress in the lumbar spine (Hartmann et al., 2016). For this reason, it has often been suggested that a correct squatting technique should involve a neutral lumbar posture throughout the entire exercise to reduce compressive forces acting, particularly on the IVDs (Kushner et al., 2015; Oshikawa, Morimoto, & Kaneoka, 2018; Schoenfeld, 2010). Indeed, it has been reported that the curvature of the lumbar spine could largely influence internal load sharing between spinal structures. For example, it has been shown that a kyphotic posture of the lumbar spine resulted in 1 MPa of lumbar intradiscal pressure when compression force is applied, compared to only 0.7 MPa in a neutral posture (Shirazi-Adl & Parnianpour, 1999). Therefore, a neutral lumbar spine posture is also recommended during scrumming (Posthumus & Viljoen, 2008), but lumbar kinematics during scrums have rarely been investigated. Therefore, it remains unclear whether players indeed adopt a neutral lumbar posture and if not, what affects their ability to adopt this posture.

Injuries to the thoracic spine do not occur frequently and these are generally less severe than cervical or lumbar spine injuries (Fuller, Brooks, & Kemp, 2007). Therefore, the focus of this thesis is the cervical and lumbar spine.
2.5 Biomechanics of the scrum

The biomechanics of the scrum have been studied often to optimise the technique for performance and to improve players' safety. Certainly the existing scrum laws have been influenced or are based on the findings of these studies. For example, the basic scrum technique requires front-row players to crouch, such that the body is positioned low to the ground, with a horizontally aligned 'straight, flat back' posture. From this position, the legs are extended to push the axial skeleton (i.e. pelvis, spine, thorax and head) forward to engage with the opposite pack (O’Shea, 2003) (Figure 2.2). Mills and Robinson (2000), Quarrie and Wilson (2000), Rodano and Tosoni (1992) and Wu, Chang, Wu and Guo (2007) investigated the effect of body position on force output and have confirmed the recommendation of a low crouched position. The authors found that the highest amount of forward forces can be generated when the distance from the ground to the trunk is equivalent to 40% of an individual's body height (Wu et al., 2007) and when the knee flexion angle is approximately 105 – 115° (Mills & Robinson, 2000; Quarrie & Wilson, 2000; Rodano & Tosoni, 1992). It should be noted that with 125°, Sayers (2008) found slightly larger knee flexion angles in a sample of five professional players, which was thought to be more effective for forward force production than smaller angles.
Schematic representation of the scrum position recommended by coaching manuals. The left part (a) shows the initial crouched position and the right part (b) represents the position adopted during the pushing phase with a knee flexion angle of 105 – 125°. Note the low body position adopted with a ‘straight, flat back’.

In biomechanical investigations, the scrum is often divided into different phases. There is currently no consensus on how to separate the scrum into phases, but it is generally performed based on specific kinetic or kinematic events. Thereby, the instant of impact is often used as the point of reference, such that there is a phase before and after impact. The phases that occur after the impact can be defined as ‘rebound phase’ and ‘sustained push phase’. An example is presented in Figure 2.3, where phases were separated based on the kinetic data output of compression forces measured using an instrumented scrum machine (Preatoni, Stokes, England, & Trewartha, 2015).
Phase separation based on forward force output (compression) measured from instrumented scrum machine. Reproduced from 'Injury and biomechanical perspectives on the rugby scrum: a review of the literature', Trewartha et al., Vol. 49, 425-433, 2015 with permission from BMJ Publishing Group Ltd.

Using a similar method to separate scrum trials into different phases, Preatoni et al. (2013) studied kinetics of machine-based scrums among players of different playing levels. The authors found that forces of up to 16.5 kN can be generated and transmitted through the front-row players' shoulders to their spines during simulated scrums (Preatoni et al., 2013). These results may partly explain why front-row players suffer from early spinal degenerative changes. As one would expect, the majority of forces generated are directed in the scrumming direction, resulting in compressive loads in the spine (Milburn, 1990; Preatoni et al., 2013; Quarrie & Wilson, 2000; Rodano & Tosoni, 1992). However, a considerable amount of generated force was also found to be directed vertically, typically downwards, during the engagement phase of machine-based scrums. These forces were found to be as high as 12-24% of the peak forward forces (Milburn, 1990; Preatoni et al., 2013). Since vertically directed forces are thought
to destabilise the scrum and increase the risk of collapse (Milburn, 1990), these forces are thought to increase the risk of spinal injury. Laterally directed forces were also reported, but often to a lesser extent (Milburn, 1990; Preatoni et al., 2013; Rodano & Tosoni, 1992). Nevertheless, lateral forces are thought to contribute to the development of degenerative changes as they result in bending and rotation of the spine (Milburn, 1990).

In an attempt to reduce the forces generated during scrums, especially during the engagement phase where peak values were found, several changes were applied to the scrummaging laws between 2007 and 2014. Before 2007, no formal scrum engagement sequence was recognised by World Rugby such that ‘crouch and hold, engage’, ‘crouch, pause, engage’ or ‘crouch, touch, pause, engage’ could be used to initiate the scrum. Thereby, players were free to dynamically engage from a large distance after crouching and shortly pausing. In the engagement sequence 'crouch, touch, pause, engage' (CTPE), however, the distance between the two packs was somewhat regulated by the front-row players being required to touch the opposing pack prior to engaging. Therefore, in order to reduce the distance between the two packs and the engagement velocity, World Rugby uniformly accepted CTPE as the formal engagement sequence in 2007. This change was followed by two other modifications to further de-emphasise the magnitude of the collision at impact: in 2013, 'crouch, touch, set' (CTS) was adopted and finally the currently valid sequence 'crouch, bind, set' (CBS) was introduced in 2014. Under the current CBS sequence, front-row players are required to bind with the opposite pack prior to engagement to better regulate the distance between the two packs.

Cazzola et al. (2015) compared scrum kinetics under three different engagement conditions (CTPE, CTS and CBS) to determine the effect of engagement sequence on peak force experienced by front-row players. Compression forces were measured using
pressure sensors placed on the shoulders of front-row players, and two-dimensional (2D) kinematics was recorded from the side and from above using four video cameras. Although lower peak forces were found compared to values from simulated scrums in previous investigations (16.5 kN) (Preatoni et al., 2013), compression forces of up to 9.8 kN were recorded during the contested scrums in this study when CTPE engagement procedure was used. The authors found that different engagement procedures significantly altered the magnitude of peak compression forces. For example, compared to CTPE, the CTS and CBS sequences showed a 10% and 35% reduction in peak compression forces at impact respectively, without changing force production during the sustained push (Cazzola et al., 2015). It was thought that the reduced distance between the two packs by 0.12 m, and therefore the resultant reduction in peak engagement velocity, was the primary factor responsible for decreased impact forces (Cazzola et al., 2015). That is, the shorter distance allowed less acceleration during engagement and hence resulted in decreased forward momentum. The different engagement sequences have also been investigated from a kinematic perspective. Swaminathan et al. (2016b) hypothesised that CBS may be a safer engagement sequence than CTPE as it might result in decreased spinal movement amplitudes. The reasoning underlying the hypothesis was that increased amplitude of spinal movement was thought to be associated with less stability and more postural adjustments, and hence greater risk of scrum collapse. The authors, therefore, used inertial sensors placed on five spinal regions to measure spinal kinematics during contested and machine-based scrums with CBS and CTPE engagement sequences. However, there was no significant decrease in the amplitude of movement during scrums with the CBS engagement sequence and the authors suggested that further modifications to the rules were needed to positively influence spinal kinematics (Swaminathan et al., 2016b). Nevertheless, this
conclusion appears somewhat arbitrary because the absence of any difference in movement amplitudes between CTPE and CBS does not mean that another engagement sequence will necessarily show larger differences. Indeed, it is conceivable that other factors, such as the number of players involved in the scrum influence spinal kinematics to a much larger extent than the type of engagement sequence. Therefore, it is important to recognise that factors influencing spinal kinematics remain largely unclear and should be further investigated.

Other researchers have used a combination of in vivo, in vitro and in silico to estimate the magnitude and characteristics of internal loads acting on each cervical vertebra during scrums (Preatoni et al., 2015; Silvestros & Cazzola, 2017). The methods adopted by these authors consisted of three separate steps. First, kinematic, kinetic and EMG data of the sternocleidomastoid and upper trapezius were collected from hookers when scrummaging against a scrum machine with the help of both tight-head and loose-head props (Figure 2.1). The scrum machine was also equipped with an instrumented dummy head to estimate forces and torques applied to the head during scrums. In a second, separate step, anatomical preparations of porcine cervical spines were tested in vitro to observe failure patterns of individual vertebrae under axial compressive loads of magnitudes similar to those found in a scrum (Holsgrove et al., 2015). In the final step, a full-body musculoskeletal computer model was developed specifically for the analysis of the scrum task (Cazzola, Holsgrove, Preatoni, Gill, & Trewartha, 2017). The kinematic, kinetic and EMG data collected from hookers was then used to drive the computer model simulations and the failure patterns of porcine cervical spines were used to investigate the loading patterns of individual vertebrae during the simulations. The authors investigated the effect of various neck flexion angles, ranging from 0 – 30°, and levels of muscular activity on internal loads acting on the fourth, fifth, and sixth
cervical vertebra (C4-C5). The results demonstrated peak compressive loads occurring 28-30 ms after impact, substantially earlier than the occurrence of the peak impact forces and before a hyperflexion movement could occur. In addition, it was found that C4 predominantly experienced shear forces, whereas C5 and C6 experienced predominantly compressive loads. The authors suggested these results supported clinical findings in injured rugby players, where C4 is the most frequently dislocated vertebra and C5 and C6 are the levels that most often sustain compression injuries.

With regard to muscle activation levels, the results indicated that a strong co-contraction of the measured neck muscles could be a ‘double-edged sword’. On the one hand, co-contraction appears to result in an increase in compressive loads, which might place vertebrae at higher risk of a compression injury, but on the other hand, co-contraction also appears to decrease shear stress at C5 and C6. The authors concluded that the results supported the ‘buckling’ injury mechanism, especially in scrum scenarios where the neck is flexed by over 20°, and that muscle activation and the vertebral level affected the loading response of the cervical spine (Cazzola et al., 2017).

2.6 Investigating scrum kinematics

Although considerable effort has been made to investigate scrum mechanics, further studies investigating injury mechanisms are required to assist in developing strategies to prevent injuries from occurring. It appears that kinematic investigations could be of particular importance because the proposed mechanisms of cervical spine injuries imply different movement patterns (i.e. hyperflexion versus ‘buckling’). Moreover, given spinal posture can substantially influence the tolerance of the spine to compressive loads and thereby possibly the risk of spinal injuries, rugby guidelines recommend
players adopt a neutral spine posture during scrummaging. However, given studies on 3D spinal kinematics are rare, it remains unknown whether these recommendations are truly technically feasible for front-row players.

Biomechanical investigations of the scrum are challenging due to the number of players, and the large forces, involved in the scrum as well as the unpredictable motion of the forward packs. These technical challenges are particularly pronounced in kinematic studies of the spine. Motion tracking is often performed using vision-based measurement systems, such as optoelectronic motion capture, which consist of multiple infrared-based cameras, each recording 2D kinematics via reflective markers attached to anatomical landmarks of the participant (Cappozzo, Della Croce, Leardini, & Chiari, 2005). Coordinates of the markers can then be calculated in 3D using photogrammetric calculations (Shapiro, 1978) to allow 3D kinematic analysis. However, these systems are typically designed to be used in a laboratory rather than in field-based environments. Moreover, the close contact between different players is likely to cause abrasion and detachment of reflective markers. Secondly, kinematics of the cervical spine in front-row players is particularly difficult to measure because the neck region is obscured by opposing players, such that vision-based measurement systems cannot be utilised. These challenges have motivated the majority of the researchers to perform their studies in laboratory settings and/or using a scrum machine rather than an opposing pack (Cazzola et al., 2016; Milburn, 1990; Rodano & Tosoni, 1992; Sayers, 2008; Wu et al., 2007). These studies have provided valuable insights into the basic biomechanics of the scrum, but how these findings can be applied to real scrums remains questionable. Using different measurement techniques, some researchers have attempted to investigate biomechanics of the scrum under more realistic conditions, i.e. during field-based, contested scrums (Cazzola et al., 2015; Du Toit, Olivier, & Buys, 2006; Swaminathan et
al., 2016a). For example, Cazzola et al. (2015) studied scrum kinematics using four video cameras. However, only 2D kinematics were analysed and the spine was considered as one rigid segment. Other researchers have used inertial sensors placed on five anatomical landmarks of the axial skeleton (Swaminathan et al., 2016a) but considering that inertial sensors are not flat, placing them on the dorsal aspect of a player’s trunk is likely to cause the same issues as with reflective markers. The close contact with other players during contested scrums is likely to result in movement or detachment of the inertial sensors. Although Swaminathan et al. (2016a) deleted any trial where sensors moved or were detached, reattaching may further decrease reliability of the results. Moreover, even in a best-case scenario without detachment, bulky sensors are likely to result in magnified soft-tissue artefact. For example, in an engaged scrum, the 7th cervical (C7) spinous process of a hooker is in direct contact with the opposite front-row players. Therefore, any movement of the opponents will cause the soft tissue of the hooker’s neck to move, even if his cervical spine remains still. In addition, a general limitation of inertial sensors is that they do not measure spatial position, only orientation. Although it is possible to calculate spatial position from inertial data via double integration of acceleration values, this method is subject to a rapid increase in estimation errors over time (You, Neumann, & Azuma, 1999). Methods exist to improve the accuracy of position estimation from inertial data, but these require specialised measurement methods (Tian, Meng, Tao, Liu, & Feng, 2015). Nevertheless, measuring head location relative to the thorax is important when investigating cervical spine kinematics because the head can translate sagittally or transversally despite maintaining orientation. Such translational head movements can influence the alignment of the cervical spine (Ordway, Seymour, Donelson, Hojnowski, & Edwards, 1999; Penning, 1978) and may be of importance to injury prevention in scrumming.
In summary, these examples illustrate the difficulty of measuring spinal kinematics during scrums and highlight that alternative measurement methods need to be developed that account for the current shortcomings.

2.7 Gaps in the literature

The literature review provided in this chapter described the role of the scrum in rugby, and presented epidemiological injury data in rugby with specific focus on spinal injuries. More importantly, the current state of knowledge, as well as the difficulties in measuring scrum and scrum-related injury biomechanics, were discussed. It was highlighted that there remains a need to investigate the mechanisms underlying scrum-related spine injuries, particularly in the cervical and lumbar spines, to better understand and prevent these injuries. The potential importance of performing kinematic investigations of the spine under ecologically valid conditions (i.e. field-based, contested scrums) was also emphasised.

Interestingly, although many different measurement methods exist, to date, only optoelectronic motion capture and inertial sensors have been explored for the measurement of spinal kinematics during scrums. Indeed, it is likely that other measurement systems, such as EMT systems (Koerhuis, Winters, van der Helm, & Hof, 2003) or alternative optical systems (Chong, Milburn, Newsham-West, & ter Voert, 2009) may allow field-based data collection with sufficient accuracy. Furthermore, it should be noted that investigations of the quality of traditional measurement systems have rarely been performed in the context of the scrum. For example, Swaminathan et al. (2016b) based the rationale of their method on studies that investigated the use of inertial sensors to measure spinal kinematics in a quiet environment (Williams, Haq, &
Lee, 2013; Wong & Wong, 2008). Moreover, these studies have not quantified the accuracy of inertial sensors for the measurement of spinal kinematics in the transverse plane. Therefore, there is not only a need to explore further possible measurement methods, but to also investigate the quality and feasibility of these measurements.

Improved methods of measuring what occurs during the scrum will also afford the opportunity to measure other specific and non-specific factors that may influence spinal kinematics and the risk of injury. For example, understanding how other players influence the spinal posture and kinematics of a front-row play may help identify specific injury mechanisms. Whilst non-specific factors, such as turf-type, are modifiable risk factors, the number of players in a scrum is a non-modifiable risk factor in a rugby match. To date, only two studies have specifically investigated spinal kinematics during scrums to evaluate the effect of potential influencing factors. One study investigated a non-specific factor (turf-type) (Swaminathan et al., 2016a) and the other a scrum-specific factor (type of engagement sequence) (Swaminathan et al., 2016b). However, although the number of players involved in the scrum could have substantial influence on spinal kinematics of front-row players during scrummaging, it has rarely been evaluated as a potential influencing factor (Sayers, 2008). Therefore, the focus of this thesis was on investigating the effect of the number of players involved in the scrum on front-row players' spinal kinematics.

Obtaining a detailed understanding of the effect of other players on spinal posture and kinematics in front-row players requires multiple research steps. Since there are a total of 16 players involved in competitive scrummaging, many different variations of scrum formations need to be investigated using a systematic approach. In the first step, spinal kinematics were investigated during machine-based one-man scrums to better understand how individual players move their spine and control spinal posture in what
was considered to be the most simple scrum-related task. The next logical steps were to increase the complexity of the scrum formation by adding players that are in direct contact with the front-row player performing the one-man scrum. For example, the scrum machine could be replaced by two opponents ('one-on-two' formation) to compare cervical spine kinematics with those in the 'one-man' scrum formation. Alternatively, the support of two second-row players could be added to the 'one-man' scrum formation ('supported' formation) to explore lumbar spine kinematics. More complex scrum formations should also be investigated, but it is important to first characterise spinal kinematics in these first three formations ('one-man', 'one-on-two' and 'supported').

With regard to kinematic parameters, to date, only the excursion and velocity of spinal kinematics have been investigated during scrums (Swaminathan et al., 2016a, 2016b). Moreover, inertial sensors were used for these measurements; hence kinematic parameters have not been examined at specific time points of the scrum. For example, given the highest compression forces are generated at impact (Cazzola et al., 2015), it is conceivable that kinematics at this time point are of particular importance. In addition, kinematic parameters that are specific to the cervical spine appear to be important to evaluate but have never been investigated previously. First, because cervical spine kinematics have only been measured via head orientation, the cervical spine has been regarded as a socket joint allowing movements in the three anatomical planes (Cazzola et al., 2017; Silvestros & Cazzola, 2017; Swaminathan et al., 2016a, 2016b). In fact, this view is an oversimplification of the true functional anatomy of the cervical spine. The cervical spine can functionally be divided into upper (C1-C2) and lower (C3-C7) parts with distinct degrees of freedoms (Kapandji, 2007) such that an analysis that considers both regions separately would provide more detail on the alignment of the cervical spine.
during scrummaging. This could be achieved by measuring the location of the head relative to the thorax in addition to its orientation. Secondly, given it has been shown that cervical intervertebral kinematics not only depend on posture of the cervical spine but also on movement direction (Anderst, Donaldson, Lee, & Kang, 2013), it is crucial to assess kinematics at and around key time points of the scrum. This approach could provide information on movement direction before and after specific time points to help infer intervertebral kinematics.

Another kinematic parameter that has never been investigated in the context of scrum-related spine injuries is movement variability within individuals. Investigating movement variability might help to better understand dynamic stability of spinal posture during scrums and the emergence of, particularly overuse, injuries. To prevent traumatic spinal injuries it is thought that maintaining the head and neck as close to neutral as possible is beneficial for optimal distribution of internal loads and to avoid movements of excessive amplitude (Posthumus & Viljoen, 2008). In contrast, increasingly rigid movement behaviour is thought to result in overuse injuries (Stergiou & Decker, 2011). For example, in sports such as running (Hamill et al., 2012) or netball (Maulder, Hume, & Bradshaw, 2012), it is thought that reduced movement variability may be associated with the occurrence of such overuse injuries. It is hypothesised that due to variability in movement, mechanical loads are applied (i.e. distributed) to different musculoskeletal structure, rather than repeatedly to one or few structures (Kurz, Stergiou, Buzzi, & Georgoulis, 2005). It is has also been reported that injured and recovering athletes can present disturbed coordination patterns with decreased movement variability. It is thought that damaged tissue, such as ligaments, may provide distorted sensory feedback that results in central nervous changes and altered movement patterns (Stergiou & Decker, 2011). Therefore, taking first steps in scrum-related movement variability
research forms an important basis not only to better understand occurrence of scrum-related overuse injuries, but also to obtain a more detailed insight in the motor skill learning and rehabilitation process in front-row players.

2.8 Conclusion

There is a need to further advance methods for the measurement of scrum biomechanics, especially for spinal kinematics in front-row players. Once an accurate and reliable alternative has been found, the effect of the number of players involved in the scrum on postural stability of the spine needs to be investigated. In addition, the role movement variability might play in the occurrence of spinal overuse injuries should also be studied. Therefore, this thesis attempts to bridge the highlighted gaps in the literature by designing, testing and validating a novel measurement method for spinal kinematics during scrums. Furthermore, first steps are taken towards the investigation of the effect of different scrum formations on spinal kinematics and the evaluation of movement variability in scrummaging.
References


forwards during machine-based scrumming. *British Journal of Sports Medicine, 49*(8), 520.


Swaminathan, R., Williams, J. M., Jones, M. D., & Theobald, P. S. (2016b). Does the new rugby union scrum sequence positively influence the hooker’s in situ spinal kinematics? *BMJ Open Sport & Exercise Medicine, 2*(1), e000064.


CHAPTER 3

General methods

3.1 Introduction

Investigating scrum biomechanics to understand mechanisms underlying scrum-related injuries is an important first step to better develop injury prevention strategies. However, investigating scrum biomechanics is technically challenging and understanding injury mechanisms is ambitious, given many factors can potentially play a role in the occurrence of spinal injuries. This chapter provides an overview of the general approach adopted in this thesis to investigate these issues.

First, an overview of the experimental progression is presented. Details are provided on the rationale behind the development of an alternative measurement method and the necessity to test the viability for field-based measurements. Finally, an overview of the custom-designed equipment and approach adopted throughout the experimental studies is presented.

3.2 General approach and experimental progression

This project developed a novel method to measure spinal kinematics during scrums and investigated the influence of scrum complexity on spinal kinematics and risk of injury. The first two studies consisted of the development and testing of the proposed measurement method. The last four studies consisted of exploring the complexity of the scrum task as possible factors that influence spinal kinematics and the risk of injury. The complexity of the scrum was modulated by varying the number of players involved.
and varying the scrum formation. It was hypothesised that machine-based one-man scrums would be the simplest version of the scrum, since there are no external perturbing factors. Therefore, in machine-based one-man scrums, the only compressive and shear forces acting on the player's spine are the ones generated by the player. For example, it was hypothesised that players could maintain their cervical spine in a posture closer to the neutral position when scrummaging alone against a scrum machine, than when scrummaging against two opponents. Similarly, it was hypothesised that players could better stabilise their lumbar spine posture during one-man scrums than during scrums with the support of two second row players pushing from behind.

### 3.3 Requirements for novel measurement methods

To date, kinematic measurements of the spine have rarely been performed in front-row players during scrums. Moreover, the authors of the rare studies investigating spinal kinematics during scrums faced the dilemma of choosing between feasibility of using reference standard methods or performing scrums under realistic conditions. While the majority of studies have opted to investigate kinematics using optoelectronic motion capture, which is often considered to be the reference standard in human motion capture (Ceseracciu, Sawacha, & Cobelli, 2014; Fleron, Ubbesen, Battistella, Dejtiar, & Oliveira, 2018; Hanley, Tucker, & Bissas, 2018), some have opted to emphasise ecological validity by employing inertial sensors. However, the validity of inertial sensors to investigate spinal kinematics in front-row players during scrummaging also remains questionable.
Therefore, an alternative measurement method is needed, which ideally fulfils the following criteria: (1) does not require bulky markers or sensors to be attached on the dorsal aspect of the spine; (2) is portable, such that it can be used for field-based scrums; (3) is versatile, such that it can be used for measurements in different scrum formations; and (4) is as reliable as traditional measurement methods.

3.4 Alternative measurement methods

3.4.1 Cervical spine

The main issues with measuring kinematics of the cervical spine is that the head and neck regions are occluded by opponents during contested scrums, and that there is a high risk for magnified soft-tissue artefact if a sensor is placed on the dorsal aspect of the cervical spine, such as the spinous process of C7. Therefore, a method that is not based on optical sensors was required and sensors had to be placed on the anterior aspect of the player. Inertial measurement units and EMT systems were both considered for this application, as they are not vision-based systems. The advantage of inertial sensors over EMT is that these sensors are wireless. However, compared to an activity such as pirouettes in gymnastics where it is important to have wireless sensors, the scrum can be considered a quasi-static activity, such that wires do not pose a significant problem to successful performance of the task. In contrast, the advantage of EMT is that these systems are capable of measuring position in space in addition to orientation, where inertial sensors measure orientation only. Translated into the application of measuring cervical spine kinematics, this means that inertial sensors can only register the orientation of the head relative to the base of the cervical spine, while EMT systems allow the measurement of the head’s orientation and location. The additional
information on head location may provide valuable insight into the alignment of the spine (Kapandji, 2007; Ordway et al., 1999; Penning, 1978) which may further enlighten our understanding of injury mechanisms. A common limitation with both inertial sensors and EMT systems is the sensitivity to large metallic objects (Welch & Foxlin, 2002), which was of concern in this research project. For example, the use of a commercial scrum machine was not feasible due to this limitation. Therefore, the methodology had to be adapted accordingly and is presented below.

3.4.2 Lumbar spine

With regard to the lumbar spine, the biggest issue is not the occlusion of the body parts by other players, but rather the risk of marker or sensor detachment because these are not flat. Therefore, a possible solution could be a vision-based measurement system that does not require the attachment of bulky reflective markers. For example, reflective markers could be replaced by painted reference points on critical anatomical landmarks. Using this approach, Chong, Milburn, Newsham-West and ter Voert (2009) have been able to perform accurate measurements of participants' spinal curvature using four consumer-grade digital cameras. The authors reconstructed 3D models of the spine using the recorded frames from the four cameras and bundle adjustment calculations, which is a highly accurate method to determine 3D points' coordinates in photogrammetry (Luhmann, Robson, Kyle, & Boehm, 2014). Using this method, the authors were able to track diurnal changes of the spine, such as shrinkage and curvature changes. Therefore, it is conceivable that this method could be adapted to the measurement of spinal kinematics during scrums.
3.5 Validation of the novel measurement method

The fact that different methods of investigating the scrum have been developed, trialled, and in some cases replaced by traditional, laboratory-based measurement systems (Preatoni et al., 2012) reflects the difficulty of designing an appropriate measurement method. Therefore, although the alternative methods proposed in this research appear feasible in theory, it was necessary to validate their use in the context of scrummaging. It was particularly important to test the practicality of their use, as well as the quality of the data. Indeed, although the final goal was to perform measurements of field-based scrums, the assessment of reliability and validation against a reference standard (optoelectronic motion capture) were the determining steps that dictated the further aspect of this research. For example, if the novel measurement method proved to be insufficiently accurate and/or reliable, the part of the research investigating spinal kinematics during scrums under different conditions would have had to be done in a laboratory using an optoelectronic motion capture system. In summary, measurement quality was expected to decrease in field- compared to laboratory-based measurements, but could not be sacrificed to achieve optimal ecological validity.

3.6 Design of a compatible scrum machine

Although the ultimate goal would be to investigate spinal kinematics during field-based, competitive scrums to obtain a 'true' representation of what occurs during scrummaging, it was important to first understand how interactions between players influence spinal kinematics. Therefore, this research started with the simplest scrum variation and increased the complexity of the scrum by progressively adding players to study the influence of external perturbations (i.e. other players) on individual players' spine
kinematics. Thus, a scrum machine was necessary and a solution to the problem posed by the sensitivity of the sensors to large metallic objects had to be found. Therefore, the first part of this project involved designing and building a custom-made, rigid wooden scrum machine (Figure 3.1) (Appendix 1).

![Custom-built scrum machine](image)

**Figure 3.1**
Custom-built scrum machine used for machine-based scrums.

The scrum machine was designed to allow scrummaging at heights between 40 and 110 cm to replicate commercial scrum sleds. In addition, to allow both laboratory and field-based measurements, the scrum machine was designed to be dismountable. In order to prevent the scrum machine from sliding while players were scrumming during laboratory-based measures, Velcro was attached to the under surface. For field-based testing, spikes were applied to its under-surface.
3.7 Placement of the sensor tracking the head

In biomechanical investigations, there are two possibilities to prevent the effect of soft-tissue artefact to distort results. The first involves the use of medical imaging, such as fluoroscopy (List et al., 2017) but fluoroscopy involves ionizing radiation. The other possibility is to attach markers or sensors via a rigid connection to the bone (Arndt et al., 2007) but this option is often invasive and therefore carries a risk for participants (e.g. infection). However, for head motion tracking, a rigid connection to the skull can be established via the teeth, such that the use of invasive techniques can be avoided. Therefore, in order to reduce the effect of soft-tissue artefact in this research, head motion was tracked using a sensor attached to a mouthpiece that had a 'tongue' extending out of the mouth (Figure 3.2). For each participant, the mouthpiece was adjusted by applying melted thermoplastic to both sides of the mouthpiece to obtaining participant's dental impression.

![Mouthpiece and Sensor](image.png)

**Figure 3.2**

a) Mouthpiece that was used to attach a sensor to track head motion. b) The sensor was attached to the mouthpiece's tongue, which extend out of the mouth when worn.
3.8 Design of a compatible jersey

As mentioned previously, kinematics of the lumbar spine were intended to be measured using a vision-based system. However, rugby is usually played with a robust jersey, such that the spine is hidden. Moreover, it is difficult to perform scrums without a jersey because players use it to bind with their team-mates to maintain the compact formation and with the opponents prior to engagement. Therefore, it was important to design a specific jersey that did not cover the spine but still allowed players to bind. For this purpose, first ideas were collected and presented to the Queensland College of Art (QCA). With the help of Christopher Miller from the QCA, different designs were conceptualised (Appendix 2) and first prototypes were created. Since all proposed designs were based on compression clothing, a local company that specialised in this type of clothing (BodyScience International Pty Ltd) was contacted. With the support of this company’s design manager, the design was further refined and subsequently 12 jerseys of different sizes were produced for data collection (Figure 3.3).

![Figure 3.3](image)

Final jersey design.
3.9 Custom-designed camera-mount

To record the players' spines during scrums, cameras had to be installed above the players. However, to allow concurrent tracking of cervical, as well as thoracic and lumbar spine kinematics, the frame holding the cameras also had to be non-metallic, such that the EMT system would not suffer from distortions. The frame was designed in an "S" shape to allow the front arms, which were holding the cameras, to be hanging over the players (Figure 3.4) (Appendix 3). These arms also held a control frame made of Polyvinyl chloride (PVC), which was required for photogrammetric processing. The dimensions of that S-shaped frame (L 4.8 x W 1.3 x H 2.4 m) were based on dimension estimations of 16 forward players in scrum formation. The cameras and the control frame were located approximately 2.4 and 1.3 m from the ground, respectively, when mounted on the frame. Therefore, when scrum height was 0.8 m, the cameras were at a vertical distance of approximately 1.1 and 1.6 m from and the control frame and the player's back, respectively.

Figure 3.4
Custom-designed camera-mount with the PVC control frame
References


Swaminathan, R., Williams, J. M., Jones, M. D., & Theobald, P. S. (2016b). Does the new rugby union scrum sequence positively influence the hooker’s in situ spinal kinematics? *BMJ Open Sport & Exercise Medicine, 2*(1), e000064.

CHAPTER 4

Cervical spine kinematics measured during rugby union scrums: Reliability of optoelectronic and electromagnetic tracking systems

This chapter includes a co-authored paper. The paper has been accepted for publication in the journal *Cogent Medicine* on July 23 2018:

Declaration of co-authorship and contribution

The candidate's contribution to this article was as follows:

- conception and design of the research project
- analysis and interpretation of research data
- drafting and editing manuscript

_________________________________ 18 September 2018

Student and Corresponding author of paper: Adrien Cerrito

_________________________________ 18 September 2018

Supervisor and co-author: Professor Peter Milburn
4.1 Introduction

In rugby union, a scrum occurs after a minor infringement and normally involves eight players from each team pushing against each other to compete for ball possession (World Rugby, 2018). The scrum is physically demanding and carries a high risk for injury (Fuller, Brooks, Cancea, Hall, & Kemp, 2007), particularly to the spine (Brooks, Fuller, & Kemp, 2005).

Understanding mechanisms of scrum-related spine injuries may assist in developing injury prevention programs, which appears particularly important for the cervical region due to the catastrophic consequences of injuries to the neck (Hutton et al., 2016). For the cervical spine, two potential injury mechanisms have been proposed. First, it has been suggested that scrum-related cervical spine injuries were due to flexion of the neck that is forced beyond physiological range (Scher, 1982). The second mechanism proposed has been described as 'buckling' where the straightened cervical spine is compressed under axially directed loads (Torg, Pavlov, O’Neill, Nichols, & Sennett, 1991). The descriptions of these distinct mechanisms suggest two different cervical spine movement patterns may contribute to cervical injuries, but this remains unclear (Dennison, Macri, & Cripston, 2012; Trewartha, Preatoni, England, & Stokes, 2015). Therefore, it is important to investigate cervical spine kinematics during the scrum task.

However, choosing the most appropriate measurement system to measure cervical spine kinematics during scrums is challenging. Many different measurement systems exist, each with advantages and limitations. Optoelectronic motion capture systems are widely used for human motion analyses (Chiari, Croce, Leardini, & Cappozzo, 2005), due to their accuracy and reliability (Eichelberger et al., 2016; Windolf, Götzen, & Morlock, 2008). Optoelectronic motion capture has been used to investigate kinematics in one-
man scrums performed against a scrum machine (Wu, Chang, Wu, & Guo, 2007), but not in field-based and/or contested scrums. In field-based, contested scrums, where the cervical region is obscured by multiple players, a portable, non-optical measurement system is required. Inertial sensors have been used to measure spinal kinematics in contested scrums (Swaminathan, Williams, Jones, & Theobald, 2016a), but they typically do not measure spatial position, rather orientation. Measuring position is important because motion of the cervical spine can occur if the head translates in a sagittal or transverse plane relative to the thorax, even if the orientation of the head does not change (Penning, 1978), thereby possibly influencing injury risk.

Alternatively, cervical spine kinematics during scrums could be measured using EMT systems, which are portable, do not require body parts to be visible and can measure spatial position. The accuracy and precision of EMT systems have also been shown to be excellent, with measurement error $\leq 5$ mm (Frantz, Wiles, Leis, & Kirsch, 2003). However, measurement quality decreases with increasing distance between the antenna emitting the electromagnetic field and the sensors (Frantz et al., 2003).

To select the most appropriate measurement system, it is necessary to know the reliability of each system during the specific task of interest (Atkinson & Nevill, 1998). Therefore, the aim of the present study was to concurrently evaluate test-retest reliability of an optoelectronic motion capture and EMT system to measure cervical spine kinematics during simulated one-man scrums.
4.2 Methods

4.2.1 Participants

Nine healthy male adults, free from current injury and with no history of neck or shoulder surgery, were included (Walter, Eliasziw, & Donner, 1998). Both player and non-player participants were included to represent a range of abilities (Portney & Watkins, 1993). Four participants were club-level front row players (24.2 ± 3.5 years; 1.79 ± 0.10 m; 104.0 ± 10.6 kg), and five were non-players (26.8 ± 1.4 years; 174.2 ± 3.9 cm; 74.9 ± 13.6 kg). Participants provided written informed consent prior to participation and the study was approved by the institution's Human Ethics committee (Appendix 4).

4.2.2 Instrumentation

Cervical spine kinematics, considered as the movement of the head relative to the thorax, were recorded using a six degrees-of-freedom EMT system (Polhemus Liberty, Polhemus, Colchester, VT, USA). One sensor was attached to the sternal notch (representing the thorax) and one sensor to an individually moulded thermoplastic mouthpiece that extended out of the mouth (representing the head). The EMT system's antenna was placed approximately 60 cm from participants. Concurrently, cervical spine kinematics were recorded using a 12-camera optoelectronic motion capture system (Vicon, Oxford, UK) with 12 reflective markers. Both measurement systems were synchronised using a Telemetry Relay Repeater and sampled at 240 Hz. To register reference frames for both measurement systems during data processing, three additional reflective markers were placed on the EMT system's antenna (Cartesian origin).

Due to the sensitivity of EMT systems to metal (LaScalza, Arico, & Hughes, 2003), a custom-made wooden scrum-machine was used, with pad height replicating commercial
scrum sleds. The scrum-machine was weighted using gravel bags with Velcro attached to the under surface to prevent lifting and sliding.

### 4.2.3 Procedure

Participants first performed a standardised warm-up routine consisting of 5-minutes of cycling at a moderate intensity, body-weight squats, resisted shoulder abduction, and head flexion/extension, lateral-flexion and rotation. After warming up, two EMT sensors were attached to the sternal notch and to the mouthpiece (Figure 4.1). Six anatomical landmarks (left and right mastoid processes, nose-bridge, process xiphoid, and the spinous processes of C7 and T7 were palpated and then digitised using a third EMT sensor mounted on a stylus (Mills, Morrison, Lloyd, & Barrett, 2007). Orientations and locations of all three sensors were recorded along with location of each anatomical landmark, such that it was possible to later calculate location of each anatomical landmark relative to the sensors. A reflective marker was attached to each landmark immediately after digitisation to ensure consistency in landmark identification between the two systems. Reflective markers were then attached to the head (four markers on a headband) and to both EMT sensors (Figure 4.1). Next, a static trial was recorded, where participants were asked to adopt the trunk, neck, and head position they considered as neutral in an upright position. Following the static trial, markers from the nose-bridge and mastoid processes were removed, as these would be occluded during scrums. Non-player participants were taught basic scrum technique according to the most recent scrum law (‘crouch, bind, set’), and participants were instructed to perform scrums as consistently as possible. Player participants were asked to perform scrums with intensity comparable to a contested scrum, and non-players were asked to perform scrums at the highest comfortable intensity. Participants performed practice trials until familiar with the technique, apparatus, and protocol, before data were recorded from
seven trials (Walter et al., 1998). Participants had 1-2 minutes' break between each trial to minimise effects of fatigue (Cazzola, Preatoni, Stokes, England, & Trewartha, 2015).

![Figure 4.1](image.png)

Sensors and reflective markers placement.

### 4.2.4 Data processing

Data from the EMT system were processed using a custom-written MATLAB script (version R2014a, MathWorks Inc., Natick, MA, USA) to reconstruct trajectories of digitised anatomical landmarks relative to the two sensors (Mills et al., 2007). Data
from the optoelectronic motion capture system were then processed, which involved removing ghost markers and filling gaps if necessary, using Vicon Nexus software (version 2.2.1, Vicon, Oxford, UK). Virtual markers on the nose-bridge and mastoid processes were reconstructed in Vicon BodyBuilder (version 3.6.2, Vicon, Oxford, UK) by using their locations relative to the head markers recorded during the static trial. Then, using the markers placed on the antenna, virtual markers representing the EMT system's global coordinate system were created. These virtual markers were used to transform optoelectronic motion capture data to align with the EMT system's global coordinate system. The transformations were performed with a custom-written MATLAB script that relied on homogeneous transform calculations (Craig, 2005) (Appendix 5). Aligning global coordinates for both systems resulted in one common global coordinate system for both sets of data. A 2nd order, zero-lag Butterworth filter with 6 Hz cut-off frequency was applied to both data sets (Swaminathan, Williams, Jones, & Theobald, 2016b).

Local coordinate systems were then created in both data sets for the head (LCS\textsubscript{H}) and thorax (LCS\textsubscript{T}) using the anatomical landmarks (Table 4.1). For the origin of LCS\textsubscript{H}, a virtual marker was created as the mid-point between mastoid processes, and served as a representation of the first cervical spinous process (C1). Relative orientation between the head and thorax was then calculated and expressed as X-Y'-Z'' Cardan angle sequence representing 1) flexion/extension (FE), 2) lateral-flexion (LF), and 3) axial rotation (ROT) (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2014). The joint angle offset from natural upright posture was removed from all scrum trials using the average rotation matrix from the static trial (Koning, Krogt, Baten, & Koopman, 2012). For analysis purposes, data from all trials were extracted from a 6 s time window that was based on the instant of impact. Impact with the scrum machine was identified for
each trial from optoelectronic motion capture data as the instant where the C7 marker stopped moving in the primary direction of scrummaging. The beginning of a trial (T1) was then set as 1 s before impact (T2). Subsequently, the sustained push (T3) and the end of the trial (T4) were defined as time points at 2.5 s and 5 s after impact, respectively. The T1-T4 time points were set in the EMT data using frame numbers from optoelectronic motion capture data.

Table 4.1
Generation of local coordinate systems for the head (LCS$_H$) and thorax (LCS$_T$)

<table>
<thead>
<tr>
<th>LCS$_H$</th>
<th>Origin: C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>X$_{Head}$: +Right</td>
<td>Perpendicular to Y$_H$ and Z$_H$</td>
</tr>
<tr>
<td>Y$_{Head}$: +Dorsal</td>
<td>C1 - NB</td>
</tr>
<tr>
<td>Z$_{Head}$: +Caudal</td>
<td>Perpendicular to the plane formed by NB, C1, and RMast</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LCS$_T$</th>
<th>Origin: T7</th>
</tr>
</thead>
<tbody>
<tr>
<td>X$_{Thorax}$: +Right</td>
<td>Perpendicular to the plane formed by T7, ProcX, and C7</td>
</tr>
<tr>
<td>Y$_{Thorax}$: +Dorsal</td>
<td>T7 - ProcX</td>
</tr>
<tr>
<td>Z$_{Thorax}$: +Caudal</td>
<td>Perpendicular to X$_T$ and Y$_T$</td>
</tr>
</tbody>
</table>

4.2.5 Statistical analysis

First, descriptive statistics (mean ± standard deviation (SD)) were calculated for each movement direction (FE, LF, and ROT) at each time point (T1, T2, and T3). Then, prior to evaluating reliability of angular kinematics at discrete time points, analyses of
variance (ANOVA) for repeated measures (p < 0.05) were performed to detect potential systematic change in angular kinematics over time (Weir, 2005). For variables that did not show systematic change over time, reliability of both measurement systems was calculated using intraclass correlation coefficients (ICC) type 3,1 (Weir, 2005). In order to be consistent with previous reliability investigations of cervical spine kinematics (Bulgheroni et al., 1998; Gelalis et al., 2009; Theobald, Jones, & Williams, 2012; Tousignant-Laflamme, Boutin, Dion, & Vallée, 2013), ICCs were interpreted according to criteria described by Fleiss (1999) (ICC < 0.4 represents poor reliability, 0.4 – 0.75 fair to good, and >0.75 excellent). In addition, standard error of the measurement of the true score (SEM), minimal detectable change (MDC) were calculated (Weir, 2005) (Appendix 5). Results describing reliability at discrete time points (ICC, SEM and MDC) were calculated for all participants, as well for the two sub-groups (players and non-players) separately. Reliability of kinematic curves was evaluated using coefficient of multiple correlation (CMC) (Kadaba et al., 1989) and standard deviation (Curve SD).

Analyses were performed using SPSS (version 22, IBM Corporation, Armonk, NY, USA) (ANOVA, ICC), Microsoft Excel 2010 (Microsoft, Redmond, WA, USA) (SEM, MDC), and MATLAB (CMC, Curve SD).

4.3 Results

Descriptive statistics are presented in Table 4.2. All ANOVAs for repeated measures were non-significant (p = 0.07 – 0.92).

Overall reliability values at discrete time points ranged between 0.44 and 0.95 for ICCs, and between 1 and 7°, and 3 and 20° for SEM and MDC values, respectively (Table
4.3). Table 4.4 and Table 4.5 present ICC, SEM and MDC results for player and non-player participants, respectively.

Standard deviation values of kinematic curves ranged between 2 and 6°, while CMC values ranged between 0.5 and 0.69, with one complex number 0.51+0.03i (Table 4.6).

Figure 4.2 illustrates kinematics from all movement directions in a representative participant.

<table>
<thead>
<tr>
<th></th>
<th>Vicon</th>
<th>Polhemus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FE</td>
<td>LF</td>
</tr>
<tr>
<td>T1</td>
<td>-29 (±16)</td>
<td>1 (±5)</td>
</tr>
<tr>
<td></td>
<td>-15 (±16)</td>
<td>0 (±8)</td>
</tr>
<tr>
<td>T2</td>
<td>-5 (±26)</td>
<td>2 (±7)</td>
</tr>
</tbody>
</table>

Table 4.2

Descriptive statistics (mean ± SD) of cervical spine kinematics [°] for each movement direction (FE, LF and ROT) at each time point (T1, T2, and T3) for both measurement systems (Vicon and Polhemus).
Table 4.3
Overall reliability results for discrete time points (T1-T3).

<table>
<thead>
<tr>
<th></th>
<th>Vicon</th>
<th>Polhemus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC (95% CI)</td>
<td>SEM (95% CI)</td>
</tr>
<tr>
<td>FE</td>
<td>0.86 (0.71-0.96)</td>
<td>6 (5-6)</td>
</tr>
<tr>
<td>T1</td>
<td>LF 0.88 (0.75-0.97)</td>
<td>2 (1-2)</td>
</tr>
<tr>
<td></td>
<td>ROT 0.94 (0.86-0.98)</td>
<td>1 (1-2)</td>
</tr>
<tr>
<td></td>
<td>FE 0.95 (0.88-0.99)</td>
<td>4 (2-5)</td>
</tr>
<tr>
<td>T2</td>
<td>LF 0.90 (0.79-0.97)</td>
<td>3 (1-3)</td>
</tr>
<tr>
<td></td>
<td>ROT 0.47 (0.22-0.79)</td>
<td>2 (1-2)</td>
</tr>
<tr>
<td></td>
<td>FE 0.92 (0.83-0.98)</td>
<td>7 (4-10)</td>
</tr>
<tr>
<td>T3</td>
<td>LF 0.88 (0.75-0.97)</td>
<td>2 (1-3)</td>
</tr>
<tr>
<td></td>
<td>ROT 0.66 (0.42-0.89)</td>
<td>2 (1-2)</td>
</tr>
</tbody>
</table>

ICC (95% CI): Intraclass correlation coefficient (3,1) with 95% confidence intervals, SEM: Standard error of the measurement [], MDC: Minimal detectable change [].
T1: Beginning of trial, T2: Instant of impact, T3: Sustained push.
Table 4.4

Reliability results for discrete time points (T1-T3) in player participants.

<table>
<thead>
<tr>
<th></th>
<th>Vicon</th>
<th>Polhemus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC (95% CI)</td>
<td>SEM (95% CI)</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.96 (0.94-0.99)</td>
<td>3 (1-3)</td>
</tr>
<tr>
<td>LF</td>
<td>0.92 (0.74-0.99)</td>
<td>2 (1-3)</td>
</tr>
<tr>
<td>ROT</td>
<td>0.94 (0.81-0.99)</td>
<td>1 (1-2)</td>
</tr>
<tr>
<td>T2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.95 (0.81-0.99)</td>
<td>2 (1-4)</td>
</tr>
<tr>
<td>LF</td>
<td>0.97 (0.87-0.99)</td>
<td>2 (1-3)</td>
</tr>
<tr>
<td>ROT</td>
<td>0.68 (0.30-0.97)</td>
<td>2 (1-2)</td>
</tr>
<tr>
<td>T3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.87 (0.60-0.99)</td>
<td>4 (1-5)</td>
</tr>
<tr>
<td>LF</td>
<td>0.91 (0.71-0.99)</td>
<td>2 (1-3)</td>
</tr>
<tr>
<td>ROT</td>
<td>0.83 (0.53-0.99)</td>
<td>1 (0-2)</td>
</tr>
</tbody>
</table>

ICC (95% CI): Intraclass correlation coefficient (3,1) with 95% confidence intervals, SEM: Standard error of the measurement [°], MDC: Minimal detectable change [°]
FE: Flexion/extension, LF: lateral-flexion, ROT: axial rotation
T1: Beginning of trial, T2: Instant of impact, T3: Sustained push
Table 4.5
Reliability results for discrete time points (T1-T3) in non-player participants.

<table>
<thead>
<tr>
<th></th>
<th>Vicon</th>
<th>Polhemus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC (95% CI)</td>
<td>SEM (95% CI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.73 (0.41-0.96)</td>
<td>7 (5-8)</td>
</tr>
<tr>
<td>LF</td>
<td>0.78 (0.49-0.97)</td>
<td>1 (0-1)</td>
</tr>
<tr>
<td>ROT</td>
<td>0.71 (0.38-0.96)</td>
<td>1 (1-2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.95 (0.85-0.99)</td>
<td>4 (3-4)</td>
</tr>
<tr>
<td>LF</td>
<td>0.82 (0.55-0.98)</td>
<td>2 (2-3)</td>
</tr>
<tr>
<td>ROT</td>
<td>0.18 (0.04-0.75)</td>
<td>1 (1-2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.77 (0.47-0.97)</td>
<td>7 (6-8)</td>
</tr>
<tr>
<td>LF</td>
<td>0.85 (0.62-0.98)</td>
<td>2 (1-2)</td>
</tr>
<tr>
<td>ROT</td>
<td>0.40 (0.09-0.87)</td>
<td>1 (1-2)</td>
</tr>
</tbody>
</table>

ICC (95% CI): Intraclass correlation coefficient (3,1) with 95% confidence intervals, SEM: Standard error of the measurement [°], MDC: Minimal detectable change [°]
FE: Flexion/extension, LF: lateral-flexion, ROT: axial rotation
T1: Beginning of trial, T2: Instant of impact, T3: Sustained push

Table 4.6
Reliability results for kinematic curves.

<table>
<thead>
<tr>
<th></th>
<th>Vicon</th>
<th>Polhemus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CMC</td>
<td>Curve SD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.69</td>
<td>6</td>
</tr>
<tr>
<td>LF</td>
<td>0.51 + 0.03i</td>
<td>2</td>
</tr>
<tr>
<td>ROT</td>
<td>0.50</td>
<td>2</td>
</tr>
</tbody>
</table>

CMC: Coefficient of multiple correlation, Curve SD: Standard deviation of kinematic curves [°]
FE: Flexion/extension, LF: lateral-flexion, ROT: axial rotation
4.4 Discussion

To help researchers opt for the most appropriate system for measuring cervical spine kinematics during scrums, this study assessed test-retest reliability of an EMT and optoelectronic motion capture system during this task.

The overall results suggest that both systems have comparable reliability. In both systems, ICCs were generally considered to be excellent (Fleiss, 1999) with seven out of nine values being > 0.75. Moreover, both systems showed fair to good reliability values in the same movement directions and at the same time points (i.e. ROT at impact.
and during the sustained push). An examination of the raw data revealed that within- and between-subject variability differed by a smaller amount in lower, compared to higher ICC values. For example, for ROT at impact, the ICC value was 0.48 (EMT data), and within- and between-subject variability was 4° and 5°, respectively (i.e. difference of 1°). In contrast, for FE at impact, the ICC value was 0.90 (EMT data), and within- and between subject variability was 4° and 14°, respectively (i.e. difference of 10°). A small between-subject variability is likely to explain the moderate ICC values, since it is known that ICC values are negatively affected by low between-subject variability (Weir, 2005).

Similarly, CMC calculations are sensitive to factors like the amplitude of movement investigated (Røislien, Skare, Opheim, & Rennie, 2012). Such constraints may explain the moderate values and the complex number obtained in this study.

It should be noted that there is no universal criteria to evaluate relative reliability indices (e.g. ICC and CMC) (Portney & Watkins, 1993) and that qualifiers, such as 'excellent' for an ICC value, should be interpreted with caution (Charter & Feldt, 2001; Portney & Watkins, 1993; Weir, 2005). The interpretation should be adapted to the investigated topic and in the light of absolute reliability results, such as SEM and MDC, to put the results into perspective (Weir, 2005).

In relation to SEM and MDC values, both measurement systems appeared again to vary similarly, with consistently lower values for LF and ROT, and higher values for FE. This pattern further supports the notion of comparable reliability across both systems. These results suggest that higher values in FE were due to decreased repeatability in head movement, which was indeed conceivable in this study because a scrum machine does not constrain head movements in extension (Preatoni, Stokes, England, &
Trewartha, 2012). In practice, the higher MDC values in FE indicate that a relatively large change in these values would be required to be confident a true change had occurred. In a contested scrum, however, the head is forced in a flexed position, such that a more consistent movement pattern might be observed in this scrum variation, but this warrants further investigation.

In the present study, only a small sample size has been included (N= 9) with participants of heterogeneous abilities. However, the 95% CI demonstrated that SEM values were relatively stable with deviations of only 0 – 3° from mean SEM. Moreover, a comparison of the overall results with the two sub-groups showed that the inclusion of inexperienced participants did not artificially 'inflate' ICC values. These results actually revealed that practicing the scrum reduces within-subject movement variability, since most ICC values were higher for experienced players than for non-player participants. This point is further supported by most of the SEM and MDC values, which were substantially lower in players than in non-players. Indeed, SEM and MDC were even lower in players than in non-players when ICC values were low. For example, for ROT at the beginning of the trial, ICC was 0.23 in players as opposed to 0.89 in non-players (EMT data). However, SEM and MDC were only 1° and 3° in players respectively, compared to 2° and 6° in non-players.

There is one limitation associated with the use of EMT for field-based measures. In this study, T1-T4 were identified using the optoelectronic motion capture system, but in the field, where it is impossible to have an equivalent system, this task would become more difficult. One possibility, if investigating contested scrums, could be to place sensors on opponents and define the moment of impact as the time point at which the smallest distance between the sensors on both opposed players is first achieved. Nevertheless, the difficulty of identifying specific time points in kinematic measurements is a problem.
common to every non vision-based measurement system, including inertial sensors (Swaminathan et al., 2016a).

In conclusion, EMT and optoelectronic motion capture systems demonstrated similar reliability, although optoelectronic motion capture appeared to provide slightly more reliable results. However, this is in line with previous work (Koivukangas, Katisko, & Koivukangas, 2013; Lugade et al., 2015) and both systems are considered to be adequately reliable to measure cervical spine kinematics during repeated scrums, for example under different conditions or before and after an intervention. Nevertheless, detecting changes in FE patterns may be difficult when investigating scrums performed against a scrum machine.
References


mechanism underpinning injury? *British Journal of Sports Medicine, 46*(8), 545–549.


Swaminathan, R., Williams, J. M., Jones, M. D., & Theobald, P. S. (2016b). Does the new rugby union scrum sequence positively influence the hooker’s in situ spinal kinematics? *BMJ Open Sport & Exercise Medicine, 2*(1), e000064.


CHAPTER 5

Close-range photogrammetry for the measurement of spinal kinematics in rugby union scrums

This chapter includes a co-authored paper. The paper has been submitted for publication in *Sports Engineering* and is currently under review:

Declaration of co-authorship and contribution

The candidate's contribution to this article was as follows:

- conception and design of the research project
- analysis and interpretation of research data
- drafting and editing manuscript

[Signature] 18 September 2018

Student and Corresponding author of paper: Adrien Cerrito

[Signature] 18 September 2018

Supervisor and co-author: Professor Peter Milburn
5.1 Introduction

Rugby union (rugby) has relatively high injury rates (47-81 injuries/1000 player hours) (Williams, Trewartha, Kemp, & Stokes, 2013; Yeomans et al., 2018) compared to other team sports, such as soccer (33 injuries/1000 player hours) (Stubbe et al., 2015). The rugby scrum is an event with particularly high injury rate (8.1 injuries/1000 scrums) (Fuller, Brooks, Cancea, Hall, & Kemp, 2007), given it involves two formations of eight players from each team pushing against each other with forces of up to 16.5 kN to compete for ball possession (Preatoni, Stokes, England, & Trewartha, 2013). More specifically, a large proportion of spinal injuries occur in front-row players who are in direct contact with the opposing team during scrums (41-71%) (Brooks, Fuller, & Kemp, 2005). Therefore, biomechanical research into spinal motion patterns is needed to better understand injury mechanisms and prevent these injuries (Dennison, Macri, & Cripton, 2012; Trewartha, Preatoni, England, & Stokes, 2015).

However, while measuring kinematics of simple tasks is not difficult using reference standard methods (i.e. optoelectronic motion capture), sports movements can be more complex and difficult to record. For example, the use of optoelectronic motion capture systems requires attachment of retro-reflective markers, which can detach during sports performance. Reattaching markers can then introduce errors due to inconsistencies in marker placement. Moreover, because retro-reflective markers are not flat, the risk of detachment is exacerbated with increasing number of players in the capture volume due to interactions between players. However, decreasing the number of athletes or players in the capture volume jeopardises the authenticity due to the simulated nature of the measurement protocol. Similar problems arise as optoelectronic motion capture systems are typically not portable. Therefore, data collection is most often performed in a laboratory, affecting the ecological validity, which is an important feature in sports.
sciences (Davids, 1988; Jobson et al., 2007). Nevertheless, despite these limitations, optoelectronic motion capture remains the current benchmark motion capture technique in sport sciences (van der Kruk & Reijne, 2018). These issues are particularly pronounced in investigations of the spine during complex tasks, such as scrummaging, due to the many players involved and the forceful interactions between players. Therefore, researchers often choose to investigate single players scrummaging against a static scrum machine to reduce that risk and improve measurement quality (Cazzola, Trewartha, & Preatoni, 2016; Milburn, 1990; Rodano & Tosoni, 1992; Sayers, 2008; Wu, Chang, Wu, & Guo, 2007). However, the number of players involved in the scrum is peculiar to the event, such that reducing the number of players does not truly replicate real scrummaging conditions.

Inertial sensors have recently been used as an alternative measurement method to measure spinal kinematics during contested scrums (Swaminathan, Williams, Jones, & Theobald, 2016a, 2016b). However, inertial sensors also have multiple disadvantages compared to optical systems, such as being affected by drifting artefacts (You, Neumann, & Azuma 1999). Moreover, the risk of detachment is not reduced compared to retro-reflective markers since sensors remain bulky. Also, detecting key events of the scrum (e.g. impact at engagement) is difficult from inertial data, such that these data are limited to movement excursion over entire scrummaging trials.

Recently, other methods have been developed to address the issues with optoelectronic motion capture systems and could represent alternatives to measure spinal kinematics during scrums. Inexpensive, portable equipment, such as digital single-lens reflex (DSLR) cameras have been successfully used in photogrammetric analyses of animal locomotion (Jackson, Evangelista, Ray, & Hedrick, 2016), disease progression in neurological pathologies (Chong, 2011), and diurnal spine shrinkage in young adults.
(Chong, Milburn, Newsham-West, & Voert, 2009). However, although the use of low-cost cameras has potential in sports-related close-range photogrammetry applications (Magre Colorado & Martínez Santos, 2015), consumer-grade cameras lack features found in professional equipment. For example, there is no hardware synchronisation of multiple DSLR cameras and lens parameters are not calibrated. Therefore, before outdoor accurate photogrammetric measurements of scrums can be performed using a system of consumer-grade cameras, characteristics of the system as well as limitations and quality of the data must be examined. Thus, the aim of this research was to investigate whether a system of five DSLR cameras is a viable method for measuring 3D spinal kinematics during scrums.

5.2 Equipment

5.2.1 Imaging system

The imaging system consisted of a wooden frame supporting five cameras approximately 2.3 m from the ground, and a hanging control frame (Figure 5.1). Cameras were aligned in a convergent set-up such that each camera viewed a portion of the control frame and a participant’s spine.

Five Panasonic Lumix DMC-Fz300 (Panasonic Corp., Osaka, Japan) cameras, with an advertised focal length of 4.5 – 108 mm, sensor size of 6.2 x 4.6 mm, and pixel size of 0.0027 mm, were used. The cameras were used in video recording mode at a sampling frequency of 50 frames per second (fps) and a resolution of 1920 x 1080 pixels. To decrease delay of shutter release, the autofocus function was disabled. Focus was therefore set in advance and kept constant during measurements. The shutter speed was 1/500 s to avoid motion blur.
Figure 5.1

Imaging system and laboratory-based experimental set-up: a) wooden frame supporting five DSLR cameras and the control frame. The figure illustrates the experimental set-up used for laboratory-based measurements with the Vicon cameras, the shutter remote control, the board with four retro-reflective targets, and the weighted collision-targets. The red dot indicates the location of the LED-based timing system; b) the five DSLR cameras in a convergent set-up.

5.2.2 Shutter remote control

A custom-built, wired remote control was designed to actuate all five shutter controls in parallel for initiation and interruption of camera shutter release.
5.2.3 Custom-designed LED-based timing system

A timing system was built using an Arduino Uno board (Arduino, NY, USA) with 18 LED lights (Figure 5.2) to synchronise all five cameras. Once triggered, a custom-written program actuated the LED lights in sequence such that each light represented a specific time unit. The resolution of the timing system was 5 ms and maximum time count was 15 s.

![Custom-designed LED-based timing system](image)

**Figure 5.2**

Custom-designed LED-based timing system used to determine consistency of camera frame rate, and to synchronise frames during data processing. Each LED light represented a specific time unit. For example, the figure illustrates an elapsed time of 4 tenth of a second (ds), 7 hundredth of a second (cs), and 5 thousandth of a second (ms).
5.3 Methods

5.3.1 Calibration procedures

5.3.1.1 Quality of camera calibration

Cameras were calibrated individually in a laboratory using the self-calibration method (Chong et al., 2009). Calibration involved determining the camera’s internal geometry (i.e. principal point (PP), offset (Xp and Yp), principal distance (PD), radial lens distortion parameters (K1, K2, K3), and lens alignment (P1 and P2)) (Luhmann, Robson, Kyle, & Boehm, 2014). Calibration was performed with a set of 16 convergent images of a high-precision invar scale bar (221 ± 0.01 mm length) placed on a rectangular photogrammetric test field. That is, one image was obtained from each edge, and one from each corner. All images were taken in upright and 90° rotated perspective (Chong et al., 2009). Bundle adjustment was carried out using Australis software (version 6.06 Photometrix, VIC, Australia). The calibration process was repeated five times for one camera from which the accuracy and reliability of point coordinate measures from 10 randomly selected targets could be calculated. The accuracy and reliability of calibration was assumed to be constant over all cameras. Accuracy and reliability were calculated in X, Y, and Z directions separately, as well as for 3D position vectors. To express accuracy and reliability, the ISO 5725-1:1994 (2007) standards were followed. Hence, Trueness, Precision and Uncertainty were used as outcomes. Trueness is defined as systematic measurement error and calculated as the average deviation from the true value. In this analysis, the ‘true’ target coordinate values were taken from the original file containing the calibration board's target coordinates. Precision and Uncertainty are measures of reliability, where Precision is the SD of repeated measures and Uncertainty is the 95.5% CI of the dispersion (i.e. two
times SD). In photogrammetry, Uncertainty has also been termed 'Coefficient of repeatability' (CR) (Kanellopoulos & Asimellis, 2015), but the terminology used in ISO 5725-1:1994 (2007) is used in this paper.

### 5.3.1.2 Quality of control frame calibration

A rectangular PVC frame (1.3 x 1.1 m) with 73 targets of different heights (0 – 22 mm) was attached to the camera support frame. Using one camera, 16 convergent images of a small calibrated test field and bridging targets in the centre of the control frame were taken at different angles, such that all 73 targets were visible on each image. These 16 images were used to calibrate the control frame. Reliability of calibration was tested by repeating the process five times. Reliability of 3D position vectors of 10 randomly selected targets was then analysed using Uncertainty because no ‘true’ value was known. In this case, however, SD was multiplied by 2.77 instead of 2 such that 99% certainty could be obtained. Increasing certainty was required in this calibration procedure as no invar scale bar was used. Moreover, given the control frame provides important information for photogrammetric calculations during data processing, it is preferable to report the highest possible measurement errors. In addition, Uncertainty values were expressed as a Relative Uncertainty, calculated as the percentage of the mean 3D vector of each randomly selected target. All target coordinates were expressed relative to a right-handed coordinate system in the object-space that was generated using three targets on the test field. One target was used to represent the coordinate system's origin, and the two others to indicate the positive direction of the X- and Y-axes. Together, the two axes formed a plane whose normal was considered to be the Z-axis.

### 5.3.1.3 Frame rate accuracy and consistency

The accuracy and consistency of the cameras’ frame rates was determined by placing all cameras on tripods pointing at the timing system. Once the system was triggered, the cameras recorded the timing system to 15 s. This procedure was repeated five times. Using a custom-written Python script (version 2.7.13) involving the OpenCV library (version 3.2.0), a frame
was extracted from each video clip where the timing system indicated 1s. Then, further frames were extracted at each subsequent second to determine and compare the number of frames recorded at the theoretical rate of 50 fps. The sum of 'exceeding' or 'missing' frames compared to the theoretical rate was calculated over the 14 s period and averaged for each camera. The mean and SD frame rate was also calculated for all cameras and for each individual camera.

5.3.2 Tracking accuracy and reliability in laboratory simulations

Accuracy and reliability of the photogrammetric application was first tested in a laboratory using four retro-reflective markers of 14 mm diameter attached to a board on wheels. The board was placed in the cameras' field of view 75 cm from the ground, which is the approximate height of a rugby player’s trunk during scrummaging (Figure 5.1). The four markers were simultaneously tracked using the five DSLR cameras and an optoelectronic motion capture system consisting of 12 Vicon cameras (Vicon T40STM, Oxford, UK) operating at 240 fps and Vicon NexusTM software (version 2.6.1). Initially, five static trials were recorded where the board was not moved. Then, 10 dynamic trials were recorded to simulate the dynamic phase of a scrum before players collide. The collision was simulated using weighted targets that the rolling board hit at the end of its trajectory (Figure 5.1). From pilot Vicon data recorded in front-row players during simulated scrums, the average forward peak velocity during the dynamic phase was 2.5 m/s that occurred 60 ms before impact. Hence, dynamic trials were designed such that the board reached a velocity of 2.5 ± 1 m/s 60 ms before impact. Impact was defined as the instant at which the front marker stopped moving in the simulated scrum direction.

For each static trial, the mid-trial frame was extracted in both measurement systems while for dynamic trials, one frame was extracted at impact (Impact) and one 60 ms before this point (Pre-impact). To ensure the best synchronisation between DSLR
cameras, the elapsed time indicated on the timing system was used to extract the correct frames (Figure 5.3).

Key still frames (mid-trial, Pre-impact and Impact) were extracted manually from each video file using Python and OpenCV. Extracted frames were digitised and bundle adjustment performed to obtain 3D coordinates of the four retro-reflective targets using Australis. Target coordinates were also obtained from Vicon data using Vicon NexusTM software. Coordinates from both data sets were then exported to Matlab (v. R2014a, MathWorks, MA, USA) where distances between two pairs of markers were separately calculated by subtracting position vectors. The two distances represented a cranio-caudal (CC) (i.e. along the spine) and a medio-lateral (ML) (i.e. side-to-side) line on a simulated player (Figure 5.3). Accuracy and reliability of distance measures were assessed using Trueness, Precision and Uncertainty. Reference values were obtained by averaging five repeated calliper measures of the distances between the two pairs of markers (Eichelberger et al., 2016). In addition to tracking distances, the orientation of the board was calculated and expressed as yaw, pitch and roll angles. Roll was calculated as rotation about the X-axis (i.e. CC distance), pitch as rotation around the Y-axis (approximately ML distance), and yaw around the normal of the plane created by X- and Y-axes (i.e. Z-axis) (Hull, 2007). To create a common coordinate system for both measurement systems, three additional retro-reflective markers were attached to the control frame (Craig, 2005). To evaluate accuracy of orientation measures, Bland-Altman analyses were performed (Bland & Altman, 2007) and the differences between Vicon and the tested photogrammetric application were plotted against the Vicon data only (i.e. reference standard) (Krouwer, 2008).
5.3.3 Tracking accuracy and reliability in field-based scrums

Accuracy and reliability was further assessed under more realistic conditions. Three front-row rugby union players were recruited to collect data in the field. Written informed consent from each participant and ethical approval from the institution’s ethics committee were obtained (Appendix 5). The board with four retro-reflective markers was attached to the tested player’s back such that the board’s X-axis was approximately aligned with the spine (Figure 5.3). Participants were asked to perform one-man scrums against a scrum machine and instructed to follow the regulatory scrum engagement call ‘crouch, bind, set’ provided by the researchers. Players performed practice trials until familiar with the protocol and apparatus and subsequently, five trials were then recorded for each participant. Still frames were extracted from the video clips at Pre-impact and at Impact and distances between the two pairs of markers were analysed in the same way as in the laboratory-based study.
Figure 5.3
Illustration of frames used to test tracking accuracy in a) laboratory, and b) rugby field environment. The cranio-caudal (CC) and medio-lateral (ML) distances between the two pairs of retro-reflective targets are illustrated. The elapsed time indicated on the LED-based timing system was used to synchronise data during data processing.

5.4 Results

5.4.1 Camera calibrations

The mean accuracy and reliability results of 10 randomly selected targets from the camera calibration process, as well as error ranges are presented in Table 5.1. The largest systematic measurement error did not exceed 3.20 mm and was found in a
target's 3D position vector. The lowest reliability was found in X coordinates with Precision and Uncertainty values of 0.49 and 0.98 mm, respectively.

### Table 5.1

<table>
<thead>
<tr>
<th></th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Z (mm)</th>
<th>3D (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Max</td>
<td>Min</td>
<td>Mean</td>
</tr>
<tr>
<td>T</td>
<td>2.56</td>
<td>3.02</td>
<td>1.89</td>
<td>1.12</td>
</tr>
<tr>
<td>P</td>
<td>0.49</td>
<td>0.54</td>
<td>0.42</td>
<td>0.20</td>
</tr>
<tr>
<td>U</td>
<td>0.98</td>
<td>1.08</td>
<td>0.83</td>
<td>0.39</td>
</tr>
</tbody>
</table>

5.4.2 Control frame calibration

The mean and SD for Uncertainty (U) and Relative Uncertainty (%U) are presented in Table 5.2 and show the estimation of targets' coordinates vary within 1.82 mm in 99% of calibration repetitions.

### Table 5.2

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>U (mm)</td>
<td>1.82</td>
<td>0.75</td>
</tr>
<tr>
<td>%U (%)</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

5.4.3 Frame rate

Cameras had a mean sampling frequency of 50.23 ± 0.01 fps, with an average of 3.16 ± 0.09 frames exceeding the 700 theoretical frames recorded in a 14 s period at 50 fps. For
each 1 s-interval and for each camera individually, the number of ‘excessive’ frames recorded was summed over the five trials (Table 5.3). From these results no clear pattern of occurrence of excessive frames could be identified, either within individual cameras, or between cameras.

Table 5.3
‘Excessive’ recorded frames summed over five trials for each 1s-interval.

<table>
<thead>
<tr>
<th></th>
<th>1-2</th>
<th>2-3</th>
<th>3-4</th>
<th>4-5</th>
<th>5-6</th>
<th>6-7</th>
<th>7-8</th>
<th>8-9</th>
<th>9-10</th>
<th>10-11</th>
<th>11-12</th>
<th>12-13</th>
<th>13-14</th>
<th>14-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera 1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Camera 2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Camera 3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Camera 4</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Camera 5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

5.4.4 Laboratory simulations

Calliper measures provided reference values for CC (368.21 ± 0.21 mm) and ML (68.07 ± 0.09 mm) distances. To put the accuracy and reliability results into perspective, T and U results are presented as absolute values and as a percentage (%T and %U, respectively) of the CC and ML distances (Table 5.4).

Data from the Vicon system showed that velocities of board movement at Pre-impact ranged between 1.63 and 3.34 m/s, with a mean ± SD of 2.47 ± 0.51 m/s.
The Bland-Altman plots (Figure 5.4) illustrate the agreement between the tested photogrammetric system and data from the Vicon system for orientation angles in static and dynamic (Pre-impact and Impact) trials. The results show a higher agreement between both measurement systems during static trials than during dynamic trials.

Table 5.4

Tracking accuracy in laboratory simulations. Accuracy and reliability are expressed as absolute and relative Trueness (T and %T), and Precision (P) and Uncertainty (U and %U), respectively.

<table>
<thead>
<tr>
<th></th>
<th>Static</th>
<th>Pre-impact</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC</td>
<td>ML</td>
<td>CC</td>
</tr>
<tr>
<td>T (mm)</td>
<td>0.17</td>
<td>0.20</td>
<td>0.60</td>
</tr>
<tr>
<td>%T (%)</td>
<td>0.0</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>P (mm)</td>
<td>0.09</td>
<td>0.14</td>
<td>7.63</td>
</tr>
<tr>
<td>U (mm)</td>
<td>0.18</td>
<td>0.28</td>
<td>15.27</td>
</tr>
<tr>
<td>%U (%)</td>
<td>0.1</td>
<td>0.4</td>
<td>4.2</td>
</tr>
</tbody>
</table>
Figure 5.4

Bland-Altman plots illustrating the mean measurement errors (solid lines) and 95% limits of agreement (dotted lines) between both measurement systems (tested system vs. Vicon) in measuring orientation angles: a) yaw, b) pitch, and c) roll.
5.4.5 Field-based scrums

The accuracy results for the field-based tests are presented in Table 5.5 and show some Uncertainty values are greater than in the laboratory-based study. Thus, simulations were performed using samples of the data at Pre-impact and Impact from the collected 15 trials (i.e. 30 data points) to determine the acceptability of the method for field-based investigations. The goal was to determine the minimum number of data points needed to achieve an average measurement error of ± 2 mm or lower. For this purpose, samples of ten, seven, five, and three randomly selected data points out of the 30 were generated and repeated 100 times using a custom-written Matlab program. The results show that with only three measures, an average error of -1.56 ± 2.38 mm could be achieved.

Table 5.5

<table>
<thead>
<tr>
<th></th>
<th>Pre-impact</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC</td>
<td>ML</td>
</tr>
<tr>
<td>T (mm)</td>
<td>-2.44</td>
<td>0.39</td>
</tr>
<tr>
<td>%T (%)</td>
<td>-0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>P (mm)</td>
<td>4.34</td>
<td>1.65</td>
</tr>
<tr>
<td>U (mm)</td>
<td>8.69</td>
<td>3.30</td>
</tr>
<tr>
<td>%U (%)</td>
<td>2.4</td>
<td>4.9</td>
</tr>
</tbody>
</table>

5.5 Discussion

A novel photogrammetric application is proposed for the measurement of spinal kinematics during rugby union scrummaging.

The quality of camera and control frame calibrations was first assessed. The mean Trueness (2.79 mm) and Uncertainty (0.01 mm) results suggest that the cameras used
can provide sufficiently accurate and reliable measures. To put this in context, errors due to soft-tissue artefacts on the players’ back are likely to be much larger. Mean (± SD) discrepancies between targets and anatomical landmark of up to 10.7 ± 4.8 mm and peak errors of 27.4 mm have been reported in a young and healthy population (Zemp et al., 2014). In addition, although the results of the present study show larger errors than for manual calibration of optoelectronic motion capture systems (accuracy of 0.12 ± 0.02 mm) (Windolf, Götzen, & Morlock, 2008), it is accepted that accuracy and reliability of measures are likely to be reduced in any field-based measurement applications (Rodano, 2002). Results from the control frame calibration (mean Uncertainty of 1.82 mm) also suggested high reliability.

The accuracy and consistency of the five cameras' frame rate was then evaluated using an LED-based synchronised timing system. This analysis showed that all cameras had similar, but not identical frame rates. Moreover, no consistent error pattern could be identified amongst the five cameras. These results highlight the importance of synchronisation during data processing and correcting for different capture onsets and camera internal clock drifting rates (Jackson et al., 2016; Welty, Bartholomaus, O’Neel, & Pfeffer, 2013). At a scrummaging speed of 2.5 m/s before impact, a discrepancy of one frame can create errors of up to 5 cm at 50 fps, which is large in the context of spinal kinematics. Jackson et al. (2016) proposed a method to account for the difference in capture onset using an audio signal recorded along with the scene of interest and that allows synchronisation after data collection. However, their method does not correct for different drifting rates. In the case of a visual-based synchronisation device, such as the timing system used in this study, automatic tracking of the time recorded could be conceivable using tools found in the field of computer vision. For example, OpenCV is an open-source software library that allows image and video processing, such as object,
pattern and/or colour tracking. Using such functions could potentially decipher the LED light code from the timing system and automatically convert it to a time stamp. Time stamps between video clips from different cameras could then be compared to allow only frames that are synchronised within a certain time window to be used for bundle adjustment.

Tracking accuracy and reliability for the estimation of distance and object orientation was then investigated and compared to a reference standard (Vicon). Vicon data showed that dynamic tests were performed at velocities ($2.47 \pm 0.51$ m/s) that were close to the scrummaging velocity found in the pilot data (2.5 m/s). Average Trueness and Uncertainty of 0.4% and 1.9% respectively, show that the general distance measurement accuracy and reliability is very high. For optoelectronic motion capture systems, Chiari, Croce, Leardini and Cappozzo (2005) reported error values in distance measurements during static trials of $0.10 - 1.30$ mm (accuracy) and $0.53 - 3.50$ mm (precision), which is comparable to $0.17 - 0.20$ mm (accuracy) and $0.09 - 0.14$ mm (precision) found in the present study. Moreover, accuracy is also comparable to that from spinal measurements in standing position ($0.74 \pm 0.4$ mm) (Chong et al., 2009). During dynamic trials, Uncertainty increases with higher object velocity (Pre-impact), but returns to clinically insignificant levels at Impact. This phenomenon is also known in optoelectronic motion capture systems, where Uncertainty values have reportedly increased up to 47 times in dynamic compared to static trials in a system of six cameras (Eichelberger et al., 2016).

Regarding object orientation, the current results also reveal higher agreement between both measurement systems during static trials than during dynamic trials. Nevertheless, the overall accuracy of the photogrammetric application in measuring orientation angles is considered to be excellent, with average measurement errors $\pm 95\%$ limits of agreement of $0 \pm 2^\circ$, $1 \pm 4^\circ$, and $-2 \pm 5^\circ$ for yaw, pitch, and roll, respectively.
Tracking accuracy and reliability was then investigated on-field with front-row players. Field-based measures showed slightly larger values with average relative Trueness and Uncertainty of 0.5% and 2.9% of the true distances, respectively. The better results found in the laboratory test could be explained by the fact that static trials were included in the mean calculations, which was not the case for field-based test results. Moreover, the movement performed by players on the field was likely to be more complex than the movement tracked in the laboratory. Comparison with literature on optoelectronic motion capture systems is difficult since accuracy and reliability for field-based measurements of sports kinematics have rarely been reported. However, Spörri, Schiefermüller and Müller (2016) investigated systematic (accuracy) and random (reliability) error in between-marker distance measurements using an optoelectronic motion capture system on a ski slope. Values ranging from 0.30 to 0.60 mm for accuracy, and from 0.30 to 0.40 mm for precision were reported, depending on the length of the measured reference distance. One distance was of similar length (390 mm) to the cranio-caudal distance in the present study (368 mm), for which Spörri et al. (2016) reported higher accuracy (0.60 mm) and precision (0.40 mm) than the present study at Pre-Impact (-2.44 mm and 4.34 mm, respectively). However, accuracy results at Impact (-0.88 mm) are comparable to those found in Spörri et al. (2016), which is important since Impact in scrummaging is of greater clinical significance. Although Precision at Impact (4.60 mm) is lower than in the results reported by Spörri et al. (2016), average measurement error can still be considered comparable to commercially available optoelectronic motion capture systems (≤ 2 mm) (Merriaux, Dupuis, Boutteau, Vasseur, & Savatier, 2017), given average measurement error of -1.56 mm is achieved with only three measures. In addition to having comparable measurement quality, the proposed photogrammetric application also has three notable advantages over
optoelectronic motion capture systems. First, markers used with the proposed photogrammetric application can be painted on the skin to avoid detachment issues faced with retro-reflective markers. Secondly, changes in lighting conditions are less likely to jeopardise measurement quality. In this study, field-based measurements were performed at night using a simple LED-based system to provide sufficient lighting yet can also be used during the day. In contrast, for example Spörri et al. (2016) were forced to perform data field-based collection at night due to the fact that optoelectronic motion capture systems use infrared-based cameras, which can suffer interference under bright lighting conditions. Finally, the application presented in this study used consumer-grade cameras, making it more accessible than expensive optoelectronic motion capture systems.

In this project, cameras recorded video files at a sampling rate of 50 fps. We acknowledge that higher sampling rates would increase accuracy and reliability, but the intention was to develop and demonstrate an application that could be used with commercially available DSLR cameras and therefore maximise the accessibility of the proposed method.

### 5.6 Conclusion

This paper presents the development and validation of a photogrammetric system for the measurement of spinal kinematics during scrums. The aim was to determine the viability of the developed photogrammetric application for on-field measurements.

The developed method consists of a simple measurement set-up that uses five off-the-shelf DSLR cameras to accurately and reliably track targets and object orientation, even
in the field. Therefore, this system can safely be used to investigate spinal kinematics during sports techniques, such as scrummaging in rugby.
References


Assessing the Feasibility of Bringing the Biomechanics Lab to the Field. *PLoS One, 11*(8), e0161757.


Swaminathan, R., Williams, J. M., Jones, M. D., & Theobald, P. S. (2016b). Does the new rugby union scrum sequence positively influence the hooker’s in situ spinal kinematics? *BMJ Open Sport & Exercise Medicine, 2*(1), e000064.


CHAPTER 6

Kinematics of the axial skeleton during one-man rugby union scrums

This chapter includes a co-authored conference paper. The paper has been presented at the 35th International conference on biomechanics in sports (2017) in Cologne, Germany. The paper has also been published in the Proceedings of the 35th International Conference of Biomechanics in Sports.

Declaration of co-authorship and contribution

The candidate's contribution to this article was as follows:

- conception and design of the research project
- analysis and interpretation of research data
- drafting and editing manuscript

______ 18 September 2018

Student and Corresponding author of paper: Adrien Cerrito

________________ 18 September 2018

Supervisor and co-author: Professor Peter Milburn
6.1 Introduction

Spinal kinematics during Rugby Union (Rugby) scrummaging has been investigated previously with respect to performance improvement and injury prevention. To date, most kinematic studies have considered the spine as one rigid segment (Cazzola, Preatoni, Stokes, England, & Trewartha, 2015; Wu, Chang, Wu, & Guo, 2007). While Swaminathan, Williams, Jones and Theobald (2016a, 2016b) divided spinal kinematics into five spinal regions, these studies examined the effect of factors that are extrinsic to the basic scrum movement (i.e. playing surface and engagement sequence), rather than investigating factors independent of external changes (e.g. individual technical skills). Moreover, these studies were based on analyses of full scrums involving the usual 16 players, even though it is recognised that full scrums are complex events where the interaction between players has the potential to influence an individual’s kinematics. Player interactions may increase the risk of injury and/or decrease performance, especially if there is a lack of spinal control.

Practicing scrums with a focus on keeping spinal control in a consistent "straight, flat back" posture is a common component of players' training programs (O’Shea, 2003). Coaches frequently 'decompose' the scrum, where, for example, individual players scrummage against a scrum machine or one or two opponents, to repeatedly practice technical skills and minimize deviation from the 'ideal' scrum technique (O’Shea, 2003). However, while repeated and consistent practice is often employed to achieve expert movement, the importance of within- and between-individual movement variability in skilled performance and injury prevention has gained attention over recent years. For example, movement variability in tasks such as the javelin throw (Bartlett, Wheat, & Robins, 2007) has been found to be greater in skilled compared to less-skilled athletes. Hence, investigating kinematics and movement variability of the axial skeleton (head,
thorax, spine, and pelvis) during scrums will provide better understanding of movement expertise and spinal injury mechanisms, especially if the effect of different player interactions is controlled. A logical first step would be to determine movement variability (representative of spinal control) during the simplest version of the task i.e. a one-man scrum. Therefore, this study aimed to investigate the repeatability of axial skeleton kinematics during one-man scrums.

6.2 Methods

Nine male front row players (mean ± SD age, 23.8 ± 4.6 years; height, 1.81 ± 0.06 m; weight, 105.2 ± 10.0 kg; years playing in front row, 6.9 ± 6.5 years) attended one testing session in a laboratory (Appendix 4). Relative kinematics between 3D body segments (head, thorax, and pelvis) and for the spine, represented by four connecting vectors (upper and lower thoracic and lumbar spines), were measured using an optoelectronic motion capture system consisting of 12 infrared cameras (Vicon T40S cameras, Vicon, Oxford, UK) and the Vicon Nexus software (v2.2.1, Vicon, Oxford, UK). Data were sampled at 240 Hz. A set of 14 reflective markers was used to track segmental kinematics and to create LCSH (four markers on a head band), LCS_T (xiphoid process, spinous processes of C7 and T7) and local coordinate system for the pelvis (LCS_P) (both posterior and anterior iliac spines). The four spinal vector segments were defined using markers attached to the spinous processes of C7, the 7th (T7) and 12th (T12) thoracic and the 3rd (L3) and 5th (L5) lumbar vertebrae. Relative orientations between the 3D segments were calculated with a rotation sequence representing 1) FE, 2) LF, and 3) ROT (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2014). Kinematics of spinal vector segments were calculated in FE and LF using the fixed angle method (Craig,
Hence, a total of five joints with two (FE, LF) or three (FE, LF, ROT) degrees of freedom were investigated, producing 12 joint angles.

Following a standardised 10-minute warm-up and marker application, ROM of the cervical spine was measured in FE, LF, and ROT. Participants were familiarised with the test procedure and practiced at least three times before data were collected from seven one-man scrums against the machine.

Impact was defined as the point at which the C7 marker stopped moving in the scrum direction. The beginning of the trial (T1) was then defined as 1 s before impact (T2), and the sustained push phase (T3), and the end of the trial (T4) as 2.5 s and 5 s after T2 respectively. All data were filtered using a 2nd order, zero-lag Butterworth filter with a cut-off frequency of 6 Hz (Swaminathan et al., 2016b). Descriptive statistics, intraclass correlation coefficients (ICC3,1), and minimal detectable change (MDC) (Weir, 2005) were calculated for the 12 joint angles at three time points (T1-T3) (i.e. for 36 joint angles). Repeatability of segmental kinematics was also calculated for the entire scrum motion using the coefficient of multiple correlation (CMC) and SD of kinematic curves.

6.3 Results

The average cervical spine ROM amplitudes were 98° (FE), 68° (LF), and 142° (ROT). During scrums, participants used, on average, 39.1% (FE), 12.2% (LF), and 5.2% (ROT) of their cervical spine motion capacity. Repeatability of joint kinematics at discrete time points is presented in Table 6.1. Relative repeatability of kinematic curves showed CMC values ranging from 0.26 + 0.12i to 0.78. In terms of absolute kinematic curve repeatability, the mean SD of the kinematic curves ranged from 1° – 4°. Figure
6.1 illustrates a mean FE curve (±SD) of the head relative to the thorax in a representative participant.

Table 6.1
Joint kinematic repeatability at discrete time points (T1-T3) for flexion/extension (FE), lateral-flexion (LF) and axial rotation (ROT).

<table>
<thead>
<tr>
<th>Joint</th>
<th>ICC (95% CI)</th>
<th>MDC (°)</th>
<th>ICC (95% CI)</th>
<th>MDC (°)</th>
<th>ICC (95% CI)</th>
<th>MDC (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T1</td>
<td></td>
<td>T2</td>
<td></td>
<td>T3</td>
<td></td>
</tr>
<tr>
<td>H-T</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.92 (0.83 – 0.98)</td>
<td>8</td>
<td>0.78 (0.57 – 0.93)</td>
<td>11</td>
<td>0.78 (0.58 – 0.93)</td>
<td>9</td>
</tr>
<tr>
<td>LF</td>
<td>0.86 (0.71 – 0.96)</td>
<td>5</td>
<td>0.89 (0.75 – 0.97)</td>
<td>6</td>
<td>0.84 (0.66 – 0.95)</td>
<td>6</td>
</tr>
<tr>
<td>ROT</td>
<td>0.93 (0.84 – 0.98)</td>
<td>4</td>
<td>0.49 (0.23 – 0.80)</td>
<td>5</td>
<td>0.77 (0.55 – 0.93)</td>
<td>5</td>
</tr>
<tr>
<td>T-P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.95 (0.88 – 0.99)</td>
<td>7</td>
<td>0.84 (0.67 – 0.95)</td>
<td>8</td>
<td>0.90 (0.78 – 0.97)</td>
<td>8</td>
</tr>
<tr>
<td>LF</td>
<td>0.92 (0.82 – 0.98)</td>
<td>5</td>
<td>0.87 (0.73 – 0.96)</td>
<td>5</td>
<td>0.69 (0.46 – 0.90)</td>
<td>5</td>
</tr>
<tr>
<td>ROT</td>
<td>0.89 (0.75 – 0.97)</td>
<td>4</td>
<td>0.85 (0.69 – 0.96)</td>
<td>5</td>
<td>0.87 (0.72 – 0.96)</td>
<td>5</td>
</tr>
<tr>
<td>UTs-LTs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.98 (0.94 – 0.99)</td>
<td>2</td>
<td>0.91 (0.80 – 0.98)</td>
<td>4</td>
<td>0.93 (0.84 – 0.98)</td>
<td>5</td>
</tr>
<tr>
<td>LF</td>
<td>0.94 (0.87 – 0.99)</td>
<td>5</td>
<td>0.84 (0.66 – 0.95)</td>
<td>5</td>
<td>0.88 (0.74 – 0.97)</td>
<td>6</td>
</tr>
<tr>
<td>LTs-ULs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.95 (0.89 – 0.99)</td>
<td>3</td>
<td>0.78 (0.58 – 0.93)</td>
<td>4</td>
<td>0.93 (0.83 – 0.98)</td>
<td>4</td>
</tr>
<tr>
<td>LF</td>
<td>0.86 (0.70 – 0.96)</td>
<td>3</td>
<td>0.83 (0.66 – 0.95)</td>
<td>3</td>
<td>0.95 (0.88 – 0.99)</td>
<td>3</td>
</tr>
<tr>
<td>ULs-LLs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>0.97 (0.92 – 0.99)</td>
<td>3</td>
<td>0.87 (0.73 – 0.96)</td>
<td>6</td>
<td>0.93 (0.84 – 0.98)</td>
<td>7</td>
</tr>
<tr>
<td>LF</td>
<td>0.95 (0.88 – 0.99)</td>
<td>2</td>
<td>0.95 (0.88 – 0.99)</td>
<td>3</td>
<td>0.91 (0.80 – 0.98)</td>
<td>3</td>
</tr>
</tbody>
</table>

H-T: Kinematics between the head and thorax, T-P: Thorax-pelvis, UTs-LTs: Upper thoracic-lower thoracic spine, LTs-ULs: Lower thoracic-upper lumbar spine, ULs-LLs: Upper lumbar-lower lumbar spine

All ICC values were statistically significant with p< 0.001
Discussion

This study explored axial skeleton kinematics and repeatability of Rugby players during one-man scrums. Compared to previous studies, players used less of their available cervical spine ROM during the one-man scrum task than when performing full scrums (Swaminathan et al., 2016a). The decreased amplitude of cervical movement observed is likely due to the simplicity of the simulated scrum task against a scrum machine, compared to the complex interactions between players that occur in full scrums.
Relative repeatability results were mixed. Intraclass correlation coefficients were generally high with 34 out of 36 ICCs higher than 0.71. Conversely, nine out of 12 CMC values were considered low to moderate. Only the three kinematic curves representing FE between the four vector segments showed CMC values between 0.71 – 0.78. However, the low ICC and CMC values did not appear to reflect a true lack of repeatability. An analysis of the data underlying the moderate ICC values revealed that the mean intra-subject variability was only 2° ± 1, but also that the mean between-subject variability was only 3° ± 1. It is well-known that repeatability is not well-measured using ICCs when the difference between participants is low (Weir, 2005). In contrast, for instance FE at T1, where the ICC was 0.92, the difference between intra- and between-subject variability was larger (9°). Coefficients of multiple correlations also have drawbacks in that they are sensitive to variations in movement amplitude, and to the number of participants tested (Røislien, Skare, Opheim, & Rennie, 2012). A comparison with the outcomes of absolute repeatability supports the view that lower ICC and CMC values were due to range and sample-size constraints rather than due to low repeatability. Of all 36 MDC values, only one was >10°, 21 were between 5° and 10°, and 14 were even <5°. In addition, no curve SD value exceeded 4°, again indicating very high repeatability. Interestingly, the highest variability values were found in FE between the head and the thorax, especially at impact (T2) and during the sustained push phase (T3), even though these phases represent the most technical, but also the most physically constraining scrum phases. It is conceivable that participants were not focussed on ensuring a consistent head position given they were performing a simple task against a fixed object compared to scummaging against opposing players where they are anticipating their head will be forced into flexion. However, the MDC of 11° in FE suggests that players and coaches should focus on ensuring consistent head
movements at impact and the push phase when using scrum machines. For tactical purposes, practicing a consistent head position to resist forced flexion and to destabilise opposing front row players might be of value. Moreover, resisting forced flexion might have a protective effect on the cervical spine. However, these hypotheses need further investigation.

A limitation of this study was that the scrum machine was not instrumented so repeatability of compression forces could not be examined. However, the fact that high levels of repeatability of axial skeleton kinematics were found suggests a low probability of inconsistent effort. Additionally, while the data smoothing method was not based on a frequency analysis, the method employed was comparable to previous work (Swaminathan et al., 2016b).

Although the exact role of movement variability in scrummaging remains unclear, this study showed that players can perform a basic scrum task consistently and that a scrum machine may be a useful starting point for learning this skill. However, one-man scrum machine-based training is unlikely to reduce movement variability or achieve movement expertise. The findings also suggest that the complexity of the scrummaging task resides in other aspects of the scrum, such as the unstable nature of full scrums with players pushing in somewhat different directions.

### 6.5 Conclusion

This study showed that high levels of repeatability of axial skeleton kinematics can be expected in front row players during one-man simulated scrums, which suggests that once a player has learned the scrum technique, scrum machine-based training should not be used to reduce movement variability. However, if a scrum machine is used, coaches
should focus on players' head position at impact and during the sustained pushing phase. The exact role of movement variability remains unclear and this study is the first in a series investigating movement variability and injuries in scrums with planned stepwise increasing complexity of scrum conditions.
References


Swaminathan, R., Williams, J. M., Jones, M. D., & Theobald, P. S. (2016b). Does the new rugby union scrum sequence positively influence the hooker’s in situ spinal kinematics? *BMJ Open Sport & Exercise Medicine, 2*(1), e000064

CHAPTER 7

Cervical spine kinematics during machine-based and opposed scrummaging

This chapter includes a co-authored paper. The paper has been accepted for publication in the *Journal of Sports Sciences* on January 03 2019:

Declaration of co-authorship and contribution

The candidate's contribution to this article was as follows:

- conception and design of the research project
- analysis and interpretation of research data
- drafting and editing manuscript

_____________  18 September 2018

Student and Corresponding author of paper: Adrien Cerrito

_____________  18 September 2018

Principal supervisor: Professor Peter Milburn
7.1 Introduction

Rugby union (rugby) is a field-based team sport that involves full contact events, such as scrummaging. Scrummaging is a means to restart the game after a minor infringement to the laws, where eight players (forwards) from each team, arranged in a compact formation, compete for ball possession by dynamically engaging and pushing against each other. Scrummaging is known for its physical nature, where each pack of eight forwards can generate up to 16.5 kN compression forces, as well as 1.8 kN and 3.9 kN lateral and vertical shear forces, respectively when scrummaging against a scrum machine (Preatoni, Stokes, England, & Trewartha, 2013). Compression forces of up to 9.8 kN have also been reported during competitive scrums involving both full scrum packs (Cazzola, Preatoni, Stokes, England, & Trewartha, 2015).

To prepare players to withstand these high loads during contested scrums in a match, coaches use different training strategies ranging from strengthening exercises to technical skill training. For example, technical skill training may involve practicing the adoption of a 'straight, flat back' posture with the head and neck in a neutral position while scrummaging to improve performance and prevent spinal injuries (O'Shea, 2003; Posthumus & Viljoen, 2008). To practice this body posture, coaches often decompose the scrum formation, such as one-man scrums where a single player scrummages against a scrum machine. However, the benefit of practicing machine-based scrummaging on players' ability to maintain this posture, particularly a neutral neck and head, is questionable for a number of reasons. First, a scrum machine is a solid structure and hence does not simulate the unstable nature of contested scrummaging where 16 players push against each other and, most likely, in slightly different directions. Secondly, due to its padding, the scrum machine constrains the head laterally, such that lateral-flexion (LF) and axial rotation (ROT) of the head is restricted. In contrast, scrummaging against opponents mainly restricts head movements in extension and may force
the head into relative flexion. Thirdly, anecdotal observations suggest that during technical skill practice, the focus often lies on achieving ideal trunk posture, while the posture of the neck and head gets overlooked. These observations are supported by the findings in Cerrito, Evans, Adams, Pizzolato, and Milburn (2017), where players exhibited high variability of head movement in flexion/extension (FE) during one-man scrummaging against a scrum machine. Moreover, it was also shown that the head remained in relative extension throughout the entire scrum trial in all participants (Cerrito et al., 2017), which is unlikely to occur during contested scrums. However, because kinematic patterns of the cervical spine have rarely been investigated during either one-man or opposed scrummaging, the formation that allows players to best practice maintaining neutral position of head and neck remains unclear. Therefore, providing more empirical data may assist coaches better develop training programs of progressive difficulty that would better prepare players to maintain neutral neck and head posture during match scrummaging.

The concern that the scrum machine does not replicate realistic scrum conditions also applies to biomechanical research. While, scrum biomechanics has often been investigated, most studies have been performed using a static scrum machine (Milburn, 1990; Rodano & Tosoni, 1992; Sayers, 2008; Silvestros & Cazzola, 2017; Wu, Chang, Wu, & Guo, 2007) and results have been used as representation of contested scrummaging that occurs during matches. For example, Silvestros and Cazzola (2017) investigated scrum-related cervical spine injuries using a combination of in vivo, in vitro and in silico (i.e. musculoskeletal computer model) analyses, where computer simulations were driven using data obtained from machine-based scrummaging. While they provided a unique insight into loading patterns applied to individual cervical vertebrae (Silvestros & Cazzola, 2017), the results remain difficult to generalise because it is unclear to what extent cervical motion patterns differ between contested and machine-based scrums.
Consequently, to help coaches build more effective training programs, to improve players' safety and to better direct further research pathways, the aim of this study was to explore cervical spine kinematics in front-row players during one-man scrumming against a static scrum machine ('machine-based') and against two opponents ('live').

7.2 Methods

7.2.1 Participants

Eleven male front-row players were recruited from five local rugby teams according to the following inclusion criteria: i) aged between 18 and 45 years, ii) no injuries in the previous 12 months that remained symptomatic, iii) no history of neck or shoulder surgery, iv) no serious illnesses (e.g. malignancy or heart condition), and v) no acute condition (e.g. inflammation or fever). All participants provided written informed consent prior to participation and the study was approved by the Institution's Human Ethics Committee (Appendix 5).

7.2.2 Data acquisition and apparatus

Cervical spine kinematics was considered as the movement of the head relative to the thorax and was measured using a six degrees-of-freedom electromagnetic motion tracking (EMT) system (Polhemus Liberty, Polhemus, Colchester, VT, USA). One EMT sensor was attached to the sternal notch (representing the thorax) and one sensor to a custom-designed mouthpiece (representing the head). The mouthpiece had a 3 cm 'tongue' that extended out of the mouth for placement of the sensor. Both sensors recorded orientation and location at a sampling frequency of 240 Hz. The EMT system was synchronised with a calibrated DSLR camera (DMC Lumix Fz300, Panasonic, Osaka, Japan) placed approximately 1.5 m above the scrum, and with a custom-designed timer with a resolution of 5 ms. While the timer was in the field-of-view the camera recorded the trials at 50 Hz to identify key time points of the
scrums during data processing. All systems were triggered simultaneously via a wired remote control based on three Arduino Uno boards (Arduino, Sommerville, MA, USA) connected in parallel.

Due to the sensitivity of EMT systems to the presence of large metallic objects in the electromagnetic field, the scrum machine and the frame holding the camera were custom-designed and made of wood and plastic respectively. The scrum machine was designed with pad heights and dimensions replicating commercial scrum sleds (i.e. allowing scrum heights between 40 and 110 cm) and was provided with spikes to its under-surface to prevent sliding during scrummaging. The scrum machine was also weighed down using gravel bags in order to prevent lifting.

7.2.3 Experimental procedure

Data were collected outdoors on players' home-field. Participants first performed a standardised warm-up that consisted of body-weight squats (2 x 10 repetitions), resisted shoulder abduction and flexion (2 kg weight, 2 x 10 repetitions each), and maximum head excursions in FE, LF, and ROT (10 repetitions each). Then, the two EMT sensors were attached to the participant and six anatomical landmarks were palpated by an experienced physiotherapist and digitised using a third sensor placed on a stylus (Figure 7.1) (Mills, Morrison, Lloyd, & Barrett, 2007). Three anatomical landmarks were on the head (right and left mastoid processes, and the nose-bridge) and three on the thorax (xiphoid process, and the spinous processes of the seventh cervical (C7) and thoracic (T7) vertebrae). In addition, C7 was marked using a black pen as a reference point for the video data. Participants then sat on a wooden stool in an upright sitting position with a neck and head position that was considered neutral. While the EMT system was recording, participants were asked to maintain this posture for 3 s and then perform a range-of-motion (ROM) trial, consisting of
maximum head movement excursion in FE, LF, and ROT (3 x each). After the ROM trial, participants were asked to practice scrummaging against the scrum machine to become familiar with the apparatus and protocol, and were advised to scrummage with the same intensity as during competitive match scrummaging during all trials.

Kinematic data were then recorded in all participants, each performing four 'machine-based' scrum trials which consisted of one-man scrums against a scrum machine. Subsequently, data were recorded in seven of the 11 participants, each performing four 'live' scrum trials which consisted of one-man scrums against two opponents (Figure 7.2). In order to avoid fatigue, participants were given a minimum of 1-2 minutes break between each trial (Cochrane, Harnett, Lopez-Villalobos, & Hapeta, 2017). The standard call of 'crouch, bind, set' was provided by the researchers to manage scrummaging engagement sequence.

![Illustration of the sensor placement (white dots) and digitised anatomical landmarks (red dots). X- and Z-axes of the two local coordinate systems (LCSH and LCST) are represented by the green and blue arrows, respectively.](image)

**Figure 7.1**

Illustration of the sensor placement (white dots) and digitised anatomical landmarks (red dots). X- and Z-axes of the two local coordinate systems (LCSH and LCST) are represented by the green and blue arrows, respectively.
128

Figure 7.2
Scrum trial examples showing the two conditions: machine-based (a) and live (b) scrums.

7.2.4 Data processing

Using a custom-written MATLAB script (v. R2014a, MathWorks Inc., Natick, MA, USA), EMT data were first smoothed using a zero-lag, 2nd order Butterworth filter with a cut-off frequency of 6 Hz (Swaminathan, Williams, Jones, & Theobald, 2016a) to attenuate high-frequency noise. Then, using sensor location (coordinates) and orientation (rotation matrices) data, coordinates of the anatomical landmarks were calculated and used to generate local coordinate systems for the head (LCSH) and thorax (LCST) (Mills et al., 2007). For the Cartesian origin of LCSH, a virtual anatomical landmark representing the first cervical vertebra (C1) was created as the midpoint between right and left mastoid processes (Figure 7.1).

Because the cervical spine can functionally be divided into lower and upper cervical spine, and because movement coupling of these two parts affects spinal alignment (Ordway, Seymour, Donelson, Hojnowski, & Edwards, 1999; Penning, 1978), two separate kinematic analyses were performed based on the EMT data. In the first analysis, cervical kinematics
were considered as head orientation relative to the thorax (Figure 7.3a, b), in line with previous work (Cazzola, Holsgrove, Preatoni, Gill, & Trewartha, 2017; Swaminathan et al., 2016a; Swaminathan, Williams, Jones, & Theobald, 2016b). The analysis of head orientation combines both the lower and upper cervical spine and therefore provides information on the summed kinematics. The rotation matrix was calculated according to the method described by Robertson, Caldwell, Hamill, Kamen, and Whittlesey (2014), and joint angles were extracted as an XYZ Cardan angle sequence representing 1) FE, 2) LF, and 3) ROT. The mean rotation matrix of the first 3 s of the ROM trial (i.e. neutral position) was used to remove the joint angle offset from all scrum trials (Koning, Krogt, Baten, & Koopman, 2012). The second analysis consisted of modelling the neck as a vector connecting the thorax to the head by tracking the relative position of C7 and C1 (Figure 7.3c, d), similar to an inverted pendulum (Kajita, Kanehiro, Kaneko, Yokoi, & Hirukawa, 2001). This analysis can be considered as the representation of the lower cervical spine, since that sub-region is responsible for gross neck movements and therefore for changes in head location relative to the thorax (Kapandji, 2007). By comparing it to head orientation results, this analysis also helps to better differentiate kinematics of the upper cervical spine. For this analysis, head postures in FE and LF were first calculated in neutral position during the ROM trial. Head posture in FE was calculated as the angle α formed by the Z-axis of LCST and the projection of the vector connecting C7 to C1 onto the sagittal plane of the thorax. Head posture in LF was calculated as the angle β between the sagittal plane of the thorax and the lateral deviation of the vector connecting C7 to C1. Then, the angles α and β were calculated for all scrum trials and values obtained from neutral position were subtracted. Since in this second analysis the neck was considered as a vector, ROT could not be calculated.

Finally, video data were visually analysed to identify two key time points in each scrum trial. The first time point was the 'bind' prior to engagement (T1) and was defined as 1 s before the
instant of impact. The 'bind' was selected because it has been reported that initial head position may affect peak compression loads experienced in the cervical spine during scrums (Silvestros & Cazzola, 2017). The second time point was the instant of impact (T2) and was identified as the time point at which the C7 marker stopped moving in the scrummaging direction. Once the impact was identified on the video file, the time indicated on the timer was used to extract the frames associated with the time stamps of T1 and T2 in the EMT data (Figure 7.4).

Figure 7.3
Analysis of head orientation (a and b) and head location (c and d) relative to the thorax as an indicator of cervical spine kinematics.
Figure 7.4

Example of T1 (‘bind’ prior to engagement) and T2 (instant of impact) identification in a machine-based scrumming trial. The marker on C7 was tracked to identify T1 and T2 and the elapsed time read on the timer was transferred to the EMT data.

7.2.4 Statistical analysis

Descriptive statistics (mean and standard deviation (SD)) were first calculated for movement excursions during the ROM trial, as well as during scrum trials using head orientation data (Figure 7.3a, b). From these data, peak FE, LF and ROT excursions during scrums were calculated as a percentage of the respective movement amplitudes observed during the ROM trial.

To evaluate the effect of scrumming condition (machine-based versus live) on cervical spine kinematics, a linear mixed effects model was used. Fixed effects comprised the time point (T1 or T2) and the scrumming condition (machine-based or live). The random effects in the model were the individuals on which the repeated measurements were taken. Estimation was conducted using a Bayesian framework as per the Markov Chain Monte Carlo (MCMC) algorithm provided in Sorensen and Gianola (2002). Modelling was
conducted using 60000 iterations after an initial burn-in period of 10000 iterations. MCMC posterior draws were thinned, with every 5th simulation being retained. The coefficients were estimated using uninformative prior distributions, in line with the current state of knowledge in this field being currently unquantified in publications. The outcomes of the linear mixed effects model are presented as summaries of the posterior distributions. For example, for both kinematic analyses (head orientation and inverted pendulum model), the posterior means and 95% credible intervals (CrI) of each movement direction (FE, LF, and ROT) were calculated for scrummaging conditions and time points. In addition, the difference (± 95% CrI) in head orientation (FE, LF and ROT) and head location (FE and LF) (inverted pendulum model) between machine-based and live scrummaging at T1 and T2 was calculated. Finally, for head orientation results, the probability that the differences between conditions exceed the minimal detectable change (MDC) defined in Cerrito et al. (2017), was calculated.

Percent movement excursion was calculated using Microsoft Excel (v. 2010, Microsoft, Redmond, WA, USA). All other statistical analyses were performed using a custom-written script in R software (v. 3.5.0) (R Core Team, 2018) involving the MCMCglmm library (Hadfield, 2010).

7.3 Results

7.3.1 Participant characteristics

Participant anthropometric data and playing history are presented in Table 7.1 and findings were consistent with that of front-row forwards presented elsewhere (Zemski, Slater, & Broad, 2015).
Table 7.1

Number of participants and their playing position, anthropometrics and playing experience.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Body mass (kg)</th>
<th>Playing experience (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loosehead</td>
<td>4</td>
<td>21.5 ± 3</td>
<td>1.87 ± 0.06</td>
<td>110.3 ± 10</td>
<td>7.0 ± 4</td>
</tr>
<tr>
<td>Hooker</td>
<td>1</td>
<td>18</td>
<td>180</td>
<td>98</td>
<td>14</td>
</tr>
<tr>
<td>Tighthead</td>
<td>6</td>
<td>27.0 ± 9</td>
<td>1.90 ± 0.04</td>
<td>115.0 ± 8</td>
<td>13.3 ± 9</td>
</tr>
<tr>
<td>Mean</td>
<td>11</td>
<td>24.2 ± 7</td>
<td>1.88 ± 0.05</td>
<td>111.7 ± 9</td>
<td>11.1 ± 7</td>
</tr>
</tbody>
</table>

7.3.2 ROM

The mean ± SD ROM values measured during the ROM trial in FE, LF, and ROT were 101° (flexion: 53° ±12°, extension: 48° ±10°), 78° (right and left: 39° ±11°), and 122° (right: 63° ±12°, left: 59° ±13°), respectively. In machine-based scrums, participants used 60.9%, 32.7%, and 20.1% of their FE, LF, and ROT capacity respectively while in live scrums, participants used 32.5%, 31.7%, and 19.6% of their FE, LF, and ROT capacity, respectively.

7.3.3 Kinematic comparison between machine-based and opposed scrummaging

Table 7.2 shows descriptive statistics (mean and 95% CrI) for each movement direction in head orientation data, with the respective difference between conditions and the probability that the difference exceeds MDC. The largest differences were found for FE at both the 'bind' (-38°) and impact (-50°). Smaller differences were found for the other movement directions at both time points.

For all variables in the second kinematic analysis (i.e. head location in inverted pendulum model), the largest differences were also found for FE (-20° at the 'bind' and -26° at impact). Table 7.3 presents all statistical results for these variables.

Figure 7.5 shows posterior distributions for FE, LF and ROT at both time points, to illustrate the differences between the two conditions in head orientation data. Figure 7.6 shows the
equivalent distributions for head location data and Figure 7.7 presents FE and LF values as bar charts for comparison between head orientation and location analyses.

**Table 7.2**

Kinematic analysis of head orientation relative to the thorax at the 'bind' (T1) and impact (T2).

<table>
<thead>
<tr>
<th></th>
<th>Machine-based</th>
<th>Opposed</th>
<th>Δ</th>
<th>Pr(Δ &gt; MDC&lt;sup&gt;1&lt;/sup&gt;)</th>
<th>MDC&lt;sup&gt;1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>95% CrI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LL</td>
<td>UL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>95% CrI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LL</td>
<td>UL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>-30°</td>
<td>-44°</td>
<td>-17°</td>
<td>8°</td>
<td>-6°</td>
</tr>
<tr>
<td>LF</td>
<td>4°</td>
<td>-3°</td>
<td>12°</td>
<td>8°</td>
<td>4°</td>
</tr>
<tr>
<td>ROT</td>
<td>-6°</td>
<td>-12°</td>
<td>-1°</td>
<td>-13°</td>
<td>-19°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>-33°</td>
<td>-46°</td>
<td>-19°</td>
<td>17°</td>
<td>3°</td>
</tr>
<tr>
<td>LF</td>
<td>0°</td>
<td>-8°</td>
<td>8°</td>
<td>5°</td>
<td>1°</td>
</tr>
<tr>
<td>ROT</td>
<td>-6°</td>
<td>-12°</td>
<td>-1°</td>
<td>-14°</td>
<td>-20°</td>
</tr>
</tbody>
</table>

Δ: Machine-based minus Opposed; Pr(Δ > MDC): Probability that Δ exceeds the minimal detectable change (MDC) defined in Cerrito et al. (2017); 95% CrI: 95% Credible Interval, LL: lower limit; UL: upper limit

FE: Flexion (+), Extension (-); LF: Right (+), Left (-); ROT: Left (+); Right (-)

**Table 7.3**

Kinematic analysis of head location relative to the thorax.

<table>
<thead>
<tr>
<th></th>
<th>Machine-based</th>
<th>Opposed</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>95% CrI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LL</td>
<td>UL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>95% CrI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LL</td>
<td>UL</td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>-4°</td>
<td>-16°</td>
<td>9°</td>
</tr>
<tr>
<td>LF</td>
<td>1°</td>
<td>-14°</td>
<td>17°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-1°</td>
<td>14°</td>
</tr>
<tr>
<td>T2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FE</td>
<td>-10°</td>
<td>-22°</td>
<td>3°</td>
</tr>
<tr>
<td>LF</td>
<td>1°</td>
<td>-15°</td>
<td>16°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-3°</td>
<td>13°</td>
</tr>
</tbody>
</table>

Δ: Machine-based minus Opposed; 95% CrI: 95% Credible Interval, LL: lower limit, UL: upper limit

FE: Flexion (+), Extension (-); LF: Right (+), Left (-); ROT: Left (+); Right (-)
Figure 7.5
Posterior distributions for FE, LF, and ROT at both time points (T1 and T2) and for both conditions (machine-based and opposed) in head orientation data.

Figure 7.6
Posterior distribution for FE and LF at both time points (T1 and T2) and for both conditions (machine-based and opposed) in head location data.
Figure 7.7
FE and LF values for both kinematic analyses (head orientation and head location).
‘Head Orientation’ represents an analysis of the total movement occurring in the cervical spine. ‘Head Location’ refers to an analysis estimating the movement occurring in the lower cervical spine.

7.4 Discussion

This study explored three-dimensional cervical spine kinematics in front-row players during scrum engagement and compared machine-based to live scrummaging. To date, few studies have investigated scrum-related kinematics and the majority of current knowledge has been based on experimental data collected during machine-based scrummaging (Milburn, 1990; Rodano & Tosoni, 1992; Sayers, 2008; Silvestros & Cazzola, 2017; Wu, Chang, Wu, & Guo,
2007). However, it is unclear how well kinematics observed during machine-based scrummaging reflects that which occurs during contested scrummaging. Comparing these two conditions is also important to provide those involved in rugby, such as coaches, physiotherapists, or exercise physiologists, with evidence regarding cervical spine kinematics and will allow more informed decision-making regarding the development of training activities.

Cervical ROM values in FE, LF and ROT collected in an upright sitting position were comparable to those found in previous studies investigating cervical mobility in rugby players (Lark & McCarthy, 2010, 2007). Hence, it was not surprising to find that the present values for cervical ROM were less than those observed in age-matched healthy males who are not involved in rugby (Ferrario, Sforza, Serrao, Grassi, & Mossi, 2002). Indeed, decreased cervical mobility is a well-known phenomenon in rugby players, particularly in forward players (Hamilton & Gatherer, 2014; Lark & McCarthy, 2007), and may be due to the increased prevalence of degenerative changes to the cervical spine observed in those players (Lark & McCarthy, 2007).

With regard to peak movement excursions of the cervical spine during scrummaging expressed as a percentage of ROM, the results appear to reflect the different physical constraints on the neck and head in machine-based versus live scrummaging. Participants utilised 60.9% of their FE capacity in machine-based, while only 32.5% in live scrummaging. In contrast, movement excursions in LF and ROT were very similar between the two conditions, with a difference of only approximately 1% in both directions. These results support the notion that scrum machines have limited potential to improve players’ engagement technique because they unnecessarily restrict head motion in LF and ROT, but not in extension. Additionally, these findings are further supported by the fact that in live scrummaging the neck and head are considerably more flexed than in machine-based
scrummaging, both at the 'bind' (T1) and at the instant of impact (T2). Moreover, these differences in movement excursion in FE largely exceed the MDC values (Table 7.2), indicating that the differences are due to the scrummaging condition, rather than to random variations. The increased flexion is likely to contribute to cervical spine injuries given greater neck flexion angles have been associated with larger compression responses in lower cervical spine vertebrae (C4-C6) and larger shear forces in C4 specifically (Silvestros & Cazzola, 2017). Similarly, it is thought that repeated compression cycles combined with flexion largely contributes to damage afflicted to cervical intervertebral discs (Callaghan & McGill, 2001) which may further increase front-row players' risk of cervical spine injuries.

Since the upper and lower cervical spine regions can move independently, analysing these results from a functional anatomy perspective provides further insight into players' movement patterns. The lower cervical segment (C3-C7) is mainly responsible for gross neck movements and therefore influences head location, whereas the upper segment (C1-C2) mainly adjusts head orientation (Kapandji, 2007). Accordingly, the results suggest that in machine-based scrummaging, the lower neck is only slightly extended at both time points, while the upper cervical spine is markedly extended (Figure 7.7). In contrast, the lower neck is notably flexed at both time points during live scrummaging. Results for head orientation at the 'bind', however, indicate less flexion than the lower segment, which suggests that participants attempted to compensate flexion in the lower segment by slightly extending the upper cervical spine in order to approach a neutral position. Then, at the instant of impact head orientation results were approximately identical to the FE results of the lower neck, which indicates that the upper cervical spine was in a neutral position. These results suggest that the extended head orientation during machine-based scrums is unrealistic, particularly at impact, since it could cause the forehead to collide with the opponents' shoulders in contested scrums.
It should be noted that, although live scrummaging generally results in increased neck and head flexion, some participants exhibited atypical patterns. In two participants, although the effect of live scrummaging resulted in a relative flexed posture of the upper cervical segment compared to machine scrummaging, the head remained in an extended posture at both time points. However, it is important to realise that the lower cervical segment was flexed at the same time, and therefore, it is possible these players focussed on their head orientation to counteract the flexion moment imposed by opponents. While the description of precise joint angles in the upper and lower cervical spine cannot be provided with certainty based on the method utilised in this paper, these kinematic patterns are yet important considerations for coaches as these patterns can potentially influence the risk of cervical spine injuries.

Regarding comparisons of head orientation in LF and ROT between both conditions, the values of dispersion (95% CrI) indicate that there is an actual difference in kinematics in 95% of the cases. However, the differences are small, which is supported by lower probabilities of exceeding MDC values (0.33-0.90). Moreover, even if exceeding MDC values, the importance of these differences would remain questionable because they would be of the order of 1-3° above MDC. Nevertheless, these results might be due to a slight difference in body positioning when scrummaging against opponents, possibly reflecting the unstable nature of live scrummaging.

It should be noted that although the results presented in this study show that machine-based and live scrummaging present different cervical spine kinematic patterns, the 'one-on-two' formation may not be a perfect representation of competitive scrums involving 16 players. Nevertheless, the results of the present study have implications for future research directions, for coaches and possibly for the rugby equipment industry. First, researchers should be aware that cervical spine kinematics during machine-based scrummaging does not represent movement patterns found in live scrummaging. Therefore, this study confirms the limited
generalisation of some previous work and strengthens the need for investigations during contested scrums.

Secondly, coaches are encouraged to pay close attention to cervical spine kinematics when practicing with a scrum machine. It appears particularly important to recognise that the cervical spine is not a single socket joint, but that the lower and upper segments of the cervical spine can move independently. In addition, a conceivable training program to improve neck and head posture could involve practicing against a scrum machine (i.e. without flexion moment applied to the neck and head) and, once mastered, increase difficulty by practicing during opposed scrummaging. The 'one-on-two' formation used in this study may be particularly beneficial as a first progression, since there are only two opponents that apply a flexion moment to the head and neck. Further progression could then involve adding players to increase the intensity of the flexion moment, but the effect of these progressions on kinematics should be investigated. Nevertheless, in addition to simple strengthening exercises, changes in technique, such as lowering the body position might also represent a conceivable way to improve players' capability to maintain a neutral neck and head posture. However, the viability of this technical suggestion needs to be assessed, particularly because excessive lowering of the body position may decrease the ability to generate forward forces (Wu et al., 2007).

Finally, the results presented in this study might stimulate the rugby equipment industry to modify the design of scrum machines. The results showed that typical scrum machines appear not to challenge and foster neck stabilisation skills in front-row players, and possible modifications to the padding could be designed to apply a flexion moment to the player's cervical spine.
7.5 Strengths and limitations

This study explored cervical spine kinematics during field-based scrummaging with a focus on the comparison between machine-based and live conditions. To the authors’ knowledge, this study was the first to consider the two sub-regions of the cervical spine (upper and lower segments) separately to provide further insight into the cervical kinematics. However, this study's main limitation was that the live condition consisted of one player scrummaging against only two opponents. Therefore, the effect of further players involved in the scrum on cervical kinematics and neck stability skills remains unknown and should further be investigated. Another limitation was that the order of the trials was not randomised. Randomisation was difficult to implement in our study because data was collected during participants’ training hours and, therefore, the authors aimed to minimise the duration of data collection. However, the authors feel that randomisation of the trial order should be considered in future studies as there could be a potential effect of learning or fatigue under the non-randomised design.

7.6 Conclusion

The present study revealed that kinematic patterns of upper and lower cervical spine were markedly different in FE between machine and live scrummaging, confirming the difficulty in generalising many of previous research findings. This study encourages coaches to pay close attention to players' cervical spines during scrummaging practice and the results suggest that scrummaging against two opponents might be an appealing option to challenge players' ability to maintain a neutral posture of the head and neck. Finally, this study may also stimulate companies that manufacture scrum machines to modify their equipment, such that
they can be used to challenge players’ ability to maintain a neutral posture by imposing a flexion moment to the head and neck.
References


145


Swaminathan, R., Williams, J. M., Jones, M. D., & Theobald, P. S. (2016b). Does the new rugby union scrum sequence positively influence the hooker’s in situ spinal kinematics? BMJ Open Sport & Exercise Medicine, 2(1), e000064.


CHAPTER 8

Cervical spine kinematics during opposed scrummaging

This chapter includes a co-authored paper. The paper has been submitted for publication in the journal *Sports Biomechanics* and is currently under review:

Declaration of co-authorship and contribution

The candidate's contribution to this article was as follows:

- conception and design of the research project
- analysis and interpretation of research data
- drafting and editing manuscript

_____________________________  18 September 2018

Student and Corresponding author of paper: Adrien Cerrito

_____________________________  18 September 2018

Principal supervisor: Professor Peter Milburn
8.1 Introduction

In rugby union (rugby), the scrum occurs after a minor infringement and consists of two eight-player formations competing for ball possession by dynamically engaging and pushing against each other with forces of up to 9.8 kN (Cazzola, Preatoni, Stokes, England, & Trewartha, 2015). Due to its physical nature, the scrum has been identified as one of the most dangerous events of the game (Fuller, Brooks, Cancea, Hall, & Kemp, 2007). For example, the scrum accounts for 41% of injuries to the cervical spine in professional front-row players (i.e. players who are in direct contact with opponents) (Brooks, Fuller, & Kemp, 2005) and has been associated with approximately 40% of all catastrophic spinal injuries occurring in rugby (Quarrie, Cantu, & Chalmers, 2002).

Two injury mechanisms have been proposed to explain the occurrence of scrum-related cervical spine injuries: hyperflexion and 'buckling' of the neck under axial compression (Trewartha, Preatoni, England, & Stokes, 2015). To date, it remains unclear which injury mechanism is predominantly responsible for these injuries (Dennison, Macri, & Cripton, 2012; Trewartha et al., 2015). Regardless, it appears that motion patterns and/or posture of the head and neck are important factors influencing the risk of injury. For example, multiple biomechanical studies have shown that cervical spine posture influences the magnitude and distribution of internal loads, as well as tolerance to compressive forces of the cervical spine (Benzel, 2012; Gunning, Callaghan, & McGill, 2001; Oktenoğlu et al., 2001). These studies have demonstrated a neutral, or close to neutral, posture can best absorb energy under axial compression and therefore provide the cervical spine highest tolerance against axial impacts (Benzel, 2012; Gunning et al., 2001; Oktenoğlu et al., 2001). Based on such studies, guidelines for ‘safe and efficient rugby technique’ were developed where front-row players are encouraged to adopt a neutral head and neck posture during scrummaging (Posthumus & Viljoen, 2008). Front-row players should maintain this posture throughout the entire scrum
and, particularly, not deviate into a flexed posture, since flexion is thought to increase the risk of injury, regardless of injury mechanism. Indeed, given hyperflexion injuries occur due to exaggerated head and neck flexion, flexed posture should be avoided. Similarly, cervical spine flexion of ≥20° is thought to increase the risk of ‘buckling’ injuries (Silvestros & Cazzola, 2017), probably because in flexion the natural lordosis present in neutral posture is ‘flattened’ such that the energy from axial impacts can be less well dissipated (Benzel, 2012; Silvestros & Cazzola, 2017; Torg, Pavlov, O’Neill, Nichols, & Sennett, 1991).

Whilst adopting a neutral cervical spine posture prior to engagement is possible, it may not be the case during engagement and the sustained push phase due to the physical constraints and movement applied by other players to the front row players’ neck. During these phases, front-row players are interlocked with their opponents, which usually results in a flexion of the cervical spine and the unstable nature of a scrum may also lead to LF and/or ROT of the cervical spine. Swaminathan, Williams, Jones and Theobald (2016b) reported that front-row players utilise 30-65% of their available range of cervical spine movement amplitude in FE, LF and ROT during scrummaging. However, because Swaminathan et al. (2016b) used inertial sensors to collect data, cervical spine kinematics were not identified at specific time points, such as the impact phase. Consequently, cervical spine kinematics at different scrummaging phases remain unclear. Considering that forces vary largely between the different scrum phases (Preatoni, Cazzola, Stokes, England, & Trewartha, 2016; Preatoni, Stokes, England, & Trewartha, 2013), it appears important to also investigate kinematics of the cervical spine during these phases. For example, impact is likely to be a key time point given that 28-30 ms after impact, a front-row player’s cervical spine experiences the greatest stress (Silvestros & Cazzola, 2017). Investigating motion patterns and/or posture of the cervical spine at different phases could thus help understand how injuries occur and direct further means of their prevention. Therefore, the aims of this study were to i) explore cervical
spine kinematics in front-row players during field-based, opposed scrums over entire trials and at key time points, and ii) to determine the effect of scrum phases on cervical spine kinematics. It was hypothesised that the cervical spine would be substantially more flexed at impact and during the sustained push phase.

8.2 Materials and methods

8.2.1 Participants

Seven male front-row players aged between 18 and 45 years (20.4 ± 2.9 years) who were currently participating in competitive rugby (i.e. healthy) were recruited from local rugby clubs. Exclusion criteria, screened via a health questionnaire, were injuries sustained in the past 12 months that remained symptomatic, history of neck/shoulder surgery, and serious illnesses (e.g. malignancy or heart condition) or acute condition (e.g. fever). Written informed consent was obtained from all participants prior to participation and the study was approved by the institution's human ethics committee (Appendix 5).

8.2.2 Apparatus and data acquisition

Using a six degrees-of-freedom EMT system (Polhemus Liberty, Polhemus, Colchester, VT, USA), cervical spine kinematics were measured as head movement relative to the thorax. One sensor was attached to the sternal notch to capture movements of the thorax and another to a custom-designed mouthpiece to track head motion (Figure 8.1). Precautions were taken to ensure no metallic objects were near the EMT system to avoid magnetic distortions. Data were sampled at 240 Hz and the system was synchronised with a calibrated DSLR camera (DMC Lumix Fz300, Panasonic, Osaka, Japan) operating in video mode at 50 Hz, as well as with a custom-designed timer with a resolution of 5 ms. The camera was placed 1.5 m above the scrum to record trials while the timer was in the field-of-view. Video data were used to identify the instant of impact and the time indicated on the timer at that instant was then used to identify impact in the Polhemus data.
Figure 8.1

a) Sensor placement on the thorax and head (black dots) and digitised anatomical landmarks (red dots).

b) Definition of rotation axes for calculation of head orientation relative to the thorax.

c) Definition of α and β angles.

8.2.3 Experimental procedure

Data collection took place on players’ respective home fields. After participants warmed up according to a standardised routine (2 x 10 repetitions of body-weight squats, as well as resisted shoulder abduction and flexion (2 kg) and 10 repetitions each of maximum head excursions in FE, LF, and ROT), the two sensors were attached. Six anatomical landmarks (right and left mastoid processes, nose-bridge, spinous processes of C7 and T7, and xiphoid process) were palpated by an experienced physiotherapist and digitised using a third sensor placed on a stylus (Mills, Morrison, Lloyd, & Barrett, 2007) (Figure 8.1). To provide a reference point for the camera, C7 was also marked using a black pen. Data were then collected during a ROM trial, where participants sat still in an upright posture for 3 s,
followed by maximum head movement excursions in FE, LF and ROT (3 x each). Participants were then instructed to perform one-man scrums against two opponents (i.e. ‘one-on-two’ formation). The 'one-on-two' formation was chosen as a best trade-off between ecological validity (i.e. opposed rather than machine-based scrummaging) and feasibility (e.g. recruitment and availability). Participants were instructed to follow the standard call 'crouch-bind-set' provided by the researchers and to scrummage with the same intensity as during competitive match scrummaging. Participants practiced the task to become familiar with the protocol before data were recorded from four trials for each participant.

8.2.4 Data processing
Polhemus data were processed using a custom-written MATLAB script (v. R2014a, MathWorks Inc., Natick, MA, USA), where a zero-lag, 2nd order Butterworth filter with a cut-off frequency of 6 Hz (Swaminathan et al., 2016b) was first applied to smooth the data. The procedure described by Mills et al. (2007) was then followed to reconstruct trajectories of the six digitised anatomical landmarks, which were used to generate LCS\(_H\) and LCS\(_T\). The Cartesian origin of LCS\(_H\) was set as the mid-point between left and right mastoid processes and represented the approximate location of C1.

Kinematic analysis was then performed in two separate ways to best represent the functional anatomy of the cervical spine. Although the cervical spine has often been treated as a socket joint (Cazzola et al., 2015; Swaminathan et al., 2016b; Swaminathan, Williams, Jones, & Theobald, 2016a), this methodology is an oversimplification of its functional anatomy. Indeed, the cervical spine can functionally be divided into the upper (C1-C2) and lower (C3-C7) cervical spine and movement can occur independently in both regions (Kapandji, 2007). The first kinematic analysis, in line with previous work (Cazzola et al., 2017; Silvestros & Cazzola, 2017; Swaminathan et al., 2016a, 2016b), consisted of calculating head orientation relative to the thorax and represented movement occurring in the entire cervical spine (i.e.
upper and lower cervical spine regions). The method described by Robertson, Caldwell, Hamill, Kamen and Whittlesey (2014) was followed to calculate rotation matrices and relative joint angles, which were extracted as Cardan angle sequence and expressed as 1) FE, 2) LF, and 3) ROT (Figure 8.1). Due to the side-to-side symmetry of vertebrae, right and left LF and ROT movements stress the same spinal structures and therefore, only absolute values were considered to denote deviation from the neutral cervical spine posture. In contrast, positive (flexion) and negative (extension) values were kept for FE movements. Joint angle offset was removed from kinematic data using a mean rotation matrix from the first 3 s of the ROM trial (i.e. neutral position) (Koning, Krogt, Baten, & Koopman, 2012). In the second kinematic analysis, the neck was considered as a line ('neck line') connecting the thorax to the head. Movements indicated by changes in ‘neck line’ inclination were viewed as the movement of the lower cervical spine because this sub-region is responsible for gross linear displacement of the head relative to the thorax (Kapandji, 2007). Movement in FE was calculated as changes in angle $\alpha$ formed by the 'neck line’ projected onto the thorax’s sagittal plane and the Z-axis of LCS$_T$ (Figure 8.1). Movement in LF were calculated as lateral deviations of the 'neck line' from the sagittal plane expressed as angle $\beta$ (Figure 8.1). Angles $\alpha$ and $\beta$ were first calculated in neutral position during the ROM trial to then subtract the joint angle offset from scrum trial data.

Cervical spine kinematics were analysed over entire trials and at three key time points (T1-T3). For this purpose, video data were visually analysed to identify the instant of impact, defined as the moment at which the C7 marker stopped moving in the scrumming direction. The 'bind' phase prior to engagement (T1) was defined as 1 s before impact (T2), and the sustained push (T3) as 2.5 s after impact (Figure 8.2). The time indicated on the timer was used to identify T1-T3 in the Polhemus data set. In addition, because in FE cervical intervertebral kinematics also vary as a function of movement direction rather than just
posture (Anderst, Donaldson, Lee, & Kang, 2013), the periods before and after T2 were also analysed for head orientation in FE to determine movement direction. An arbitrary period of 50 Polhemus data frames (i.e. ~0.2 s) prior to and after T2 (Pre_T2 and Post_T2 respectively) was selected for analysis to ensure to cover the phase where the largest stresses are applied to spinal structures (Silvestros & Cazzola, 2017) (Figure 8.2).

![Illustration of the time points (T1-T3). The three time points are indicated as red lines in the graph representing FE kinematics in a representative participant. The grey shaded area illustrates the ~0.4 s time window between Pre_T2 and Post_T2.](image)

**Figure 8.2**

8.2.5 Statistical analysis

In head orientation data, peak movement excursions as well as the time of occurrence during the scrum trials were first identified in kinematic curves for movements in all three planes (FE, LF, and ROT). Peak movement excursions during scrums were then calculated as a percentage of peak movement excursion recorded during ROM trials.
Joint angles from both kinematic analyses (head orientation and 'neck line' inclination) at T1, T2 and T3 were then used to describe cervical spine posture at the three time points. The differences in joint angles between T1 and T2, as well as between T2 and T3 were used to compare kinematics at different time points. A linear regression model within a Bayesian framework was used to analyse these data. A Monte Carlo Markov Chain (MCMC) algorithm was then used to generate samples from the posterior distributions (Sorensen & Gianola, 2002). The coefficients were modelled using non-informative normal prior distributions. The MCMC algorithm was performed for 60000 iterations, with a burn-in period of 10000 iterations. Thinning was set such that every 100\textsuperscript{th} simulation was retained. Estimates of interest included summary of posterior distributions (means and 95\% Credible Intervals (CrI)) describing movement excursions at T1, T2 and T3 in both kinematic analyses. In addition, summaries of posterior distributions of differences in joint angles between time points (Δ) were calculated. For head orientation results, the probability with which Δ is likely to exceed minimal detectable change (MDC) values defined in Cerri, Evans, Adams, Pizzolato and Milburn (2017) was also calculated.

Finally, to analyse movement directions prior to and after T2 in FE head orientation data, the slopes between Pre_T2 and T2, as well as between Post_T2 and T2 were calculated. Movement directions were evaluated based on the algebraic sign of the slopes, with positive sign denoting a flexing movement and a negative sign denoting an extending movement. Mean slopes before and after T2 were calculated and interquartile range (IQR) was used to describe dispersion. In addition, individual as well as mean ± SD kinematic curves for FE head orientation were qualitatively inspected to describe the course of the movement. All statistical analyses were performed using a custom-written script in statistical software R (v. 3.5.0) (R Core Team, 2018) involving the MCMCglmm library (Hadfield, 2010).
8.3 Results

8.3.1 Peak movement excursion

Participants utilised 60% of their maximum movement capacity in flexion and 30% in extension during opposed scrummaging. In 67% of the cases, peak flexion was reached within a ~0.4 s time window around T2 and in 20% of the cases it occurred after T2. Peak extension was reached after T2 in 47% of the cases. In LF and ROT, 23% and 26% of the respective movement capacity was utilised, mainly before T2 (53% and 47% of the cases, respectively).

8.3.2 Kinematics at T1, T2 and T3

In both head orientation (Table 8.1) and ‘neck line’ inclination (i.e. α and β angles) (Table 8.2), the largest movement excursions were found in FE at T2, with flexion angles of 17° and 16°, respectively.
### Table 8.1

Kinematic analysis of head orientation relative to the thorax at the ‘bind’ (T1), impact (T2) and sustained push (T3).

<table>
<thead>
<tr>
<th></th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Descriptive</strong></td>
<td><strong>Δ</strong></td>
<td><strong>Pr(Δ &gt; MDC)</strong></td>
<td><strong>MDC</strong></td>
</tr>
<tr>
<td><strong>FE</strong></td>
<td>Mean (95% CrI)</td>
<td>Mean (95% CrI)</td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>-4° (-17°, 9°)</td>
<td>T1–T2: -21° (-41°, -2°)</td>
<td>Pr = 0.92</td>
</tr>
<tr>
<td>T2</td>
<td>17° (3°, 30°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>3° (-11°, 16°)</td>
<td>T2–T3: 14° (-3°, 31°)</td>
<td>Pr = 0.63</td>
</tr>
<tr>
<td><strong>LF</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>8° (5°, 11°)</td>
<td>T1–T2: 7° (5°, 10°)</td>
<td>Pr = 0.94</td>
</tr>
<tr>
<td>T2</td>
<td>11° (7°, 14°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>9° (6°, 12°)</td>
<td>T2–T3: 7° (4°, 10°)</td>
<td>Pr = 0.80</td>
</tr>
<tr>
<td><strong>ROT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>12° (7°, 16°)</td>
<td>T1–T2: 8° (4°, 11°)</td>
<td>Pr = 0.98</td>
</tr>
<tr>
<td>T2</td>
<td>11° (7°, 16°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>12° (7°, 16°)</td>
<td>T2–T3: 6° (3°, 10°)</td>
<td>Pr = 0.81</td>
</tr>
</tbody>
</table>

Δ: Difference between time points; Pr(Δ > MDC): Probability that Δ exceeds the minimal detectable change (MDC) defined in Cerrito et al. (2017); 95% CrI: 95% Credible Interval.

<table>
<thead>
<tr>
<th></th>
<th>Descriptive</th>
<th>$\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (95% CrI)</td>
<td>Mean (95% CrI)</td>
</tr>
<tr>
<td>FE</td>
<td>T1</td>
<td>14° (8°, 20°)</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>16° (10°, 21°)</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>10° (4°, 16°)</td>
</tr>
<tr>
<td>LF</td>
<td>T1</td>
<td>12° (7°, 17°)</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>12° (7°, 17°)</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>14° (8°, 18°)</td>
</tr>
</tbody>
</table>

$\Delta$: Difference between time points; 95% CrI: 95% Credible Interval
FE: Flexion (+), Extension (-); LF: Lateral-flexion
T1: The ‘bind’; T2: Impact; T3: Sustained push

Table 8.2

Kinematic analysis of ‘neck line’ inclination at the ‘bind’ (T1), impact (T2) and sustained push (T3).

### 8.3.3 Differences in joint angles between time points

The largest differences in head orientation (Table 8.1) and ‘neck line’ inclination (Table 8.2) between time points were found in FE between T1 and T2 (-21°) and in LF between T2 and T3 (7°), respectively.

### 8.3.4 Direction of FE movements before and after T2

Mean cervical spine movement direction was into flexion prior to T2 with a mean slope of 0.49 and IQR of 0.39, which represents a mean head flexion of 25° performed in ~0.2 s.

Mean movement direction after T2 was into extension with a mean slope of -0.34 and IQR of 0.27, which represents a mean head extension of 17° performed in ~0.2 s (Figure 8.3).
8.3.5 Kinematic FE curve around T2

Individual and mean kinematic curves between Pre_T2 and Post_T2 showed that movement directions were uniform before and after inflection point was reached (Figure 8.3). However, although all curves showed similar traces, inflection point was not consistently reached at the same time point. Mean inflection point was reached 22 ms after impact and the IRQ showed dispersion of 40 ms (Figure 8.3).
8.4 Discussion

This study explored 3D cervical spine kinematics in front-row players during opposed scrummaging and investigated the effect of different phases of the scrum on motion patterns and/or posture of the cervical spine. To date, few studies have investigated cervical spine kinematics during scrummaging against opponents (Swaminathan et al., 2016a, 2016b) and none have characterised these kinematics at specific time points. Providing evidence regarding kinematics at specific time points, and particularly at and around the instant of impact, is important to better understand how scrum-related injuries to the cervical spine could occur (Silvestros & Cazzola, 2017).

Movement excursion values were found to range between 23% and 60% of participants' peak movement capacities, which is similar to what has been found in previous work (Swaminathan et al., 2016b). However, Swaminathan et al. (2016b) reported slightly larger values (30-65%), possibly due to the fact that the authors investigated kinematics during scrums involving 16 players. With only one front-row player scrummaging against two opponents, there are less interactions than when 16 players are involved, which is likely to result in a more stable scrum with less positional adjustments. Nevertheless, even in this reduced scrum formation, 60% of movement capacity is utilised in flexion, which represents a substantial deviation from the neutral posture and may lead to large stresses on spinal structures (Skrzypiec, Pollintine, Przybyla, Dolan, & Adams, 2007). Moreover, peak flexion most frequently occurs at or around the instant of impact, which is a critical moment in a scrum given large forces are dynamically applied to the player's spine (Cazzola et al., 2015; Silvestros & Cazzola, 2017). According to the literature, flexing the neck at and/or around the instant of impact particularly increases the risk of traumatic cervical spine injuries, due to the combination of dynamically applied compression forces and the 'flattened' cervical spine that cannot absorb large forces (Silvestros & Cazzola, 2017). Movements in other planes show
smaller excursions that most frequently occur when there is no contact between opposing players (LF and ROT) or during the sustained push phase (extension). Therefore, these movements may load spinal structures to a lesser extent during scrummaging. However, it should be noted that the sustained push phase also involves large compressive and shear forces (Cazzola et al., 2015) and that important deviations, not only into extension (-11°), but also into flexion (16°), LF (6° – 12°) and ROT (7° – 16°) can also occur during that phase. Given forces are applied at a much lower rate during the sustained push phase than at impact, it is conceivable that deviations from the neutral posture during the sustained push phase may contribute to overuse injuries (Milburn, 1990). However, this hypothesis requires further investigation because it could also be argued that constrained kinematics imply large stabilising action from neck muscles, which in turn apply large compressive forces to spinal structures and may lead to overuse injuries (Swaminathan et al., 2016b).

Absolute joint angle values at key time points were used to characterise cervical spine kinematics during scrummaging. These results show that head orientation in FE is close to neutral (-4°) when binding with opponents prior to engagement. At impact, the orientation of the head indicates substantial flexion of the cervical spine (17°) and a return to nearly neutral 2.5 s after impact (3°). Posture in LF and ROT appears to be further away from neutral at the 'bind' (8° and 12°, respectively) and during the sustained push (9° and 12°, respectively) than in FE, but closer to neutral at impact (11° in both cases). Hence, excursions in LF and ROT appear to be more stable than in FE that shows more variability between time points. Indeed, the differences in head orientation show larger differences between time points in FE (-21° and 14°) than in LF (7° in both differences) and ROT (8° and 6°). Moreover, the difference between T1 and T2 in FE is likely to exceed the MDC value by 13° with a probability of 0.92. That is, impact has a 92% probability of having an effect on cervical spine kinematics that can be considered 'true'. Although movements in other planes also have high
probabilities of exceeding the respective MDC values (0.80 – 0.98), these movements only exceed MDC values by a few degrees (1° – 4°).

When considering joint angle values obtained from 'neck line' inclination, it appears that flexion and extension is not homogeneously distributed throughout the cervical spine. Indeed, ‘neck line’ inclination values for FE show that the lower cervical spine is flexed throughout the entire scrum trials. Although there is a similar trend compared to the results found in head orientation in FE, with an increased flexion at impact, the differences in time points are smaller (-2° and 6°). These results suggest that the lower cervical spine is flexed throughout the scrum trial, while the upper cervical spine is probably extended at the ‘bind’ and during the sustained push phase. It is conceivable that players adopt this posture with the flexed lower cervical to allow sufficient anterior displacement of the head to allow interlocking with opponents without hitting opponents’ shoulders with their head. In contrast, players possibly extend their upper cervical spine to compensate for the flexed posture in the lower cervical spine. It is also possible that flexing the lower part of the cervical spine is particularly deleterious because that is the part of the cervical spine that is frequently affected by scrum-related injuries, such as facet joint dislocation (Trewartha et al., 2015). However, the reasons for this particular motion pattern should be further explored to determine whether and how this motion pattern can be improved.

‘Neck line’ inclination in LF show similar motion patterns compared to head orientation in LF. Posture in LF appears to be stable at the three time points (12°, 12° and 14°, respectively) and comparing the magnitudes of LF excursions in the lower and upper cervical spines reveals that most movement is performed in the lower cervical spine. It is therefore conceivable that a deviation into LF in the lower cervical spine could also increase the risk of unilateral facet joint dislocation because LF results in decreased articular congruence on the contralateral side of the movement direction (Kapandji, 2007). However, the clinical
significance of LF movement mainly occurring in the lower cervical spine is unclear yet and should be further investigated.

The slopes calculated prior to and after impact indicated that gross movement direction was towards flexion before impact and towards extension after impact. These results highlight again, that the engagement leads to an inevitable flexion of the neck in front-row players. On average, in this ~0.4 s time window between Pre_T2 and Post_T2, inflection point is reached just after impact (22 ms). However, there is an inconsistency in the time reaching inflection point (~40 ms) such that movement direction at impact, and consequently intervertebral kinematics (Anderst et al., 2013), vary to some extent. More importantly, movement direction and intervertebral kinematics can vary when the largest forces are applied to the spinal structures (i.e. 28-30 ms after impact), which might have significant clinical implications. According to Anderst et al. (2013), at a given head flexion angle, cervical vertebrae are in a more flexed position when coming from a relative flexion than from a relative extension. These authors have also shown that the inverse is true. Applied to the results of the present study, this implies that intervertebral angles are generally rather extended at impact and rather flexed 28-30 ms after impact. This rather flexed intervertebral alignment 28-30 ms after impact could potentially have additional influence on the risk of injury. However, given the reason for the variance in the time to reach inflection point is not clear, it is important to further investigate this parameter in future studies. Nevertheless, it appears critical to implement this intervertebral kinematic behaviour into musculoskeletal models to further study the risk of injury (Cazzola, Holsgrove, Preatoni, Gill, & Trewartha, 2017).

In summary, the results indicate that scrum phases have a pronounced effect on cervical spine kinematics, particularly in FE. Due to interlocking with opponents, front-row players are forced into neck flexion, which is likely to increase the risk of cervical spine injury (Silvestros & Cazzola, 2017). It is particularly important to note that the flexion angle found
in front-row players (17°) is close to the critical threshold of 20° reported by Silvestros and Cazzola (2017), at which the risk of injury increases substantially. Moreover, the movement direction observed 28-30 ms after impact could possibly further increase that risk of cervical spine injury by affecting spinal alignment. These findings may help clinicians and coaches develop training and rehabilitation programs. For example, it appears important to include exercises to strengthen the neck extensor muscles to protect the cervical spine from excessive flexion. Moreover, proprioceptive and kinaesthetic training could help players better coordinate movements occurring in the upper and lower cervical spine regions. However, given interlocking with opponents is critical to the scrummaging task, it is difficult to conceive a way to prevent neck flexion completely in front-row players. Coaches could consider teaching front-row players to adopt a lower body position to align trunk and head, but the efficacy of this strategy is questionable because opponents could copy this technique to avoid losing advantage. Hence, the issue of the flexed neck would remain. It is therefore conceivable that prevention strategies may need to focus on de-emphasising the impact through modifications of the scrum laws. In recent years, the engagement sequence has already been modified several times to reduce the forces involved at impact (Cazzola et al., 2015). Given neck flexion appears to be inevitable, it might be conceivable to adopt a new engagement sequence where both forward packs start pushing against each other after front-row players have interlocked. This way, the forward packs could not build momentum and there would be no dynamically applied forces. Moreover, as can be seen in Figure 8.3, Table 8.1 and Table 8.2, the magnitude of cervical spine flexion is greater at impact than during the sustained push, although front-row players are also interlocked during the sustained push. Hence, the momentum involved in the impact appears to have an effect on the magnitude of cervical spine flexion that could be avoided if the scrum contest started with interlocked front-row players. However, feasibility as well as effect on internal loads applied to spinal
structures should first be tested in such scrums with modified engagement sequence to direct further steps.

The study's main limitation was that no full scrums involving 16 players were used. Participants were investigated in the 'one-on-two' formation. Although the 'one-on-two' formation is more ecologically valid than machine-based scrummaging, kinematics presented in this study might still differ from those in competitive scrums. A second limitation was that kinetic data were not collected simultaneously. It is likely that concurrent collection of kinematic and kinetic data is key to identify precise injury mechanisms.

**8.5 Perspective**

This study is the first to characterise cervical spine kinematics in detail during opposed scrummaging during entire trials and with respect to key time points (the 'bind', impact and the sustained push). Therefore, by relating the findings to kinetic patterns reported in previous studies (Cazzola et al., 2015; Silvestros & Cazzola, 2017) a better understanding of the occurrence of scrum-related cervical spine injuries can be obtained.

Current findings have potential implications in research, as this study may stimulate further improvement in musculoskeletal models (Cazzola et al., 2017) by allowing separate movement in upper and lower cervical spine, as well as by implementing more detailed intervertebral cervical kinematics in accordance with movement direction (Anderst et al., 2013). These amendments might provide more detailed predictions when performing simulations. The findings also have potential implications for those involved in rugby, such as coaches and physiotherapists, who can benefit from more detailed characterisation of kinematic patterns to better prepare or rehabilitate players' prior to scrummaging. Finally, the findings have potential implications for governing bodies by highlighting that current
recommendation for 'safe and effective technique' (Posthumus & Viljoen, 2008) might be unrealistic and other means for injury prevention may be necessary, such as further modifications to the scrum laws.
References


Swaminathan, R., Williams, J. M., Jones, M. D., & Theobald, P. S. (2016b). Does the new rugby union scrum sequence positively influence the hooker’s in situ spinal kinematics? *BMJ Open Sport & Exercise Medicine, 2*(1), e000064.


CHAPTER 9

The influence of second-row players on lumbar spine kinematics of front-row players during rugby union scrummaging

This chapter includes a co-authored paper. The paper has been submitted for publication in the *European Journal of Sport Science* and is currently under review:

Declaration of co-authorship and contribution

The candidate's contribution to this article was as follows:

- conception and design of the research project
- analysis and interpretation of research data
- drafting and editing manuscript

_________________________________   18 September 2018

Student and Corresponding author of paper: Adrien Cerrito

_________________   18 September 2018

Principal supervisor: Professor Peter Milburn
9.1 Introduction

Rugby union (rugby) is a sport that involves frequent full-contact events, such as scrumming, where two formations of eight players (forwards) engage and push against each other to gain ball possession. Not surprisingly, rugby has a higher injury rate compared to other team sports that do not involve full-contact events (Trewartha 2013). The scrum has been identified as a particularly dangerous event with 8.1 injuries per 1000 scrums, compared to, for example, the tackle where 6.1 injuries occur per 1000 tackles (Fuller, Brooks, Cancea, Hall, & Kemp, 2007). Moreover, scrumming has been associated with 41% of cervical, 56% of thoracic, and 71% of lumbar spine injuries in players who are in the first line of the scrum (front-row players) (Trewartha, Preatoni, England, & Stokes, 2015). Spinal injuries represent a major concern due to their potentially, albeit rare, catastrophic consequences (Kaux et al., 2015). However, less severe spinal injuries, such as IVD prolapse, nerve root or soft-tissue damage occur more frequently and may lead to pain, transient neurological symptoms and inability to play (Fuller, Brooks, & Kemp, 2007). For example, data from 546 professional rugby players collected over two seasons revealed that non-catastrophic injuries to the lumbar spine were responsible for 1244 days of absence from training and competition, and that lumbar IVD injuries were the most common scrum-related spine injury diagnosis (Fuller, Brooks, & Kemp, 2007). However, although these data highlight the necessity to prevent scrum-related lumbar spine injuries, few studies have investigated lumbar spine biomechanics during scrumming (Swaminathan, Williams, Jones, & Theobald, 2016a, 2016b).

Nevertheless, biomechanical studies investigating internal loads in the lumbar spine have shown that the neutral lumbar spine posture could help decrease stress applied to spinal structures when exposed to compressive loads. For example, in an upright position, the kyphotic lumbar spine posture generates higher intradiscal pressure (1 MPa) in lumbar IVDs
than the neutral lumbar spine posture (0.7 MPa) when compressive loads are applied (Shirazi-Adl & Parnianpour, 1999). Similarly, the posterior portion of lumbar IVDs are more likely to fail under load when the lumbar spine is axially rotated (Newell et al., 2017). Based on these studies, adopting a neutral lumbar spine posture during many sports-related tasks has been promoted by sport scientists (Mawston & Boocock, 2012; Oshikawa, Morimoto, & Kaneoka, 2018; Schoenfeld, 2010), including scrummaging. For example, in a guideline for ‘safe and effective technique’, Posthumus and Viljoen (2008) suggest players should adopt a neutral lumbar spine posture during scrummaging. However, it has been reported that lumbar spine movement in front-row players significantly deviates from a neutral posture during contested scrummaging. Indeed, Swaminathan et al. (2016a) have shown that front-row players utilise 79-98% of their available range of lumbar movement in FE, 66-94% in LF, and 21-96% in ROT. Although causal relationship between lumbar spine posture and scrum-related injuries has not been investigated, it is conceivable that the large movement excursions reported by Swaminathan et al. (2016a) contribute to considerable strain on spinal structures and therefore to lumbar spine injuries. Yet, because Swaminathan et al. (2016a) investigated lumbar spine kinematics during contested scrums involving all 16 players, it remains unclear what factors influence posture during scrummaging. Front-row players’ ability to adopt and/or maintain a lumbar spine posture close to neutral could be affected by intrinsic factors (e.g. poor technique, reduced joint mobility or altered proprioception), by extrinsic factors (e.g. external perturbations in the form of interactions between players), or by both intrinsic and extrinsic factors. Hence, given there are no empirical data to determine the respective influence of the two factor types (i.e. intrinsic and extrinsic) on the ability to adopt a neutral lumbar spine posture during scrummaging, it is difficult for coaches and physiotherapists to design effective training or rehabilitation programs. Therefore, it is important to understand what type of factor influence lumbar spine posture in scrumming front-row players.
To determine the role of intrinsic type of factors on lumbar spine posture, lumbar spine kinematics must be investigated during one-man scrums, where individual players scrummage alone against a scrum machine. To determine the effect of extrinsic factors, lumbar spine kinematics must then be investigated during scrummaging with more players to generate interactions (i.e. external perturbations). Although many different scrum formations could be investigated, an important first step is to investigate the effect of adding two second-row players to the one-man scrum formation because of their considerable contribution to the total force production of the full scrum (Milburn, 1990). Thus, it is conceivable that the second-row players’ push could deform the front-row players' spine if they are unable to rigidly maintain a neutral posture. Therefore, the aim of the present study was to explore and compare lumbar spine kinematics in front-row players during one-man scrums and during scrums with the support of two second-row players. It was hypothesised that front-row players can maintain lumbar posture closer to the recommended neutral position when scrummaging alone than when scrummaging the support of second-row players due to their forward push.

9.2 Methods

9.2.1 Participants

Fifteen male front-row players were recruited from local rugby clubs. Players were included if they met the following inclusion criteria: i) being 18-45 years of age, ii) healthy, iii) currently playing, and iv) having no history of neck or shoulder surgery. A health questionnaire was used to screen players for health-related exclusion criteria: i) any injury in the past 12 months, which remained symptomatic and restrained from participating in normal training and/or competition, ii) serious illness (e.g. heart condition), and iii) acute condition
(e.g. fever). All players provided written informed consent prior to participation and the study was approved by the institution's ethics committee (Appendix 5).

9.2.2 Instrumentation

Spinal kinematics were recorded during simulated scrums against a static scrum machine using five calibrated DSLR cameras (DMC Lumix Fz300, Panasonic, Osaka, Japan) in movie mode. A photogrammetric control frame was hung in the cameras’ field-of-view to provide reference points for the photogrammetric processing. This method has been validated previously for measurement of 3D spinal geometry (Chong, Milburn, Newsham-West, & ter Voert, 2009). The cameras were mounted on a frame at approximately 1.5 m above the scrum and operated at 50 Hz (Figure 9.1). The measurement system was synchronised with a custom-designed LED-based timer placed in the field-of-view of all cameras and indicated the elapsed time during each trial with a resolution of 5 ms (Figure 9.1).

The scrum machine was custom-made such that it replicated a commercial scrum-sled's padding characteristics, allowing a scrummaging height of 40-110 cm. It was weighed down using gravel bags and spikes placed on its under-surface prevented sliding.
9.2.3 Experimental procedure

Data were collected on participants' respective home fields. Participants warmed up following a standardised routine consisting of body-weight squats (2 x 10 repetitions), shoulder abduction and flexion against resistance (2 kg mass, 2 x 10 repetitions each) and maximum head movement excursions (10 repetitions in FE, LF, and ROT each). A total of 10
anatomical landmarks (AL) were marked using a hypoallergenic pen: four on the thorax (spinous processes of C7 and T12, and left and right angulus costae of the 10th rib), two on the lumbar spine (spinous processes of L3 and L5) and four on the pelvis (Buganè, Benedetti, D’Angeli, & Leardini, 2014; Kadaba, Ramakrishnan, & Wootten, 1990; Leardini et al., 2007) (Figure 9.2). The pelvis was defined using left and right posterior superior iliac spines, as well as iliac crests, consistent with the procedure used in Cerrito, Evans, Adams, Pizzolato, and Milburn (2017). The AL on the iliac crest was identified as the point on the iliac crest that was at mid-distance between the anterior and posterior superior iliac spines.

Participants were then asked to practice scrummaging until familiar with the equipment and protocol. They were instructed to follow the call ‘crouch-bind-set’ provided by the researchers and to scrummage with intensity comparable to competitive scrums during all trials.

A static calibration trial was first recorded for each participant, where spinal posture was captured for 3 s in a crouched position. Then, kinematic data were recorded from scrums performed under two conditions: 1) alone against the scrum machine ('one-man scrum’), and 2) with the support of two second-row players pushing from behind ('supported scrum’). All 15 participants performed four one-man scrum trials and 11 participants performed four supported scrums.

9.2.4 Data processing

Data were analysed at key time points. For this purpose, still frames were extracted from the video clips from each camera using a custom-written Python (v. 2.7.13) script and the OpenCV library (v. 3.2.0). First, still frames were extracted from the static trial at 1.5 s (i.e. half-time). Then, in each scrum trial, still frames were extracted at three time points. The instant of impact, defined as the instant at which the marker of C7 stopped moving in scrummaging direction, was first identified. Then, the 'bind' phase (T1) was determined at 1 s
before the instant of impact (T2). The 'sustained push' phase (T3) was then identified 2.5 s after impact (Cerrito et al., 2017). Since the effective sampling rate of consumer-grade DSLR cameras does not precisely match the set rate (i.e. 50 Hz in this case) and is subject to drifting (Welty, Bartholomaus, O’Neel, & Pfeffer, 2013), the time indicated on the LED-based timer was used to achieve best synchronisation between the five cameras, rather than the frame number.

Extracted still frames were imported into the photogrammetry software Australis (v. 6.06, Photometrix, VIC, Australia), where ALs were digitised and calculation of the 3D coordinates was performed (Chong et al., 2009). The 3D coordinates were then imported into MATLAB (v. R2014a, MathWorks, MA, USA), where they were used to create two local coordinate systems (LCS_p and LCS_T) using a custom-written script (Figure 9.2). Based on homogeneous transform calculations (Craig, 2005), all AL coordinates were transformed into the LCS_p. Hence, the pelvis was considered as the origin of all spinal movements. Kinematics of the lumbar spine were calculated using the coordinates of T12, L3 and L5 (Figure 9.2). Thus, the lumbar spine was considered as two vectors representing upper (T12-L3) and lower lumbar spine (L3-L5), connected via a socket joint. Motion in FE was calculated using the orientation of the upper and lower lumbar spine vectors projected onto the sagittal plane of the pelvis. Motion in LF was calculated as medio-lateral displacement of the two vectors from the sagittal plane (Hestenes, 2002). To obtain a representation of lumbar spine motion, the lower lumbar spine was subtracted from the upper lumbar spine in both FE and LF calculations. Since the lumbar spine consisted of two vectors, ROT could only be calculated indirectly via the relative orientation between thorax and pelvis using an XYZ Cardan angle sequence (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2014). It was acknowledged, however, that lumbar movement excursion in ROT is small (~1° at each vertebral level) (Kapandji, 2007) and that the calculated orientation of LCS_T can be influenced by movement.
in the thoracic spine, as well as in the rib cage. Given the side-to-side symmetry of vertebrae, all movement excursions in LF and ROT were converted to absolute values to denote deviations from the neutral position. In contrast, since spinal structures are loaded differently during flexion compared to extension (Kapandji, 2007), positive (flexion) and negative (extension) values were kept in FE. In addition, joint angle offset measured from the static calibration trial was removed from LF and ROT in all scrum trials. This procedure was not performed for FE because it cannot be assumed that the lumbar spine is in neutral position when players are crouched. Indeed, it is possible that the adoption of a crouched position can influence the magnitude of lordosis/kyphosis, because the hip joint may be in end-of-range position (Oshikawa et al., 2018). Therefore, raw values were used for analysis.
Figure 9.2

a) Anatomical landmarks used to generate two local coordinate systems (i.e. LCS$_P$ and LCS$_T$).

b) Movement in FE and LF was calculated relative to the sagittal plane of the pelvis. Movement in ROT was calculated as rotation around the Z-axis of LCS$_P$. ROT was calculated from the rotation matrix describing thorax orientation relative to the pelvis.

9.2.4 Statistical analysis

Descriptive statistics (mean ± SD) were calculated for participant characteristics.

To examine the effect of scrummaging condition (one-man versus supported scrums) on lumbar spine kinematics in FE, a linear mixed effects model was used. The time points (T1-
T3) and the scrum condition constituted the fixed effects of the model. The random effects were the individual participants on which the repeated measurements were performed. To examine the effect of scrummaging condition on lumbar spine kinematics in LF and ROT, a linear regression model was used because the random effect of individual participants was negligible. A Bayesian framework with a Markov Chain Monte Carlo (MCMC) algorithm was used to conduct the estimation (Sorensen & Gianola, 2002). A burn-in period was set to 10000 iterations, and modelling was conducted using 60000 iterations. Thinning of the MCMC posterior draws was set such that every 5th simulation was retained. Given there have not been any similar investigations conducted, the coefficients were estimated using vague prior distributions. The estimates of interest, calculated from posterior distributions, were the posterior means ± 95% credible intervals (CrI) of each movement direction (FE, LF, and ROT) for both scrummaging conditions and at each time point. In addition, the differences (± 95% CrI) between one-man and supported scrummaging at T1, T2 and T3 were calculated. Finally, the probability that the differences between conditions exceed the minimal detectable change (MDC) defined in Cerrito et al. (2017), was calculated.

All statistical analyses were performed using a custom-written script in R (v. 3.5.0) (R Core Team, 2018) with MCMCglmm library (Hadfield, 2010).

9.3 Results

9.3.1 Participant characteristics

The mean age of participants was 24.9 ±6 years. The mean body mass (110.1 ±10 kg) and height (1.86 ±0.07 m) were comparable to those found in Zemski, Slater, and Broad (2015) for rugby forwards. Participants had an average of 10.9 ±7 years of playing experience.
### 9.3.2 Effect of scrummaging condition

Table 9.1 presents the summary of posterior distributions (means and 95% CrI) for all movement directions at all time points and under both scrummaging conditions. Table 9.1 also shows the differences between both conditions, as well as the MDC values for each movement direction and the probability with which the difference in kinematics exceeds the respective MDC value. The largest differences were found for FE, particularly at T2 (-12°) and T3 (-14°). These two differences also showed the highest probabilities of exceeding their respective MDC values (Pr = 1.00). Figure 9.3 illustrates posterior distributions of all movement directions and at all time points.

<table>
<thead>
<tr>
<th></th>
<th>One-man</th>
<th>Supported</th>
<th>Δ</th>
<th>Pr(Δ &gt; MDC)</th>
<th>MDC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>95% CrI</td>
<td>Mean</td>
<td>95% CrI</td>
<td></td>
</tr>
<tr>
<td><strong>T1</strong></td>
<td>FE</td>
<td>0° (-5°, 5°)</td>
<td>3° (-2°, 8°)</td>
<td>-3° (-6°, -1°)</td>
<td>Pr = 0.64</td>
</tr>
<tr>
<td></td>
<td>LF</td>
<td>1° (0°, 1°)</td>
<td>1° (1°, 2°)</td>
<td>0° (0°, 1°)</td>
<td>Pr = 0.00</td>
</tr>
<tr>
<td></td>
<td>ROT</td>
<td>1° (1°, 2°)</td>
<td>2° (1°, 2°)</td>
<td>0° (0°, 1°)</td>
<td>Pr = 0.00</td>
</tr>
<tr>
<td><strong>T2</strong></td>
<td>FE</td>
<td>-9° (-14°, -4°)</td>
<td>3° (-3°, 8°)</td>
<td>-12° (-16°, -8°)</td>
<td>Pr = 1.00</td>
</tr>
<tr>
<td></td>
<td>LF</td>
<td>3° (2°, 3°)</td>
<td>1° (0°, 2°)</td>
<td>2° (1°, 3°)</td>
<td>Pr = 0.03</td>
</tr>
<tr>
<td></td>
<td>ROT</td>
<td>3° (2°, 4°)</td>
<td>1° (0°, 2°)</td>
<td>2° (1°, 4°)</td>
<td>Pr = 0.00</td>
</tr>
<tr>
<td><strong>T3</strong></td>
<td>FE</td>
<td>-12° (-16°, -7°)</td>
<td>3° (-3°, 8°)</td>
<td>-14° (-17°, -11°)</td>
<td>Pr = 1.00</td>
</tr>
<tr>
<td></td>
<td>LF</td>
<td>1° (1°, 2°)</td>
<td>2° (1°, 2°)</td>
<td>0° (0°, 1°)</td>
<td>Pr = 0.00</td>
</tr>
<tr>
<td></td>
<td>ROT</td>
<td>2° (2°, 3°)</td>
<td>2° (0°, 3°)</td>
<td>1° (1°, 2°)</td>
<td>Pr = 0.00</td>
</tr>
</tbody>
</table>

Δ: One-man minus Supported; Pr(Δ > MDC): Probability that Δ exceeds the minimal detectable change (MDC) defined in Cerrito et al. (2017); 95% CrI: 95% Credible Interval

**T1**: the 'bind'; **T2**: impact; **T3**: sustained push

FE: Flexion (+), Extension (-); LF: Lateral-flexion; ROT: Axial rotation

Table 9.1

Outcomes of the linear mixed-effects model presented as summary of posterior distributions.
Illustration of posterior distributions of all movement directions and at all three time points (T1 = the 'bind', T2 = impact, T3 = sustained push). The black lines represent one-man scrummaging and the grey lines represent the supported scrummaging.

9.4 Discussion

To date, it is recognised that lumbar spine injuries are frequent in front-row players (Fuller, Brooks, & Kemp, 2007) and it is likely that large deviations from the neutral lumbar spine posture during scrummaging contribute to these injuries (Newell et al., 2017; Shirazi-Adl & Parnianpour, 1999). However, it remains unclear what types of factor influence players’ lumbar postural stability during scrummaging. This study explored and compared lumbar spine kinematics in rugby front-row players during one-man scrums against a scrum machine and during scrums with the support of two second-row players.

The results show that during one-man scrums, front-row players adopt a flat lumbar spine posture at the ‘bind’ prior to engagement. The narrow range of dispersion (95% CrI) also indicates that players adopt this posture relatively consistently (range -5° – 5°). It is
conceivable that players have difficulty adopting neutral posture in this position because hip joints are flexed maximally such that a posterior pelvic tilt can occur, particularly if players have reduced range in their hip joints (Oshikawa et al., 2018).

Further, results show that at the instant of impact and during the sustained push phase in one-man scrums players adopt a pronounced lordotic lumbar position. These results suggest that players actively try to match the ‘ideal’ posture recommended by coaches and the literature (Posthumus & Viljoen, 2008). Although it has been suggested that players should adopt the ‘ideal’ posture throughout the entire scrum event (Posthumus & Viljoen, 2008), it is certainly more important to adopt this posture when players are pushing forward. That is, adopting a straightened or kyphotic lumbar posture is less deleterious prior to engagement when no compression forces act on the spine compared to during engagement or the sustained push phase.

In contrast, in scrums with the support of two second-row players, front-row players generally adopt a substantially more kyphotic lumbar posture. Nevertheless, this difference is small at the ‘bind’ (-3°) because the lumbar spine also loses its neutral lordosis in one-man scrums. There is also only a relatively small probability (Pr = 0.64) that this difference exceeds the MDC value. That is, there is only a 64% probability that the difference in FE at the ‘bind’ between both scrumming conditions can be considered a ‘true difference’ that is not due to random variability. However, the difference in lumbar posture in FE is much more pronounced at the instant of impact (-12°) and during the sustained push (-14°). These differences exceed the MDC values by 6° and 7° respectively, and can be considered ‘true differences’ with a 100% certainty. These results suggest that considerable time should be devoted to the practice of the adoption of a neutral posture during supported scrums, because a kyphotic lumbar spine posture is likely to contribute to injuries. Indeed, Shirazi-Adl and Parnianpour (1999) have shown that intradiscal pressure in lumbar IVDs was higher when
compressive forces are applied to the kyphotic (~1 MPa) than to the neutral (~0.7 MPa) lumbar spine. In addition, neutral posture also decreased the strains applied to the IVD annulus fibres, especially in the two lowest vertebral levels (Shirazi-Adl & Parnianpour, 1999). Moreover, it is important to highlight that the study by Shirazi-Adl and Parnianpour (1999) did not consider loading rate, whereas Wang, Parnianpour, Shirazi-Adl, and Engin (2000) demonstrated that high loading rates considerably increase intradiscal pressure (+12%) and IVD annulus fibre strain (+18%). Therefore, considering the high rate of loading at the instant of impact, it is likely that scrummaging with the support of second-row players contributes to damage afflicted to the IVD when front-row players adopt kyphotic lumbar posture. Interestingly, comparing the results with the literature also reveals that the best postural correction might indeed be the adoption of the posture observed during one-man scrums. Hwang, Kim, and Kim (2009) used a similar approach to the one used in the present study to estimate neutral lumbar lordosis in adult males in standing position and reported a lordosis angle of 14° in a representative participant. Hence, although the lordosis angle is variable between individuals, it is conceivable that players adopt a lumbar posture that is close to the neutral lumbar lordosis at impact and during the sustained push in one-man scrums. However, the observed lumbar posture is slightly more flexed than 14° by 2° – 5°.

Shirazi-Adl and Parnianpour (1999) concluded in their study that a slightly decreased lordosis, compared to the neutral posture, protects the annulus fibres of the IVDs even more from strains, without increasing intradiscal pressure, ligament strains or loads on facet joints. Therefore, players appear to adopt the 'ideal' posture during one-man scrums, but not when two second-row players are pushing from behind. It should be noted, however, that an accurate comparison between the results of the present study and those found in the literature is difficult due to differences in study design and/or methodology. Therefore, the hypothesis suggested above needs to be further investigated.
With regards to the other movement directions, players show little excursion in LF and ROT (1° – 3°). Moreover, the results show no, or only small, differences in LF and ROT (0° – 2°) between the two scrummaging conditions. These results could suggest that second-row players are well coordinated with their forward push such that equal or similar amounts of forces are applied simultaneously to the right and left buttock of the front-row player. In such a case, the front-row player does not have to resist off-centred forces that could result in side-bending or torsional moments. However, these results could also suggest that front-row players are particularly effective in resisting these forces. Alternatively, both could be true, where second-row players are coordinated and front-row players are able to resist some amount of off-centred forces. Regardless, the results demonstrate that adding two second-row players to a one-man scrum formation does not substantially affect the front-row player’s lumbar posture in LF and ROT. Nevertheless, given it has been reported that in contested scrummaging 66-94% and 21-96% of the total movement capability is utilised in LF and ROT respectively (Swaminathan et al., 2016a), it appears to be important to further investigate different scrum formations. Indeed, it is known that particularly ROT can further reduce the resistance of the IVD to compressive loads (Newell et al., 2017).

The results of the present study have important implications for professionals who are involved in the technical and physical preparation, or in the rehabilitation, of front-row players. The results suggest that the addition of two second-row players substantially perturbs the lumbar spine posture adopted by front-row players during scrummaging, resulting in lumbar spine kyphosis. This posture can place additional load on lumbar structures potentially leading to injuries, especially to the IVD. Hence, a possible training progression could be to practice the neutral lumbar spine posture with the one-man scrum formation in the first instance. Then, once the posture is mastered in this formation, time should be spent on practicing the same posture with two second-row players pushing from behind. The
importance of this progression becomes even clearer when considering that, in a competitive scrum, a total of eight players are involved, which would likely further increase the unstable and unpredictable nature of the scrum. Therefore, it is conceivable that adding even more players could magnify the alteration in lumbar posture in front-row players and could represent further progression that could be implemented in a training or rehabilitation program. However, the effect of scrum formations with additional players on lumbar spine kinematics is currently unclear and should be investigated.

Nevertheless, there are several conceivable strategies coaches and physiotherapists could adopt to improve spinal posture in front-row players during scrums. First, improving physical deficits, such as weakness of the back and abdominal musculature, could be considered. Secondly, a more technical approach could integrate breathing techniques to increase spinal stiffness (Hodges, Martin Eriksson, Shirley, & Gandevia, 2005). Indeed, it has been shown that breathing manoeuvres, such as a forced exhalation could increase spinal stiffness (Kibler, Press, & Sciascia, 2006), which could make it more resistant against deformation. This technique is widely used in other sports such as weightlifting, tennis, and martial arts, and may represent an interesting technique to investigate (Callison, Berg, & Slivka, 2014; Turner, Baker, & Miller, 2011).

The present study has three main limitations that should be considered. First, kinetic data were not concurrently collected. Having force data would better monitor the consistency in force production over the repeated trials and detect any effects of fatigue. However, given participants had 1-2 minutes' break between trials, fatigue was not expected to occur (Cochrane, Harnett, Lopez-Villalobos, & Hapeta, 2017). Secondly, full ROM of the lumbar spine in a crouched position was not measured. Collecting ROM data could allow more detailed conclusions on movement excursion values observed during the scrum trials. However, performing a reliable ROM trial involving end-of-range lumbar flexion to
extension and side-to-side LF and ROT is a difficult task and was therefore not performed. Thirdly, it is important to realise that scrummaging conditions are likely to be different during competitive scrums than during 'one-man' or 'supported' scrums. Therefore, the results presented in this study might not represent kinematics found in competitive scrums. However, it was the purpose of this study to break down the scrum into these formations in a first step and it is acknowledged that further formations should be investigated in future studies.
References


CHAPTER 10

General discussion

In this thesis a novel method for the measurement of kinematics of the axial skeleton (i.e. pelvis, spine, thorax, and head) was developed and first steps were taken to investigate the influence of different scrum formations on spinal kinematics. The development of the measurement method, as well as the testing for accuracy and reliability, were presented in two studies. In four further studies, experimental data were collected to investigate spinal kinematics during scrummaging. A summary of each study is provided below, followed by a synthesis of the research findings and discussion about future research directions. Finally, the general conclusion of the thesis is presented.

10.1 Summary of the research

10.1.1 Study 1

Measuring cervical spine kinematics in rugby scrummaging is important from an injury prevention perspective. However, choosing an appropriate measurement system is challenging. Since reliability of a measurement system is critical for meaningful interpretation of results, this study evaluated the test-retest reliability of an electromagnetic tracking (EMT) and an optoelectronic motion capture system for measurement of cervical spine kinematics during scrummaging. Reliability of joint kinematics at discrete time points was evaluated using intraclass correlation coefficients (ICC), standard error of measurement, and minimal detectable change (MDC). Reliability of kinematic curves was assessed using coefficient of multiple correlations (CMC) and standard deviations (SD). In both systems, seven ICC values
were considered to be excellent (> 0.75), while two were fair to good (0.44 – 0.66) according to the criteria of Fleiss (1999). Minimal detectable change values for flexion/extension (FE) were found to be higher than for other movement directions, and CMC values were only moderate. Overall, reliability was comparable in both systems and was considered to be sufficient for the investigation of cervical spine kinematics during repeated scrums. This study therefore supported the use of EMT to measure spinal kinematics in further research steps taken in this thesis.

10.1.2 Study 2

Measuring spinal kinematics during rugby union scrummaging is important to better understand potential injury mechanisms and begin to develop prevention strategies. However, the nature of the scrum task makes it difficult to utilise standard methods such as optoelectronic motion capture systems. For example, the close and intense interactions between players during scrums are likely to result in detachment of retro-reflective markers. Alternative methods such as the use of low-cost cameras to perform close-range photogrammetric measurements could represent viable solutions but such methods need to be assessed for accuracy and reliability. Therefore, the aims of this study were to develop a system using five off-the-shelf cameras, to determine the quality of the calibration procedures and to assess tracking accuracy and reliability in both laboratory and field-based measurements. The results showed that the calibration procedures achieved high accuracy (0.04 – 3.20 mm) and reliability (0.00 – 0.98 mm). However, the results also showed that an external device providing synchronisation signal is required to identify key frames from the five cameras as frame rates were inconsistent. Errors in derived distance measures ranged between 0 and 1% (accuracy), and 0.1 and 4.2% (reliability) of the true distances in laboratory-based measures. Field-based measures revealed slightly larger errors but accuracy and reliability were considered sufficient for the proposed application.
10.1.3 Study 3

Understanding kinematics and movement variability of the axial skeleton (head, thorax, spine, and pelvis) during scrums in rugby union is important from a performance and injury prevention perspective. The aim of this study was to investigate repeatability of axial skeleton kinematics during one-man simulated scrums. Nine front row players performed scrums against a static scrum machine, and results showed high levels of repeatability. The outcomes of this study suggest that the difficulty in performing scrums well might not reside in the basic technique but be more associated with external factors, such as the interaction between players in a full scrum. Therefore, the results suggested that expert movement may better be achieved by practicing scrums under more realistic conditions than against a static scrum machine.

10.1.4 Study 4

The aim of this study was to compare cervical spine kinematics in rugby union front row players during machine-based and opposed scrummaging. Cervical spine kinematics were measured via EMT sensors attached to the head and thorax. Joint angles were extracted from each trial at two time points ('bind' prior to engagement and at the instant of impact) for comparison between scrummaging conditions. The effect of scrummaging condition on spinal kinematics was evaluated using a mixed effects model and estimations were based on a Bayesian framework. With differences ranging from 38° to 50°, the results showed that the cervical spine was consistently more flexed when scrummaging against opponents than against a scrum machine. In contrast, there were little differences in the excursion of lateral-flexion (LF) (range 5 – 8°) and axial rotation (ROT) (7°) between the two conditions. The findings from this study provided clear information on motion patterns in different scrum formations and suggested that the current design of scrum machines may not promote the same pattern of movement that occurs in opposed scrums. The results highlighted that findings from previous
studies that have investigated kinematics during machine-based scrummaging may not be
generalisable to a competitive scrummaging context.

10.1.5 Study 5

The aims of this study were first, to explore cervical spine kinematics in rugby union front-row
players during opposed scrummaging over entire trials and at key time points and secondly, to
determine the effect of scrum phases on cervical spine kinematics. Location and orientation of
the head relative to the thorax were captured during four trials in seven front-row players using
an EMT system. Kinematic analysis was performed such that movement occurring in the upper
and lower cervical spine regions could be inferred from kinematic data of the entire cervical
spine. Results from the entire cervical spine showed that participants utilised 60% of their total
movement capacity in flexion with peak flexion most frequently occurring at or around the
instant of impact. Other movement amplitudes were lower with 30%, 23%, and 26% of capacity
utilised in extension, LF and ROT, respectively. Amplitudes in these movements most
frequently peaked before impact or during the sustained push phase after impact where applied
forces are less dynamic. Impact increased flexion by 21° compared to the posture before
engagement. The increase in flexion primarily occurred in the upper cervical spine, given the
lower cervical spine was flexed throughout the entire trials (10° – 16°). Differences between
time points in LF in the lower cervical spine were low (7° – 8°). These results suggested that
cervical spine flexion appears to be inevitable, particularly at impact. Therefore, the current
safety recommendation to adopt neutral cervical spine posture may be difficult to apply and
further strategies for injury prevention should be explored.

10.1.6 Study 6
In rugby union scrummaging, front-row players often sustain acute and overuse lumbar spine injuries which can lead to physical impairment and to absence from play. Poor lumbar spine posture adopted by front-row players during scrummaging may contribute to these lumbar spine injuries. However, few studies have investigated lumbar spine kinematics in front-row players during scrummaging and therefore little is known about what factors influence lumbar spine posture. The focus of the present study was on determining whether individual technique and/or interactions with other players affect front-row players’ ability to adopt and/or maintain a neutral lumbar spine posture. For this purpose, lumbar spine kinematics were investigated in 15 front-row players during scrums under two conditions: i) one-man scrums, and ii) scrums with the support of two second-row players. Lumbar spine kinematics were recorded using the photogrammetric system presented in chapter 5. A Bayesian approach was used to determine the effect of scrummaging conditions which showed that players adopted neutral posture when scrummaging alone. In contrast, players adopted a kyphotic posture when support was provided by second-row players which may contribute to lumbar spine injuries. Only small differences were found between scrummaging conditions in LF and ROT of the spine. The results suggested that training and rehabilitation programs should focus on practicing a neutral posture during scrums involving second-row players.

10.2 Synthesis of the research findings

The work presented in this thesis serves to advance the field of scrum-related biomechanics through the development of a novel method for the measurement of 3D spinal kinematics. Moreover, it expands the state of knowledge on kinematics of the cervical and lumbar spine in front-row players during scrummaging, thereby providing further indication on how technique may be improved and injuries be better prevented.
In rugby union front-row players, scrum-related spine injuries represent a major concern particularly those affecting the cervical and lumbar spine (Fuller, Brooks, & Kemp, 2007; Trewartha, Preatoni, England, & Stokes, 2015). Although 3D kinematic investigations of the spine during scrums could provide information that may help develop more effective means for injury prevention, these studies are rare. One of the reasons for the lack of such studies is that recording spinal kinematics during field-based competitive scrummaging is technically challenging. Moreover, most traditional measurement systems are unsuitable for this task highlighting a need for an alternative method. In chapters 4 and 5 of this thesis, an alternative measurement method is proposed to address the limitations faced with traditional measurement systems. The results of these two chapters showed that a measurement method combining EMT and close-range photogrammetry can represent a viable alternative for the measurement of 3D spinal kinematics during scrummaging. Overall reliability of the EMT system for the measurement of the cervical spine was high and comparable to that of an optoelectronic motion capture system. However, relatively high MDC values (10° – 20°) were found in FE in both measurement systems, indicating it may be difficult to detect small changes in posture in the sagittal plane during repeated scrums. The low-cost photogrammetric system developed as a part of the present research presented sufficient tracking accuracy (0.38 – 2.44 mm) and reliability (0.53 – 4.60 mm) during field-based measures for the intended application. The measurement procedure was developed to be portable and to allow measurements performed both in- and outdoors, as well as for any scrum formation to increase its versatility. Indeed, given ecological validity of measures is important in sports science (Davids, 1988; Jobson et al., 2007), the ultimate goal would be to investigate scrum biomechanics during field-based, competitive scrummaging to obtain optimal representation of 'true' scrummaging conditions. However, because the scrum has the peculiar characteristic of involving 16 players, different
scrum formations needed to be investigated first to better understand the influence interactions between players may have on spinal posture in front-row players.

First steps have been taken in this thesis to investigate spinal kinematics during scrums under different formations and these studies are presented in chapters 6 to 9. The results presented in chapter 6 showed that during one-man scrums performed in a laboratory environment, movement variability was generally low indicating players performed the scrum technique very consistently, except for FE in the cervical spine. These results suggest that the complexity of the scrum task may reside in other aspects of the scrum, such as maintaining a neutral spinal posture during the scrum while generating and transmitting pushing forces.

Regarding the large movement variability for FE in the cervical spine, these results indicated that scrummaging against a scrum machine does not replicate realistic conditions. Indeed, movement variability for FE in the cervical spine was large at impact and during the sustained push which are two highly critical phases as they imply large forces and a misalignment of the cervical spine could result in serious injuries (Cazzola, Preatoni, Stokes, England, & Trewartha, 2015; Preatoni, Stokes, England, & Trewartha, 2015). Therefore, the results indicated that the basic scrum technique can be learnt with the 'one-man' formation and practiced in early stages using a scrum machine but training should rapidly evolve towards more realistic scrummaging scenarios.

In other sports, such as running (Hamill, Palmer, & Van Emmerik, 2012), it has also been suggested that movement variability should be considered in relation to occurrence of overuse injuries. However, the role movement variability plays in the development scrum-related overuse injuries is difficult to determine (Swaminathan, Williams, Jones, & Theobald, 2016b) and remains unclear after the study presented in chapter 6. This aspect should be further
investigated under different scrum conditions, in computer simulations with repeated scrum iterations and/or in cohort studies.

The results presented in chapter 7 supported the conclusion drawn in chapter 6, which highlighted that scrum machines have limited potential to improve technique particularly for the adopted head and neck posture. Comparing cervical spine kinematics between scrums in 'one-man' and 'one-on-two’ (i.e. opposed) formations showed that motion patterns were substantially different between conditions. Differences of up to 50° in FE were found between both scrummaging conditions, with opposed scrums resulting in a more flexed neck posture than during one-man scrums. In LF and ROT, only small differences were found between scrummaging conditions. These results further suggested that the time spent on practicing one-man scrums against a scrum machine should be kept to a minimum since this training does not replicate competitive scrum conditions well, where the cervical spine is forced into flexion.

However, those who are involved in preparation and/or rehabilitation of front-row players should be aware that coordination between the upper and lower cervical spine regions is more complex than previously assumed (Cazzola et al., 2015; Silvestros & Cazzola, 2017; Swaminathan et al., 2016b; Swaminathan, Williams, Jones, & Theobald, 2016a) and that practicing against a scrum machine may represent a safe environment to improve neck posture prior to competitive scrumming. Indeed, neck flexion is likely to be heterogeneously distributed between upper and lower cervical spine regions, where the lower cervical spine is flexed and the upper cervical spine is in neutral or even extended posture. Therefore, coaches could purposefully use a scrum machine to practice neutral cervical spine posture, as per recommendations for ‘safe and effective technique’ (Posthumus & Viljoen, 2008) and improve coordination between upper and lower cervical spine before progressing with opposed scrums.
In the study presented in chapter 8, cervical spine kinematics were further investigated during opposed scrummaging in the ‘one-on-two’ formation. The results showed that players used up to 60% and 30% of their movement capacity in flexion and extension respectively. In contrast, only 23% and 26% of the total movement range was utilised in LF and ROT, respectively. Most frequently, peak flexion occurred at or around impact. Reaching peak flexion at or around impact is likely to increase the risk of injury given this phase imparts the largest loads to the players’ cervical spine (Silvestros & Cazzola, 2017) and the flexed cervical spine is less able to absorb large forces before failure of spinal structures occurs (Benzel, 2012). Indeed, at impact the cervical spine was increasingly flexed by 21° compared to the posture before engagement. Conversely, LF and ROT appeared to be more stable through the different phases of the scrums and often reached peak values before engagement. It should also be noted, however, that significant movement excursions were observed in all planes during the sustained push phase which might contribute to overuse injuries.

This study was the first to consider movement direction in the sagittal plane prior to and after impact as an additional parameter influencing spinal alignment and the risk of cervical spine injury. The results showed that the gross movement direction before impact was towards flexion, with the mean change of direction (i.e. inflection point) reached 22 ms after impact. In contrast, after the inflection point, movement direction was towards extension. This movement pattern may represent an additional factor influencing the risk of cervical spine injury because in a given posture, the cervical intervertebral alignment is more flexed when moving towards extension than towards flexion (Anderst, Donaldson, Lee, & Kang, 2013). However, it is important to note that there was some inconsistency with the time to reach inflection point such that the involvement of this parameter in scrummaging safety remains unclear.

In the final study, presented in chapter 9, lumbar spine kinematics were explored in one-man scrums and in one-man scrums with additional support from two second-row players pushing
from behind (supported scrums). The results showed that players adopted a ‘flattened’ lumbar spine posture prior to engagement but adopted a posture close to neutral at impact and during the sustained push phase. In contrast, during supported scrums, front-row players adopted a much more kyphotic posture (12° – 14°) than during one-man scrums which is likely to contribute to overuse injuries to the lumbar spine. Indeed, it has been reported multiple times that the lumbar spine can resist compressive loads best when in a posture close to neutral (Shirazi-Adl & Parnianpour, 1999; Wang, Parnianpour, Shirazi-Adl, & Engin, 2000).

Movements in other planes (LF and ROT) showed only small differences between one-man and supported scrums which may indicate, for example, that front-row players were particularly skilled at preventing lumbar spine LF and ROT. Alternatively, these findings could also indicate that second-row players were well coordinated such that no movement around antero-posterior and cranio-caudal axes were generated in the front-row player’s lumbar spine.

10.3 Future research directions

10.3.1 Methodological considerations

In this thesis, kinematic analyses were based on forward kinematic calculations and kinematic evaluations were performed by comparing the results with basic biomechanical studies of the spine (Anderst et al., 2013; Oktenoğlu et al., 2001; Shirazi-Adl & Parnianpour, 1999; Wang et al., 2000). To reduce these limitations, future studies could consider introducing the recorded data into a musculoskeletal model and simulation framework such as OpenSim. Using musculoskeletal modelling could allow the application of certain geometric constraints to the studied joints, such as maintaining a certain distance between two anatomical landmarks, to decrease the effect of soft-tissue artefact. Cazzola, Holsgrove, Preatoni, Gill and Trewartha (2017) have developed a musculoskeletal model to investigate loads applied to the cervical
spine and this model has been used to study scrum biomechanics (Silvestros & Cazzola, 2017). Using such a musculoskeletal model allows direct estimation of loads applied to individual cervical vertebrae rather than having to compare results with the basic biomechanical studies (Anderst et al., 2013; Oktenoğlu et al., 2001; Shirazi-Adl & Parnianpour, 1999; Wang et al., 2000).

However, the study presented in chapter 7 emphasised that cervical spine kinematics captured during machine-based scrummaging does not accurately represent cervical spine kinematics in opposed scrums. Although Silvestros and Cazzola (2017) accounted for this issue by exploring scrum scenarios with an increasingly flexed neck model, it remains unclear whether adding a flexion offset to a set of recorded kinematic data represents ‘true’ motion patterns. In this thesis, it has been demonstrated that measuring cervical spinal kinematics during opposed scrummaging is feasible using EMT and, therefore, it is suggested recording cervical spine kinematics in this scrum formation to drive musculoskeletal models.

Moreover, the study presented in chapter 8 also highlighted that musculoskeletal models of the cervical spine could be improved to better represent the functional anatomy of the cervical spine. The cervical spine can be divided into upper (C1-C2) and lower (C3-C7) cervical spine regions (Kapandji, 2007) and given both regions can move independently, the coordination between both regions can have significant influence on the alignment of the cervical spine (Ordway, Seymour, Donelson, Hojnowski, & Edwards, 1999; Penning, 1978). Therefore, improvements in musculoskeletal models could involve kinematic separation of the upper and lower cervical spine regions and/or dependence of cervical intervertebral alignment on movement direction, rather than only head orientation since movement direction has also been shown to influence intervertebral kinematics (Anderst et al., 2013).

10.3.2 Experimental considerations
Understanding the occurrence of injuries and the factors that influence the risk of injury are highly complex tasks. Many factors can be influential and all should be investigated using a systematic approach involving multiple research steps. In this thesis, only a small part of all possible interactions between players has been investigated. Therefore, future experimental studies should investigate the influence of other scrum formations on front-row players’ spinal kinematics. For example, the next step could involve a combination of the 'opposed' and the 'supported' formations. This scrum formation, where front-row players would scrummage against two opponents with the support of two second-row players could possibly magnify the effects found in this thesis. More formations could then also be investigated until full scrum formation is reached.

In the study on lumbar spine kinematics presented in chapter 9, specific intrinsic factors that could potentially influence lumbar spine posture were not investigated. For example, it would help coaches and physiotherapist to know whether hip joint hypomobility or poor lumbo-pelvic proprioception can affect lumbar spine posture during scrums and whether these factors are actually prevalent in front-row players. This knowledge would allow the development of further training and rehabilitation strategies to better prevent new or recurrent injuries to the lumbar spine.

More drastic means of injury prevention could also be explored, such as further modifications of the engagement sequence as suggested in the study presented in chapter 8. For example, an engagement sequence, where players start pushing after front-row players have interlocked, is conceivable. Such a sequence would decrease the dynamically applied forces at impact, while keeping the contested aspect of the scrum during the sustained push. Such modifications should be investigated by collecting in vivo data and possibly analysing these data in silico to obtain detailed spinal loading profile.
Finally, factors that are not specific to scrummaging should also be investigated. For example, fatigue can influence control of spinal stability (Granata, Slota, & Wilson, 2004) and has also been suggested as a potential risk factor for injury (Williams, Trewartha, Kemp, & Stokes, 2013). It is therefore conceivable that fatigue accumulated during a match could influence spinal kinematics in front-row players during scrums and lead to injuries. The effect of fatigue could be investigated by collecting kinematic data during scrums before and after a fatiguing protocol, such as the Bath University Rugby Shuttle Test (Roberts, Stokes, Weston, & Trewartha, 2010).

10.4 Conclusion

In conclusion, this study demonstrated that an alternative measurement method consisting of an EMT and a close-range photogrammetry system can be used to accurately and reliably capture spinal kinematics in front-row players during scrummaging. This, or a similar method could be used in future studies to further investigate spinal kinematics in front-row players during contested scrummaging. This method allows a more versatile use than, for example, optoelectronic motion capture systems and allows a more detailed kinematic analyses than, for example, inertial sensors.

The first steps in exploring spinal kinematics in front-row players during scrummaging and investigating the effect of scrum complexity on the kinematics revealed that one-man scrums against a scrum machine might be a good formation to learn the basic scrum technique, but has limited potential to improve that technique. Adding players to the ‘one-man’ scrum formation significantly influences front-row players’ cervical and lumbar spine kinematics and is thought to augment the risk of spinal injury because the spine is often forced into postures that increase loads applied to spinal structures. Coaches and clinical practitioners should be aware of these
effects resulting from interactions between players to carefully design training or rehabilitation programs. Furthermore, researchers should be particularly aware that the functional anatomy of the cervical spine is more complex than a socket joint and that movement direction in FE may also play an important role in the occurrence of cervical spine injuries. Finally, with regard to cervical spine injuries specifically, it appears difficult to further prevent these injuries via technical or muscular strengthening training, such that further modifications to the scrum engagement law could be considered.
References


Swaminathan, R., Williams, J. M., Jones, M. D., & Theobald, P. S. (2016b). Does the new rugby union scrum sequence positively influence the hooker’s in situ spinal kinematics? *BMJ Open Sport & Exercise Medicine, 2*(1), e000064.


Appendices

Appendices 1 to 3 show material used to develop the alternative measurement method presented in this thesis.

Appendices 4 and 5 present the ethical clearance to perform the experimental studies with participants provided the ethics committee of Giffith University.
Appendix 1

Structural design of the scrum machine used in this research project
Appendix 2

Design of the jersey used by players in this research project
Brief

Develop a rugby jersey for front rowers that has an open back in order to scan the back in the action of scrumming. Understanding the forces and movements of the back under the immense pressure of scrums.

Must have a much visible space of the back as possible for the red scanning dots to be visible.

Requires bind point on jersey below the shoulder/arm area. May not be necessary for preliminary tests.

Initial Concept Sketches

Fig. 1 Fig. 2

Fig. 3 Early development considered numerous options. Initial ideas looked to use existing jerseys as a base.

In Fig. 3, exploring the possibility of using cutting out large chunks of the jersey to reveal as much of the back as possible. This could be an option although strength and longevity are an issue.

Fig. 4

All designs are using a form of elastic stretchy strapping across either that back or around the entire torso. This could be easily stitched onto an existing jersey. Initially cutting out sections to reveal the most area and then reinforcing select areas with strapping.

Fig. 5

Fig. 6
Further Development

Further development and research considered a potential to design a one-piece suit for extra strength. Early prototypes can be created by stitching together a top and bottom and removing the back area, then reinforcing the weakest most necessary points with elastic strapping.
Material Research

Further research into material types leads to more opportunities with varying material/fabric types. Stretchy see through fabrics are one that may be worth testing. Base fabrics for this type of project are the following:

- **Spandex** - Stretch fitting fabric.
- **Neoprene** - Stretchy fitting fabric.
- **2-Way stretch Mesh** - Somewhat see through, may be a possibility dependant upon testing. Various colours available.
- **Polyester/Spandex Mix** - Stretchy durable, less stretchy than spandex and neoprene.
- **Fish net Mesh** - Somewhat see through, may be a possibility dependant upon testing.
- **Elastic Strap** - Used for bracing across body and across back where necessary.
- **Elastic Rope** - Used for bracing across body and across back where necessary.
- **Elastic Adjustable Strap** - Possible to use Velcro strap to help fix and adjust to a variety of body types and for bind grip.

Testing of various types would be necessary to understand the best solutions.
Prototype Possible Solution

First prototypes could be very easily and cheaply made from existing products bought of the shelf, i.e. the garment below from King Gee. This is relatively cheap and could provide a solid base to work from.

Initial designs could be done as follows:

1. Purchase blank
2. Cut away back section.
3. Stitch in reinforcement. Elastic straps to go all the way around the body for extra strength. These would need to be removable in order to put the suit on.
4. Stitch together with bottoms.
Costing

Suggested costing for base products and elements are as follows:

**KING GEE**
COMPRESSION SHORT SLEEVE TOP -
$49.99

**KING GEE**
COMPRESSION SHORTS
$49.99

**SPOTLIGHT**
BIRCH ELASTIC
$2.99 - $6.99 p/m

**SPOTLIGHT**
PLASTIC D RING
$2.39 - $3.49
Appendix 3

Structural design of the frame that was used in this research project to mount the cameras and attach the control frame. Figure A represents a side-view and Figure B a back-view.
Appendix 4

Ethical approval for the studies 'Cervical spine kinematics measured during rugby union scrums: Reliability of optoelectronic and electromagnetic tracking systems' (chapter 4) and 'Kinematics of the axial skeleton during one-man rugby union scrums' (chapter 6). Approval document received via email from Office for Research on July 30 2015:

GRiffith University Human Research Ethics Committee

30-Jul-2015

Dear Dr. Evans

I write further to the additional information provided in relation to the provisional approval granted to your application for ethical clearance for your project "Repeatability of head and neck kinematics in simulated scrums" (GU Ref No: AHS/42/15/HREC).

The additional information was considered by Office for Research. This is to confirm that this response has addressed the comments and concerns of the HREC.

Consequently, you are authorised to immediately commence this research on this basis.

The standard conditions of approval attached to our previous correspondence about this protocol continue to apply.

Regards

Ms Kim Madison
Policy Officer
Office for Research
Bray Centre, Nathan Campus
Griffith University
ph: +61 (0)7 373 58043
fax: +61 (07) 373 57994
email: k.madison@griffith.edu.au
Appendix 5

Mathematical formulae used for kinematic and statistical calculations in chapters 4, 5, 6, 7, 8 and 9.

- Homogeneous transform used to align coordinate systems:

\[ A_P = \hat{\alpha}^B_T \hat{B}^P \]

where \( A_P \) and \( B_P \) represent the 3D coordinate vectors of the same point P relative to the reference frames \{A\} and \{B\}, respectively. \( \hat{\alpha}^B_T \) describes the orientation and location of the reference frame \{B\} relative to \{A\}.

- Definitions of the used reliability indices:

  o Standard error of the measurement (SEM):

  \[ SEM = SD \sqrt{ICC(1 - ICC)} \]

  where SD is the standard deviation of the values around the grand mean and ICC is the intraclass correlation coefficient for that variable.

  o Minimal detectable change (MDC):

  \[ MDC = SEM \times 1.96 \times \sqrt{2} \]
Appendix 6

Ethical approval for the studies 'Close-range photogrammetry for the measurement of spinal kinematics in rugby union scrums' (chapter 5), 'Cervical spine kinematics during machine-based and opposed scrumming' (chapter 7), 'Cervical spine kinematics during opposed scrumming' (chapter 8) and 'The influence of second-row players on lumbar spine kinematics of front-row players during rugby union scrumming' (chapter 9). Approval email received from Office for Research on May 2 2017:

GRiffith University Human Research Ethics Committee

Dear Dr Kerrie Evans

I write in relation to your application for ethical clearance for your project "Spine and head kinematics in field-based Rugby scrums" (GU Ref No: 2017/254). The research ethics reviewers resolved to grant your application a clearance status of "Fully Approved".

This is to confirm receipt of the remaining required information, assurances or amendments to this protocol.

Consequently, I reconfirm my earlier advice that you are authorised to immediately commence this research on this basis.

The standard conditions of approval attached to our previous correspondence about this protocol continue to apply.

Regards

Kim Madison | Human Research Ethics

Office for Research
Griffith University | Nathan | QLD 4111 | Level 0, Bray Centre (N54)
T +61 7 373 58043 | email k.madison@griffith.edu.au