Tierney, G. J., Gildea, K., Krosshaug, T., Simms, C. K. (2019). Analysis of ball carrier head motion during a rugby union tackle without direct head contact: A case study. *International journal of sports science & coaching, 14(*2), 190-196.

Analysis of ball carrier head motion during a rugby union tackle without direct head contact: a case study

Gregory J. Tierney[1]

gtierne@tcd.ie

Kevin Gildea[1]

kgildea@tcd.ie

Tron Krosshaug[2]

tron.krosshaug@nih.no

Ciaran K. Simms[1]

csimms@tcd.ie

[1] Trinity Centre for Bioengineering, Trinity College Dublin, Ireland

[2] Oslo Sports Trauma Research Centre, The Norwegian School of Sport Sciences, Oslo, Norway

Short Title: High ball carrier head kinematics in a rugby union tackle

Corresponding Author:
Gregory Tierney
Trinity Centre for Bioengineering
Trinity College Dublin
Dublin 2
Ireland
gtierne@tcd.ie
+353 89 2381688

Abstract

Rugby union players can be involved in many tackles per game. However, little is known of the regular head loading environment associated with tackling in rugby union. In particular, the magnitude and influencing factors for head kinematics during the tackle are poorly understood. Accordingly, the goal of this study was to measure head motion of a visually unaware ball carrier during a real game tackle to the upper trunk with no direct head contact, and compare the kinematics with previously reported concussive events. Model-Based Image-Matching was utilised to measure ball carrier head linear and angular velocities. Ball carrier componential maximum change in head angular velocities of 38.1, 20.6 and 13.5 rad/s were measured for the head local X (coronal plane), Y (sagittal plane) and Z (transverse plane) axes respectively. The combination of a high legal tackle height configuration and visually unaware ball carrier can lead to kinematics similar to average values previously reported for concussive direct head impacts.

Introduction

Head injuries remain a considerable concern in rugby union. An emerging field in brain injury research is the study of repeated sub-concussive head impacts [1-3], defined as "head impacts that do not result in symptoms typically used to define concussion [4]". The definition of sub-concussive impacts presents challenges as a lower threshold for sub-concussive impacts has not been established. However, for practical purposes, events that result in less than 10g head acceleration have generally not been considered in rugby union head kinematic studies [5 6]. In sports such as boxing and soccer, sub-concussive head impacts have been linked with acute changes in brain function [2], structural changes in white matter [1], biomarkers of neuronal injury [3] and short term cognitive impairments [7]. Thus, although the long-term effects are not yet fully understood, it is believed that repetitive sub-concussive impacts can lead to long term neurodegenerative complications [8].

Head linear and angular kinematics are linked to brain injury [9-13]. Studies generally focus on the magnitude of a single hit [9-13]. For example, McIntosh et al. [9] found that concussive direct head impacts cause on average 103g of peak resultant head linear acceleration and a change in head angular velocity of 33 rad/s. However, there is an emerging concept of neuronal vulnerability to injury due to repetitive sub-concussive loading if the time between hits is sufficiently small (up to 24 hours) [4 14 15]. Merchant-Borna et al. [4] argues that injury thresholds should not be based on a single hit but that the number and magnitude of hits and the time between hits should also be considered. In extreme cases, rugby union players can be involved in over 30 tackles per game [16]. However, little is known of the regular head loading environment associated with rugby union. In particular, the magnitude and influencing factors for head kinematics during regular rugby union play without any direct head contact are poorly understood, even though a recent video review found that 1 in 7 head injury assessments in rugby union could not be associated with a specific collision event [17].

During one season of an amateur rugby union team, King et al. [5] recorded 181 impacts (0.9% of total impacts) over 95g (head linear acceleration concussion injury threshold utilised for comparison by King et al. [5]) and 4452 impacts (21.5% of total impacts) over 5500 rad/s^2 (head rotational acceleration concussion injury threshold utilised for comparison by King et al. [5]). However, no diagnosed concussive head impacts were included in this dataset. King et al. [5] reported that inertial head loading (no direct head contact) most likely accounted for a high proportion of these large head kinematic values recorded. However, no further assessment was provided.

In rugby union, the ball carrier can be visually unaware of an approaching tackler, i.e. not anticipating the tackle [18], and failing to brace may result in a higher susceptibility to injury [18] and could lead to higher inertial head loading. Direct measurement of head kinematics during tackling with on-field measurement devices remains challenging [5]. An alternative approach is to use Model-Based Image-Matching (MBIM) [19] [20]. This approach uses multiple camera views of an impact and a computerised skeletal model to extract six degree-of-freedom head kinematics directly from video. Accordingly, the goal of this exploratory study is to use MBIM to measure head kinematics of a visually unaware ball carrier during a real game shoulder tackle [21] to the upper trunk and to compare to average concussion kinematics values reported in the literature for direct head impacts [9]. The approach provides a case specific example to the body of evidence on the regular head loading environment in rugby union.

Methods

Similar to a previous video analysis study on knee injuries in rugby union [22], video search engines (e.g. YouTube) were utilised to identify suitable clips. The three selection criteria utilised were 1) contact was to the upper trunk (Figure 1) of the ball carrier [23]; 2) The ball carrier was visually unaware of the tackle (tackler approaching outside the ball carrier's peripheral vision [24 25]); 3) there was a minimum of three synchronisable camera views of the tackle event available for MBIM reconstruction [19]. Although Tierney et al. [24 25] found that the ball carrier is visually unaware during roughly one-third of side-on tackles, only one tackle event satisfied all criteria (due to criterion #3). In this single tackle event, the ball carrier had just passed the ball and was impacted around the left scapula by the tackler (Figure 2). The player received on-field medical attention but was not immediately removed from play and the subsequent medical history is unknown. The tackle was reviewed by the on-field referee/video referees and was deemed legal play as the tackler had committed to the tackle before the ball was passed. The video data was freely available online and no medical data was obtained/reported in this study, so ethical permission was not required, similar to other rugby union video analysis studies [22 26 27].

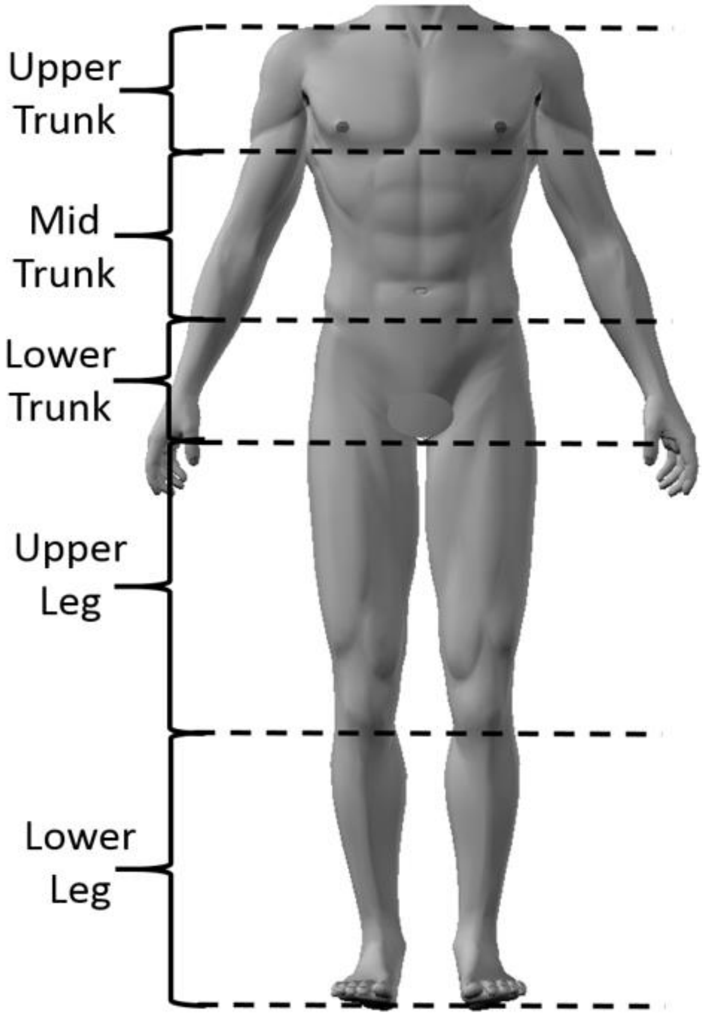

Figure 1. The body regions of the ball carrier.

MBIM has been previously described in detail by Krosshaug and Bahr [28]. Briefly, this method uses a multibody skeleton model to estimate human body joint angle time-histories from multiple camera views of human movement. For every video frame, the skeleton model joint angles are manually adjusted to match the segment position and orientation of the model with respect to the target athlete in the multiple camera views. The MBIM technique has been validated previously for six degree of freedom tracking of the pelvis [28], hip [28], knee [28], ankle [29] and head [19]. The MBIM analysis has been shown to be repeatable by both a single researcher and multiple researchers for six degree of freedom head motion data (Intra-class Correlation Coefficients (ICC) greater than 0.9 for six degree of freedom head displacement measurement) [19]. The method has previously shown Root Mean Square (RMS) errors of less than 20 mm for linear displacement and less than 0.04 rad for rotational displacement for reconstructing head motion in a vehicle cadaver head-windscreen impact [19]. However, RMS errors up to 5.38 rad/s were reported or the MBIM method for measuring angular velocity during direct head impacts [19]. The MBIM method is considered suitable for measuring componential angular velocity during indirect head impacts (i.e. inertial head kinematics as a result of an impact to the body) for which lower frequency head motion is typically associated with [30].

In this case, matching was conducted on synchronised video of three camera views of the tackle. Each video had a resolution of 720p and frame rate of 25 fps. One researcher performed the matching using 3-D animation software Poser 4 and Poser Pro Pack (Curious Labs Inc, Santa Cruz, California). The surroundings were built in a virtual environment based on the dimensions of the rugby field. The videos were imported into the Poser workspace background and the surroundings were then matched to the background video footage for every camera view. As the camera locations were unknown, this was achieved by manually adjusting the camera positioning tool which contains three translational and three rotational degrees of freedom, as well as variable focal length. Since the cameras were moving during the impact, the environment matching was conducted for each individual video frame. A skeleton model from Zygote Media Group Inc (Provo, Utah, US) was manipulated to fit the player's head for each video frame (Figure 2). Linear closing speed estimates were also calculated by tracking the players' pelvises using the MBIM approach utilised by Krosshaug and Bahr [28].

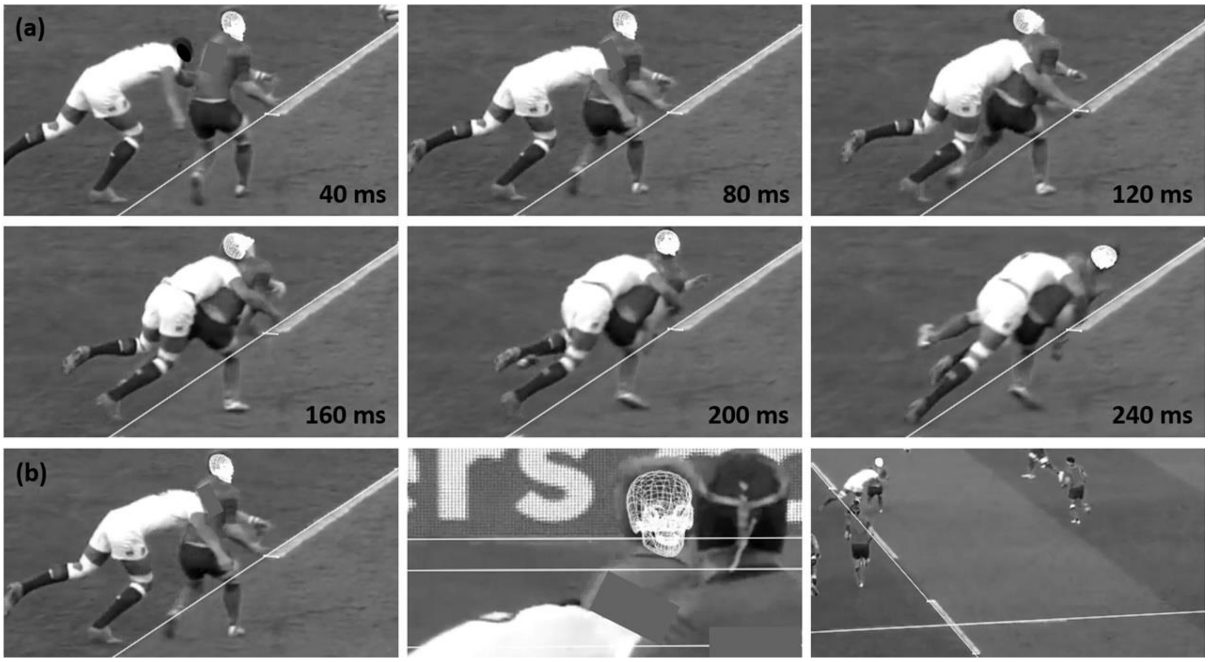

Figure 2. (a) A time lapse of the upper trunk active shoulder tackle with the MBIM matching for one camera view and (b) the MBIM matching for three camera views at time t=80ms.

This approach yielded head successive rotation angles of order yaw-pitch-roll (or Z-Y-X see Figure 3 [19]) and linear position measurements every 40ms. The time derivatives of the yaw, pitch and roll angles were calculated using the Matlab gradient function and hence the components of the body local head angular velocity (Figure 3) every 40ms were calculated [19]. The same method was used to calculate the head and pelvis linear velocity components in the global coordinate system (Figure 4). The maximum change in head componential angular velocity values were compared to the average concussion values reported in the literature for unhelmeted sports [9]. The comparison was not conducted for the maximum change in head linear velocity results, as componential data is not available for unhelmeted sports [31].

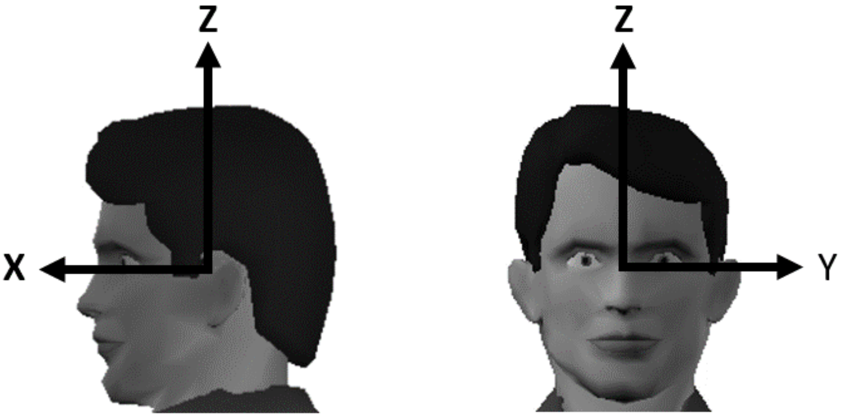

Figure 3. The local axes of the head.

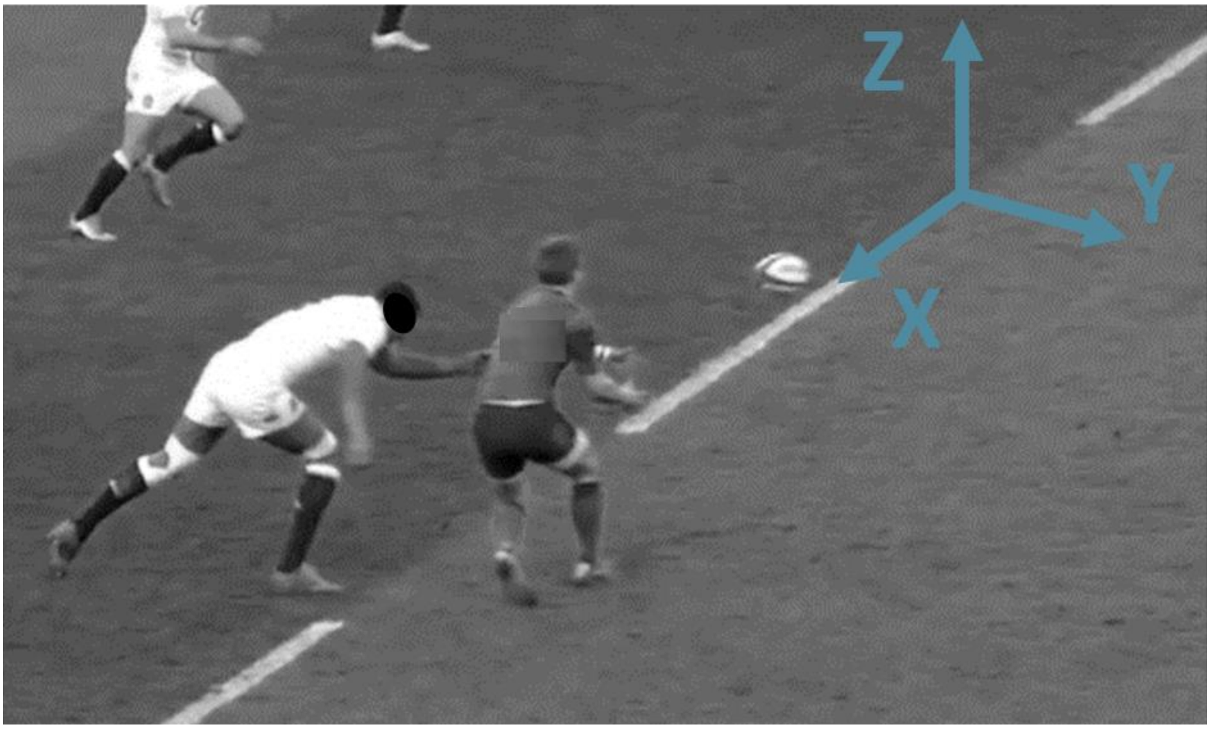

Figure 4. The global coordinate system utilised for the MBIM method.

Results

The componential change in head linear velocity is mostly in the global Y direction (lateral for the player) (Figure 5). The componential head angular kinematics from this case are similar to the reported average values for concussive direct head impacts in unhelmeted sports such as rugby and Australian rules football [9] (Figure 6). For the X (coronal plane) and Y (sagittal plane) components, the maximum change in head angular velocity is greater than in average concussive cases. The linear and angular velocity values for each time frame can be seen in Appendix A. Although it was a side-on tackle [24 25 32], the resultant tackler closing speed was 5.5 m/s (-2.5 m/s, 4.9 m/s and -0.6 m/s in the global X, Y and Z direction, respectively). The resultant ball carrier closing speed was 3.1 m/s (-0.6 m/s, -3.0 m/s and -0.3 m/s in the global X, Y and Z direction, respectively).

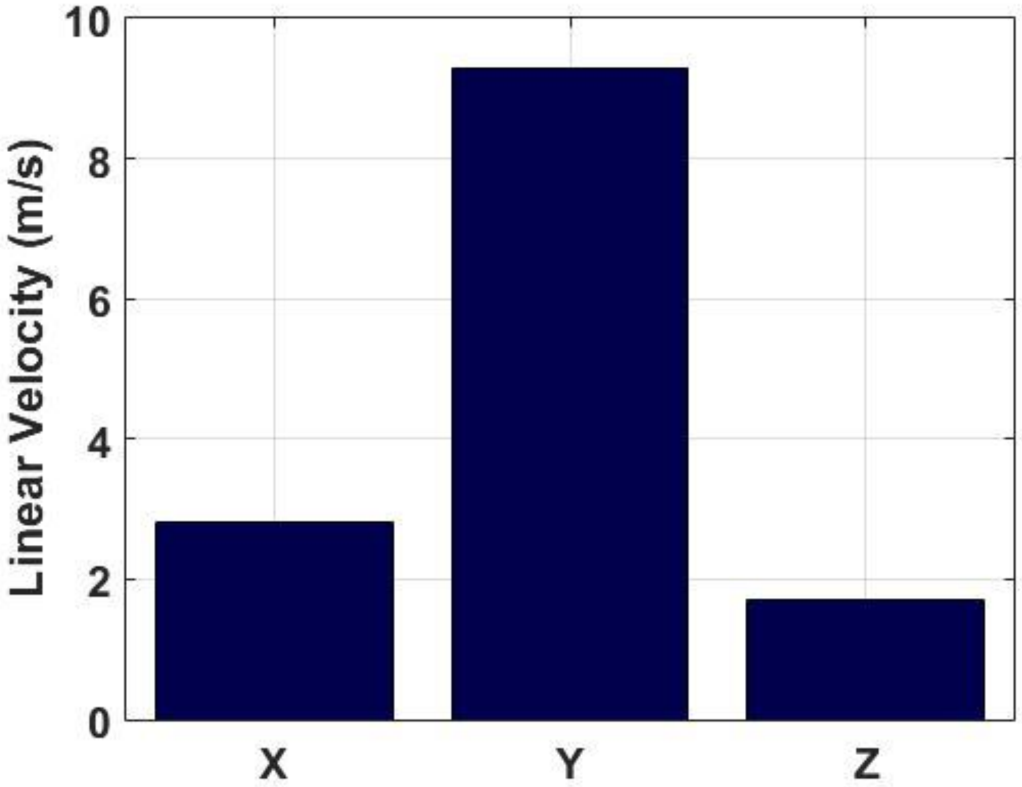

Figure 5. The componential change in head linear velocity results for the ball carrier about the global coordinate system (Figure 4).

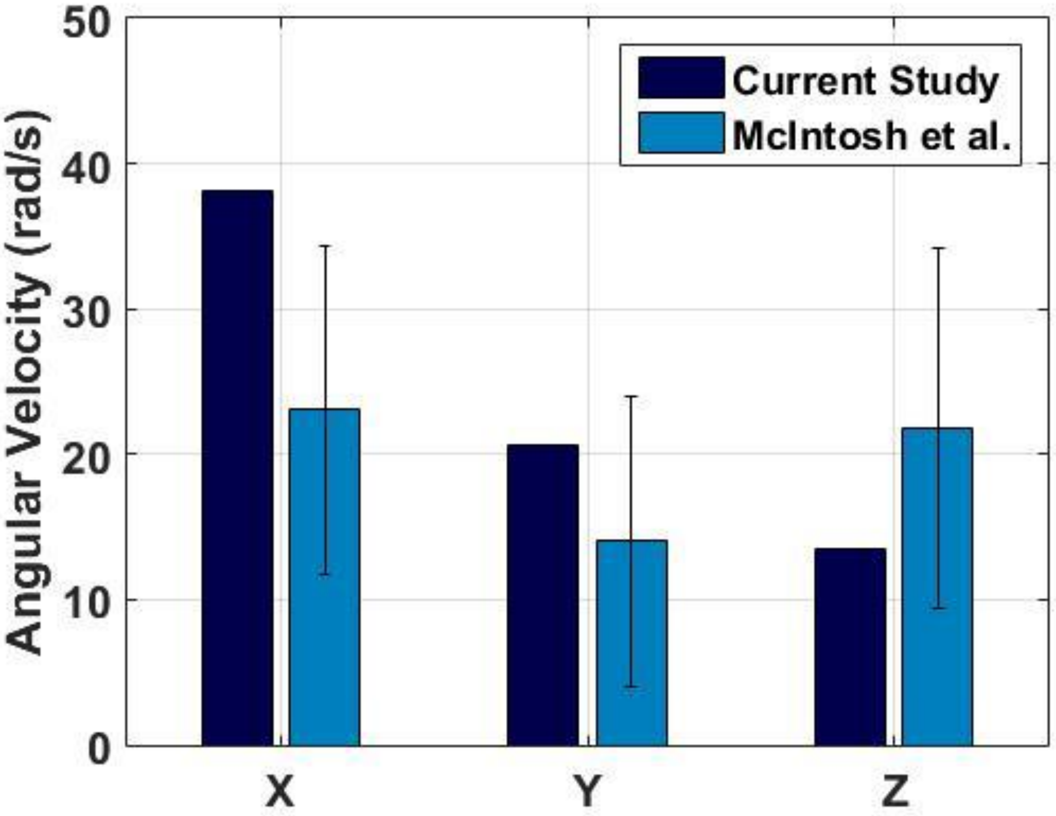

Figure 6. The maximum change in head angular velocity results about the head local coordinate system (Figure 3) from inertial head loading in this study compared to the corresponding average concussion values from direct head impacts reported in the literature [9].

Discussion

This case study used the MBIM method to measure head kinematics of a visually unaware ball carrier during a rugby union shoulder tackle to the upper trunk. Componential head angular velocities were similar to the average values reported for concussive direct head impacts in unhelmeted sports [9] (Figure 6). Although the long term medical outcome of this case is unknown, these results support the finding that legal shoulder tackles to the upper trunk where the ball carrier is visually unaware is a concern for inertial head loading [30]. A conclusion regarding injury risk associated with these tackles requires correlation with injury data and this should be a focus of future work. Longitudinal studies considering blood biomarkers, medical imaging, concussion history, medical reports, injury data and overall head impact exposure would be of benefit.

In this case study, the ball carrier was impacted by the tackler just after passing the ball. The tackle was subsequently reviewed by the on-field referee/video referees and regarded as legal play as the tackler was committed to the tackle before the ball was passed. It could be considered difficult for a ball carrier to protect themselves/brace when impacted from behind and without the ball in their hands. Further work should look at these types of tackles to examine their incidence as well as propensity for injury and high head kinematics.

Recent studies [30 33] have proposed a biomechanical justification for tackling lower around the mid/lower trunk (Figure 1) in rugby union, for which this case study provides further support. Upper body tackles [26 27], especially when primary contact is with the ball carrier's upper trunk [23], are the main cause of direct head impacts for the tackler. A recent study [34] identified that tackling at the upper trunk has a high propensity to result in tackler direct head impacts and emphasised the importance of tackling lower risk body regions such as the lower trunk. For the ball carrier, studies using multibody models and staged tackles in a motion analysis laboratory [30 33] have found that higher tackle heights, particularly to the upper trunk but below the legal limit (line of the shoulders), can result in significantly higher inertial head kinematics in comparison to tackles below the upper trunk. Thus, if contact in this case had been made below the upper trunk of the ball, the ball carrier's inertial head kinematics would likely have been reduced, potentially by over 50% [33]. The energy transmitted during an impact is attenuated along a damped/deformable linkage system through viscous dissipation [35]. Thus, the head kinematics resulting from an impact to the body are inversely related to the distance of the impact from the head. The overall ball carrier angular momentum about the point of contact is conserved in the tackle. This results in a lower rotational inertia above the point of contact when the tackle height is greater and hence greater head rotations.

Limitations

Root mean square errors up to 5.38 rad/s and 1.29m/s were measured for componential angular and linear velocity reconstruction in the MBIM validation study, respectively [19]. This should be considered when interpreting the current results. Linear and angular acceleration were not measured using the MBIM method as the sample frequency (video frame rate) was too low (25 Hz) and head acceleration measures typically require 1000 Hz sampling frequency [5]. The frame rate of 25 fps could be considered low for inertial head angular velocity measurement. It is possible that higher frequency head motion was unmeasured. The time duration associated with the head kinematics measured in this study (Appendix A) are much longer than those typically associated with concussive direct head impacts (peak values usually measured within 54 ms [36]). Only one case was analysed in this current study. Much larger sample sizes were utilised by Mcintosh et al. [9] and this should be considered when interpreting the kinematic result comparisons. The study would have benefited from access to immediate and follow up medical data, if applicable, from this case.

The MBIM approach is currently a time-consuming process as it requires manual frame-by-frame matching. This case took approximately 60 hours to complete. Further work should look at automating/semi-automating the MBIM technique. The sample size for this study was only one due to the selection criteria required for the MBIM technique. Access to multiple camera view synchronised video footage directly from the sports broadcaster could have allowed more cases to be analysed.

Conclusion

Model-Based Image-Matching was utilised to measure maximum changes in head linear and angular velocities of a visually unaware ball carrier during a real game tackle to the upper trunk. Even though no direct head/neck contact occurred in this case, the head angular kinematics were similar to the average values previously reported for concussive direct head impacts in unhelmeted sports. The combination of a high legal tackle height configuration and a visually unaware ball carrier can lead to high inertial head kinematics. Previous work indicates that a lower tackle height would reduce this. Further biomechanical and clinical collaborative research is required to conclude on the long-term effects of tackles generating high head rotational velocity changes.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received funding from the Irish Research Council for this article.

References

1. Bazarian JJ, Zhu T, Blyth B, et al. Subject-specific changes in brain white matter on diffusion tensor imaging after sports-related concussion. *Magn Reson Imaging* 2012;30(2):171-80.
2. Breedlove EL, Robinson M, Talavage TM, et al. Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *J Biomech* 2012;45(7):1265-72.
3. Neselius S, Brisby H, Theodorsson A, et al. CSF-biomarkers in Olympic boxing: diagnosis and effects of repetitive head trauma. *PloS one* 2012;7(4):e33606.
4. Merchant-Borna K, Asselin P, Narayan D, et al. Novel method of weighting cumulative helmet impacts improves correlation with brain white matter changes after one football season of sub-concussive head blows. *Ann Biomed Eng* 2016;44(12):3679-92.
5. King D, Hume PA, Brughelli M, et al. Instrumented mouthguard acceleration analyses for head impacts in amateur rugby union players over a season of matches. *The American journal of sports medicine* 2015;43(3):614-24.
6. King DA, Hume PA, Gissane C, et al. Similar head impact acceleration measured using instrumented ear patches in a junior rugby union team during matches in comparison with other sports. *J Neurosurg Pediatr* 2016;18(1):65-72.
7. McAllister T, Flashman L, Maerlender A, et al. Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. *Neurology* 2012;78(22):1777-84.
8. Baugh CM, Stamm JM, Riley DO, et al. Chronic traumatic encephalopathy: neurodegeneration following repetitive concussive and subconcussive brain trauma. *Brain imaging and behavior* 2012;6(2):244-54.
9. McIntosh AS, Patton DA, Fréchède B, et al. The biomechanics of concussion in unhelmeted football players in Australia: a case–control study. *BMJ Open* 2014;4(5) doi: 10.1136/bmjopen-2014-005078
10. Frechede B, McIntosh AS. Numerical reconstruction of real-life concussive football impacts. *Medicine and science in sports and exercise* 2009;41(2):390-8. doi: 10.1249/MSS.0b013e318186b1c5 [published Online First: 2009/01/08]
11. Takhounts EG, Craig MJ, Moorhouse K, et al. Development of brain injury criteria (BrIC). *Stapp car crash journal* 2013;57:243-66. [published Online First: 2014/01/18]
12. Kinematic rotational brain injury criterion (BRIC). Proceedings of the 22nd Enhanced Safety of Vehicles Conference Paper; 2011.
13. Newman J, Barr C, Beusenberg MC, et al. A new biomechanical assessment of mild traumatic brain injury. Part 2: Results and conclusions. *Proceedings of the International Research Council on the Biomechanics of Injury conference* 2000;28:-.
14. A model of repetitive, mild traumatic brain injury and a novel pharmacological intervention to block repetitive injury synergy. Proceedings of the International Research Council on the Biomechanics of Injury conference; 2012. International Research Council on Biomechanics of Injury.
15. Slemmer JE, Weber JT. The extent of damage following repeated injury to cultured hippocampal cells is dependent on the severity of insult and inter-injury interval. *Neurobiol Dis* 2005;18(3):421-31.
16. Deutsch M, Kearney G, Rehrer N. Time–motion analysis of professional rugby union players during match-play. *Journal of sports sciences* 2007;25(4):461-72.
17. Tucker R, Raftery M, Fuller GW, et al. A video analysis of head injuries satisfying the criteria for a head injury assessment in professional Rugby Union: a prospective cohort study. *Br J Sports Med* 2017:bjsports-2017-097883.
18. Hendricks S, O'Connor S, Lambert M, et al. Video analysis of concussion injury mechanism in under-18 rugby. *BMJ Open Sport & Exercise Medicine* 2016;2(1):e000053.

19. Tierney GJ, Joodaki H, Krosshaug T, et al. Assessment of model-based image-matching for future reconstruction of unhelmeted sport head impact kinematics. *Sports Biomechanics* 2017:1-15. doi: 10.1080/14763141.2016.1271905
20. An Assessment of a Novel Approach for Determining the Player Kinematics in Elite Rugby Union Players. IRCOBI Conference; 2015; Lyon, France.
21. Fuller CW, Ashton T, Brooks JH, et al. Injury risks associated with tackling in rugby union. *Br J Sports Med* 2010;44(3):159-67.
22. Montgomery C, Blackburn J, Withers D, et al. Mechanisms of ACL injury in professional rugby union: a systematic video analysis of 36 cases. *Br J Sports Med* 2016:bjsports-2016-096425.
23. The effect of intended primary contact location on tackler head impact risk. IRCOBI Conference Proceedings; 2017.
24. Tierney GJ, Denvir K, Farrell G, et al. The effect of technique on tackle gainline success outcomes in elite level rugby union. *International Journal of Sports Science & Coaching* 2017 doi: doi:10.1177/1747954117711866
25. Tierney GJ, Denvir K, Farrell G, et al. Does player time-in-game affect tackle technique in elite level rugby union? *Journal of Science and Medicine in Sport* 2017
26. Tierney GJ, Denvir K, Farrell G, et al. The Effect of Tackler Technique on Head Injury Assessment Risk in Elite Rugby Union. *Med Sci Sports Exerc* 2017
27. Tierney GJ, Lawler J, Denvir K, et al. Risks associated with significant head impact events in elite rugby union. *Brain Inj* 2016;30(11):1350-61. doi: 10.1080/02699052.2016.1193630
28. Krosshaug T, Bahr R. A model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences. *Journal of biomechanics* 2005;38(4):919-29. doi: 10.1016/j.jbiomech.2004.04.033 [published Online First: 2005/02/17]
29. Mok K-M, Fong DT-P, Krosshaug T, et al. An ankle joint model-based image-matching motion analysis technique. *Gait & posture* 2011;34(1):71-75.
30. Tierney GJ, Simms CK. The effects of tackle height on inertial loading of the head and neck in Rugby Union: A multibody model analysis. *Brain Inj* 2017:1-7. doi: 10.1080/02699052.2017.1385853
31. McIntosh AS, McCrory P, Comerford J. The dynamics of concussive head impacts in rugby and Australian rules football. *Medicine and science in sports and exercise* 2000;32(12):1980-4. [published Online First: 2000/12/29]
32. Tierney GJ, Simms CK. Can tackle height influence tackle gainline success outcomes in elite level rugby union? *International Journal of Sports Science & Coaching* 2017:1747954117751345.
33. Tierney GJ, Richter C, Denvir K, et al. Could lowering the tackle height in rugby union reduce ball carrier inertial head kinematics? *J Biomech* 2018
34. Tierney GJ, Simms CK. Can tackle height influence head injury assessment risk in elite rugby union? *Journal of Science and Medicine in Sport* 2018 doi: 10.1016/j.jsams.2018.05.010
35. Kim W, Voloshin AS, Johnson SH. Modeling of heel strike transients during running. *Human Movement Science* 1994;13(2):221-44.
36. Use of MADYMO's human facet model to evaluate the risk of head injury in impact. Proceedings of the 21st ESV conference, paper No 07; 2007.

Appendix A. The ball carrier head linear and angular velocity values for each time frame

	Linear velocity (m/s)			Angular velocity (rad/s)		
Time (ms)	X	Y	Z	X	Y	Z
0	-0.9	-3.7	0.1	0.2	0.1	-0.4
40	-0.9	-3.5	0.1	0.3	0.2	-1.1
80	-0.9	-0.5	0.3	-13.3	-8.5	3.9
120	-0.8	3.4	0.2	-10.0	-9.7	-9.6
160	-0.1	2.9	-0.9	14.2	4.7	2.7
200	-1.2	3.4	-1.4	24.7	10.9	-7.6
240	-2.9	5.6	-1.4	16.0	5.1	-5.1