Title: Could lowering the tackle height in rugby union reduce ball carrier inertial head loading?

ABSTRACT

There is mounting evidence of reduced long-term cognitive ability in rugby players, even in those without a reported history of concussion. The tackle height law is an area of controversy. However, little is known about the effects of repetitive inertial head loading in rugby. Furthermore, the magnitude and influencing factors for head kinematics are generally unknown. In this exploratory study, 45 multibody front-on shoulder tackles simulated with the MADYMO pedestrian model and 20 staged rugby tackles executed by professional rugby players in a marker-based 3D motion laboratory were used to assess the effect of tackle height on ball carrier head kinematics. The peak resultant head linear accelerations, angular accelerations and change in angular velocities were measured and examined. The results suggest that tackle height strongly affects the head kinematics experienced by the ball carrier. In particular, higher ball carrier head kinematic values were identified for upper trunk tackles compared to mid/lower trunk tackles in both the multibody simulations and the staged rugby tackles. Average ball carrier peak resultant head linear acceleration, angular acceleration and change in angular velocity values for upper trunk tackles were greater than for mid/lower trunk tackles by a factor of 1.5, 2.5 and 1.7, in the multibody simulations, respectively, and 1.8($p=0.102$), 2.2($p=0.025$) and 2.3($p=0.004$), in the staged tackles, respectively. The results of the study support the proposition of lowering the current tackle height laws to below the chest.

Key Words: Chronic Injury; Brain Injury;Concussion

INTRODUCTION

Rugby Union is a contact sport resulting in high injury rates (Brooks et al., 2005), with tackling being the most common cause of injury (Fuller et al., 2010). The mechanics of acute injuries in rugby, for example concussion arising from direct head impacts, have been studied (Fréchède and McIntosh, 2007, McIntosh et al., 2014). However, there is also mounting evidence of reduced long term cognitive ability in rugby players, even in those without a history of concussion (Alexander et al., 2015, Shuttleworth-Edwards and Radloff, 2008, Hume et al., 2016). This includes reduced visuomotor processing speeds (Shuttleworth-Edwards and Radloff, 2008) and short term visual memory (Alexander et al., 2015) in comparison to athletes from non-contact sport controls. Furthermore, Hume et al. (Hume et al., 2016) found that rugby players have longer reaction times, slower psychomotor speeds and reduced visual and verbal memory in comparison to age matched norms.

The study of repeated sub-concussive head impacts, defined as "head impacts that do not result in symptoms typically used to define concussion such as loss of consciousness, amnesia, confusion and headache (Merchant-Borna et al., 2016)" is an emerging field in brain injury research (Bailes et al., 2013). Sub-concussive head impacts in boxing and soccer have already been associated with acute changes in brain function (Breedlove et al., 2012, Talavage et al., 2014), structural white matter changes (Bazarian et al., 2012, Koerte et al., 2012), biomarkers of neuronal injury (Neselius et al., 2012, Neselius et al., 2013) and short term cognitive impairments (McAllister et al., 2012). They have also been associated with long term white matter changes (Bazarian et al., 2014, Shin et al., 2014), lower brain volume (Bernick et al., 2015) and long term cognitive defects (Killam et al., 2005). Thus, although the long term significance of these changes is not fully understood, the evidence indicates that repetitive sub-concussive impacts can lead to long term neurodegeneration (Baugh et al., 2012, Stern et al., 2011).

Rugby union is a territorial and dynamic sport characterised by high impact collisions (Tierney and Simms, 2017c, Tierney et al., 2017c). By measuring impact forces on a tackle bag, one study found that tacklers' shoulders can experience contact forces over 3500 N (Usman et al., 2011). This can result in substantial inertial loading of the head for the ball carrier, though this has not been quantified. The tackler is expecting a collision but the ball carrier may sometimes not observe the tackler approaching, and failing to brace for impact may result in a higher susceptibility to injury (Hendricks et al., 2016). For an amateur rugby union team over one season, King et al. (King et al., 2015) recorded 181 impacts (0.9% of total impacts) over 95g (linear acceleration concussion injury threshold) and 4452 impacts (21.5% of total impacts) over 5500 rad/s^2 (rotational acceleration concussion injury threshold) even though no concussive head impacts were included in the dataset. It was hypothesised in this study that inertial loading of the head probably accounted for a high proportion of these large head kinematic values recorded, however no protocol was followed to examine this. It is possible that this inertial loading environment in regular rugby union play is due to legally tackling higher up on the body (without contacting the head or neck) (Tierney and Simms, 2017b). This may contribute to the development of some of the clinical deficits reviewed above. A correctly executed or technically proficient tackle (Tierney et al., 2017b, Tierney et al., 2017a) high up on the ball carrier´s body (without contacting the head or neck) may not result in an acute injury or require clinical intervention. However, the cumulative effect of inertial head loading during these impacts over a long period of time may have an adverse effect on long term brain health. Tackling lower down on the ball carrier may reduce the high inertial head loading environment and long term brain health risk (Tierney and Simms, 2017b). However, this aspect of rugby is poorly understood and a greater understanding of the demands and biomechanics of rugby tackling is required.

Tackle heights have been a recent area of concern in relation to head impact causation for players (Tierney et al., 2016b, Tierney and Simms, 2017a, Tierney et al., 2017c). Recent studies have found that upper body tackles were the greatest cause of direct head impacts within the game (Tierney et al., 2016b), particularly when intended primary contact is with the upper trunk of the ball carrier (Tierney and Simms, 2017a). The tackle height law in rugby union is currently set at the line of the ball carrier's shoulder, and any contact above this line is illegal (Fuller et al., 2010). The tackle height law has been an area of concern with respect to injury for many years (Scher, 1978). It has been suggested that future law changes must ensure that the ball carrier is better protected (Fuller et al., 2010). Lowering the tackle height has been recommended since the 1970s (Scher, 1978), but the evidence base for this is limited. Before tackle height laws can be changed, it is essential to examine the biomechanics of tackling on ball carrier head kinematics to understand the demands that the tackle places on the ball carrier when safely executed and if changes would affect this.

Direct measurement of head loading during tackling with on-field measurement devices is challenging (Wu et al., 2016b, King et al., 2015). An alternative approach or first step is to use multibody modeling (McIntosh et al., 2014, Fréchède and McIntosh, 2007) and/or staged rugby tackles in a marker-based 3D motion laboratory. Multibody modelling approaches utilize human body models to assess human response predictions for a broad range of loading conditions (TNO, 2015). The outer geometry of these models is usually modelled using ellipsoids and/or facets. The models have numerous input parameters (geometry, inertial/structural properties, contact characteristics and initial conditions) (Fréchède and McIntosh, 2007, McIntosh et al., 2014). Motion analysis laboratories capture 3D motion data by utilising marker-based optoelectronic motion capture systems. These approaches allow a tackle to be reconstructed in a controlled environment. This can help with the understanding of head kinematics during a tackle and the influence of tackle height. Accordingly, Tierney and Simms (Tierney and Simms, 2017b) recently used multibody modelling to show that tackles to the upper body caused greater inertial head and neck loading than tackles to the lower body, particularly for the ball carrier. However, the upper and lower body tackle definitions covered a wide range of body regions and there was no experimental evidence to support predictions. The goal of this exploratory study is to use multibody simulations of tackling, together with human volunteer tackles in a marker-based 3D motion analysis laboratory to examine the effects of tackle heights on head kinematics. In particular, this study examines the effect on ball carrier head kinematics of lowering the tackle height to below the chest, in front-on shoulder tackle events (Fuller et al., 2010), where no direct contact is made with the head. This allows us to study actual collisions in a controlled environment, as well as simulate more severe collisions in a modelling environment.

METHODS

Multibody Modelling

The multibody model simulations in this study use the dataset of Tierney and Simms (Tierney and Simms, 2017b). This study builds on those findings by further assessing the effect on ball carrier head kinematics of tackle contacts on more specific body regions, as well as lowering the tackle height to below the chest. The multibody model test methodology used in this study has been previously described in detail (Tierney and Simms, 2017b). Briefly, 45 multibody front-on shoulder tackles with no direct impact to the head/neck were developed using a video analysis approach and the MADYMO 50^{th} percentile pedestrian model as a basis (TNO, 2015). The model has been validated for various blunt impact locations (pelvis, abdomen, thorax and shoulder) (TNO, 2015) and although further validation for application to rugby is needed, it can be considered suitable for preliminary impact analysis in rugby (Tierney and Simms, 2017b). There is no direct validation of the model for head acceleration. However, the model has been validated for head translations, rotations and velocity (Elliott et al., 2012). The model has also been used to assess head accelerations in automotive research (Yin et al., 2017, Van Rooij et al., 2003, Sankarasubramanian et al., 2011). In this study each rigid body mass, moment of inertia and height values were scaled based on average elite player height and mass (1.86 m and 101 kg, respectively) (Fraas et al., 2014). For the tackle simulations, the ball carrier and tackler trunk angle were the only parameters varied to allow for a high level of control when examining the effect of tackle height on ball carrier head kinematics (Appendix A and Fig. 1).

Fig. 1: The player to player configuration for the Multibody simulations for the conditions of the ball carrier incoming trunk angle of 60 degrees and tackler incoming trunk angle of a) 0 degrees, b) 30 degrees and c) 60 degrees.

Initial velocities were based on the average elite tackler and ball carrier speeds recorded 0.1s prior to impact (5.6 m/s and 4.8 m/s, respectively) (Hendricks et al., 2012). The coefficient of friction for player-to-player contact was set at 0.34 (Fréchède and McIntosh, 2007). Player-to-player and player-to-ground contact evaluations using the built-in MADYMO contact stiffness functions were applied. An integration timestep of 1e-5 s was used. All simulations were run using an unlocked joint condition (Tierney and Simms, 2017b). This results in the joints of the body being free to articulate within the physiological range of motion with minimal resistance. This muscle activation condition can be regarded as a low awareness state (Tierney and Simms, 2017b). A previous sensitivity analysis has shown that varying the abovementioned parameters has little influence on the prediction trends (Tierney and Simms, 2017b).

The simulations were run for 35 ms to include the upper bound of duration for a rugby impact in which the head experiences >10g of resultant linear acceleration (King et al., 2015). For each tackle simulation, the ball carrier peak resultant head linear acceleration, angular acceleration and change in angular velocity values were extracted, as these global parameters correlate with mild traumatic brain injury (McIntosh et al., 2014).

Tackle height analysis

To assess tackle heights, the ball carrier model was split into 7 regions and each tackle simulation was categorised, based on impact location, from 1-7 (see Fig. 2 and Appendix A) and the average head kinematics were compared between groups.

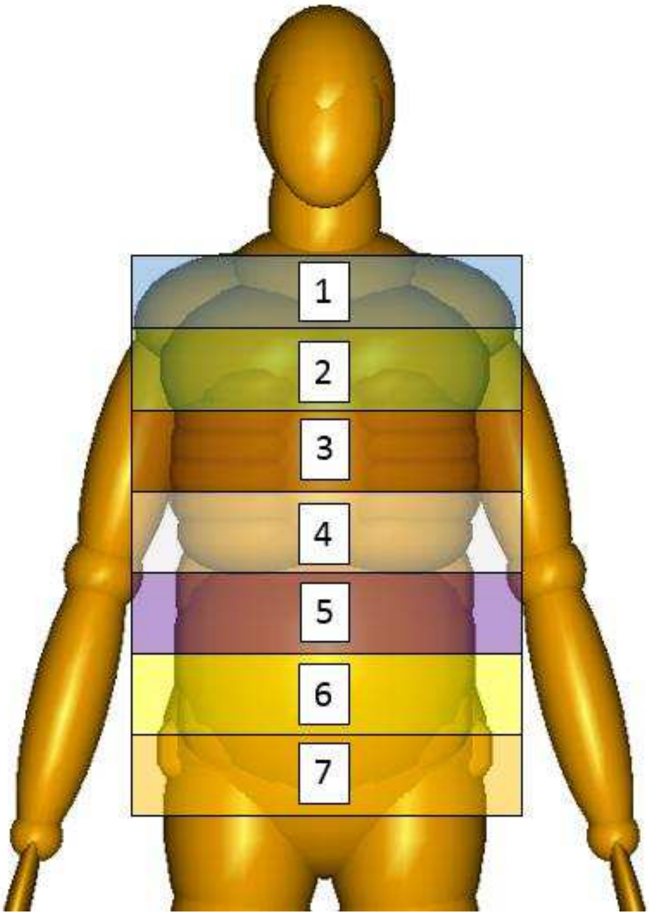

Fig. 2. The ball carrier multibody model split into seven regions to assess impact location.

To assess the general effect of lowering the tackle height law to below the chest, the 7 impact location categories were merged into two main impact locations. The upper trunk category (regions 1-3 in Fig. 2) was defined as at or above the chest whereas the mid/lower trunk category (regions 4-7 in Fig. 2) was defined as below the chest. Mean time histories (±1 SD) were plotted for each head output of interest (head angular acceleration etc) for upper and mid/lower trunk tackles. The ratios of peak resultant head linear acceleration, angular acceleration and change in angular velocity values between upper and mid/lower trunk tackles, based on the mean time histories, were also calculated.

Staged rugby tackle laboratory trials

Two pairs of professional rugby players performed twenty tackles (10 tackles per pair; each player conducted 5 tackles as the ball carrier and 5 tackles as the tackler) in a marker-based 3D motion laboratory. Ethical approval was given by the Trinity College Dublin Faculty of Health Sciences Ethics Committee (Ref #160501). The players were positioned 2.5 metres apart and initiated the tackles from a standing start. The players were instructed to vary the tackle height on the ball carrier such that a number of upper trunk tackles and mid/lower trunk tackles were executed, i.e. tackles above and below the chest of the ball carrier respectively, see Fig. 3.

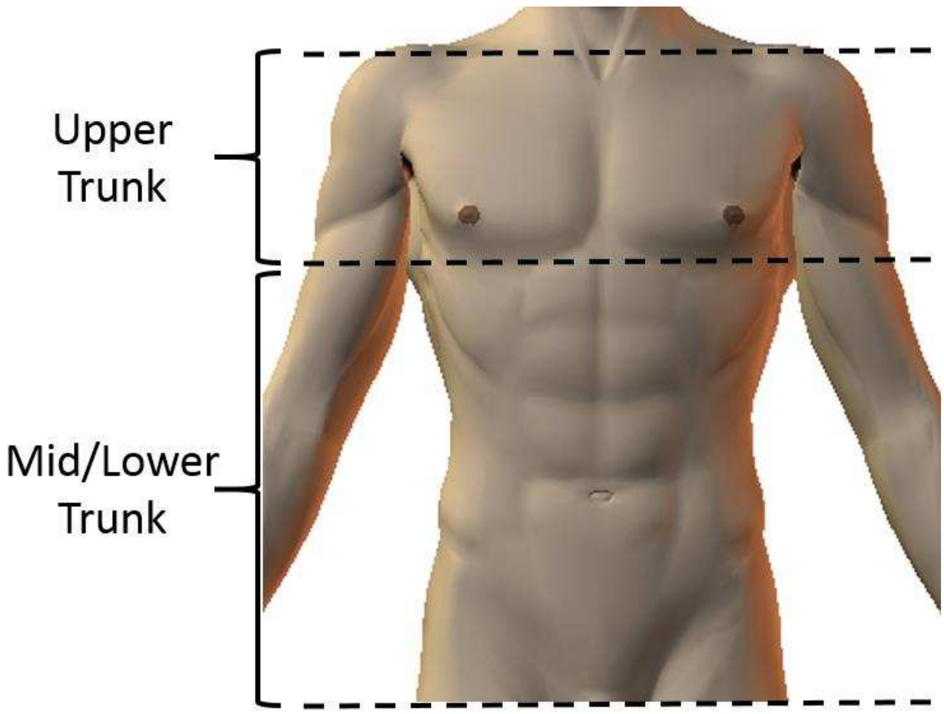

Fig. 3. Upper trunk and mid/lower trunk tackles based on the impact location on the ball carrier.

Marker-based motion analysis

A side, front and oblique view of each tackle was recorded with video cameras (Bonita 720C, Vicon, UK) recording at 66.6 Hz. These cameras were synchronised with a 10 camera infra-red motion analysis system (Bonita-B10, Vicon, UK) recording at 200 Hz. Subjects wore their own athletic footwear. Reflective markers were secured to the shoe or to the skin using tape, at bony landmarks on the lower limbs, pelvis, trunk, arms and head. Markers were attached according to the Plug-in-Gait Model protocol. Additional markers (C5, left and right ribcage and sacrum) were placed to allow reconstruction of the markers needed to apply the Plug-in-Gait Model. The model utilised 43 reflective markers (10 mm radius) attached to each subject. This marker configuration allowed for a three-dimensional description of the head, trunk, upper arm, forearm, pelvis, upper leg, shank and foot (see Fig. 4).

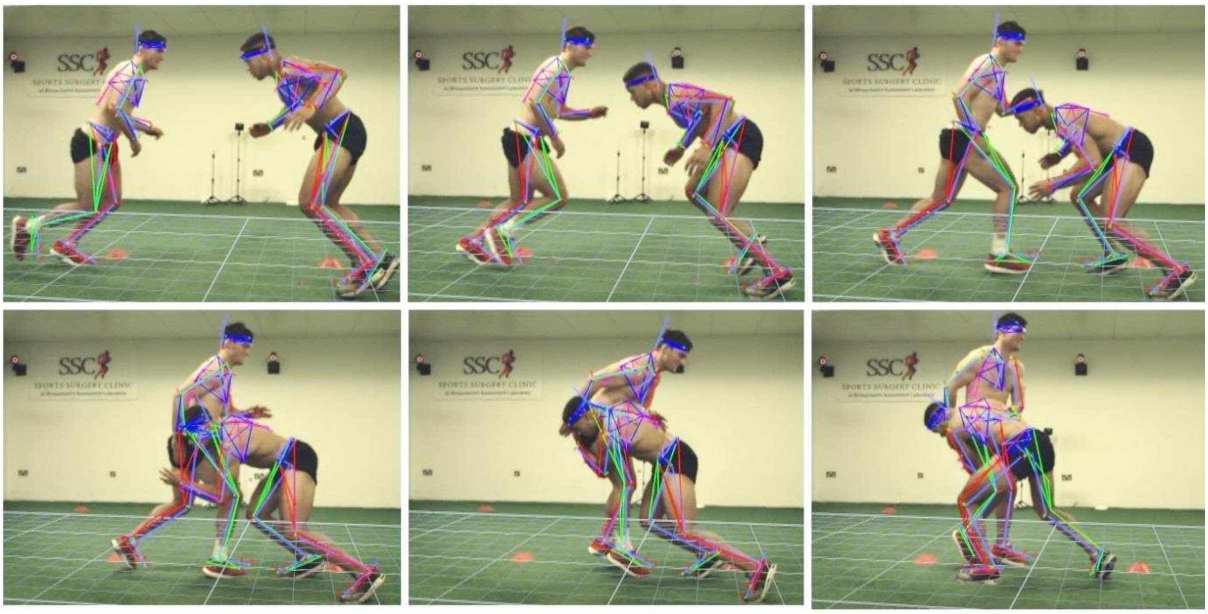

Fig. 4. An image sequence of a staged mid/lower trunk tackle with plug-in-gait model overlay.

Kinematic and statistical analysis

The Plug-in-Gait Model was used to calculate the ball carrier’s successive head rotation angles about the global coordinate system and allowed head position to be determined, from which angular and linear head kinematics were computed (Tierney et al., 2017d). Furthermore, the location of the ball carrier and tackler's whole body centre of gravity was exported from the Plug-in-Gait Model to allow the calculation of both ball carrier and tackler impact speeds (Hendricks et al., 2012). A zero lag four-way filter with a 15 Hz cut of frequency was applied to the Plug-in-Gait model data.

All statistics were calculated using SPSS (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.). The resultant ball carrier peak linear acceleration, angular acceleration and change in head angular velocity were compared between upper trunk and mid/lower trunk tackles using the Mann-Whitney U test (the data was non-normally distributed based on a Shapiro-Wilk test). Effect Size (ES) was assessed using the SPSS Z-statistic and calculating the r-score (Field, 2013) with r values of <0.1, 0.1 - <0.3, 0.3 - <0.5 and ≥0.5 considered indicative of a trivial, small, moderate and large effect sizes respectively (Field, 2013). The resultant ball carrier and tackler impact speeds were compared for upper trunk and mid/lower trunk tackles using a Student t-test as this data was normally distributed. Cohen's d was calculated to assess effect sizes (Burger et al., 2016). Cohen's d effect sizes of <0.2, 0.2 - <0.6, 0.6 - <1.2, and 1.2 - ≤2 were considered trivial, small, moderate, and large, respectively (Burger et al., 2016).

RESULTS

Multibody Modelling

It is clear from Fig. 5 that tackle height affects ball carrier head kinematics. For the ball carrier, linear acceleration increases as the tackle height increases. A sharp increase occurs for peak angular acceleration and change in angular velocity as tackle height increases from region 7 to region 4. It then appears to level off.

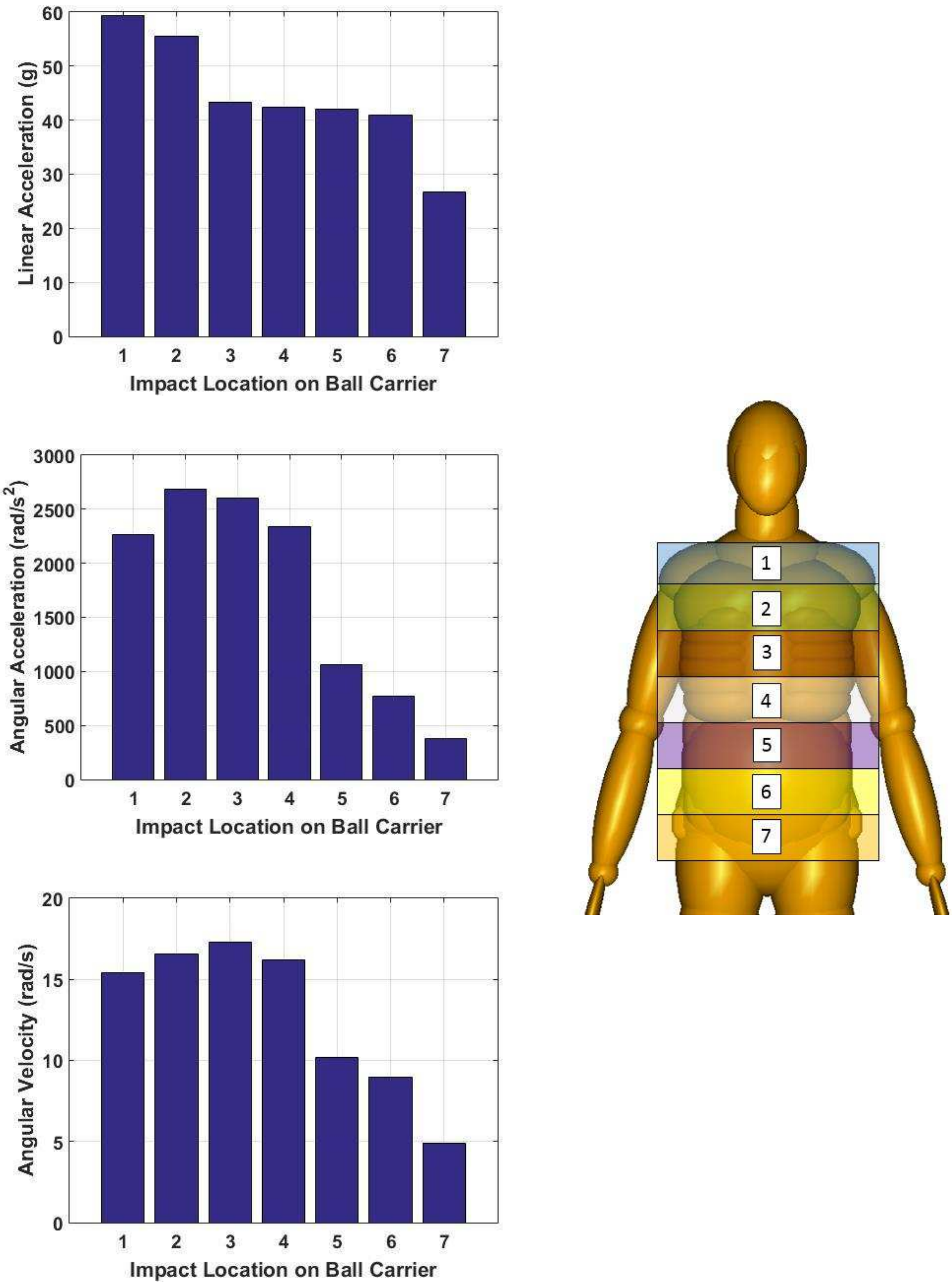

Fig. 5. Multibody simulations: the predicted effect of tackle height, based on ball carrier impact location, on ball carrier head kinematics.

Fig. 6 illustrates that the multibody simulations predict a difference between upper and mid/lower trunk tackles, with upper trunk tackles causing much greater head kinematics for the ball carrier. Average ball carrier peak resultant head linear acceleration, angular acceleration and change in angular velocity values for upper trunk tackles were greater than for mid/lower trunk tackles by a factor of 1.5, 2.5 and 1.7, respectively.

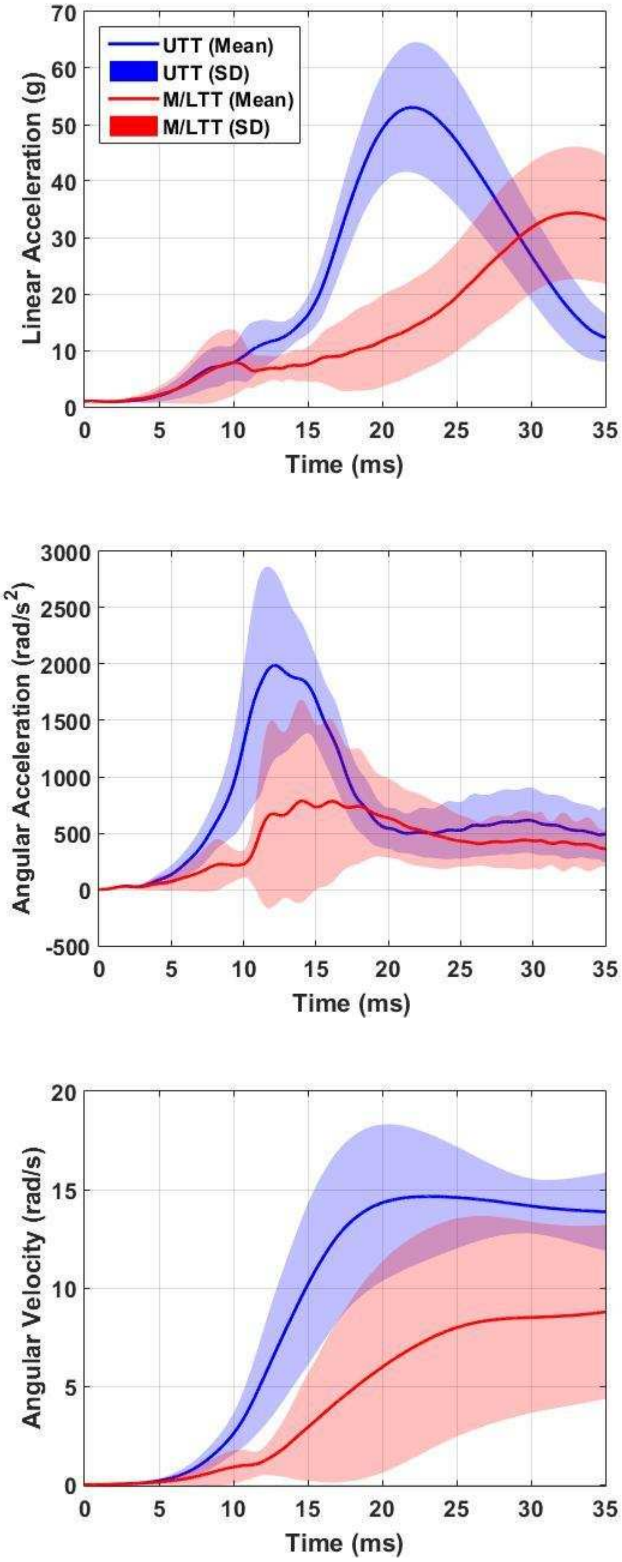

Fig. 6. Multibody simulations: The mean (±1 SD) head kinematic time histories for Upper Trunk Tackles (UTT; Blue) and Mid/Lower Trunk Tackles (M/LTT; Red) for the ball carrier.

Staged Rugby Tackles

Fig. 7 illustrates that the median peak resultant head linear and angular acceleration and change in head angular velocity values for human volunteer upper trunk tackles are greater than mid/lower trunk tackles. Both angular acceleration (p=0.025; ES=0.50) and change in angular velocity (p=0.004; ES=0.64) showed statistical significance and a large effect size. However, differences in linear acceleration did not show statistical significance and had only a moderate effect size (p=0.102; ES=0.36). Median ball carrier peak resultant head linear acceleration, angular acceleration and change in angular velocity values for upper trunk tackles were greater than for mid/lower trunk tackles by a factor of 1.8, 2.2 and 2.3, respectively. Table 1 shows that the mean impact speeds of the tackler and ball carrier were slightly higher for upper trunk tackles. However, this difference was not statistically significant.

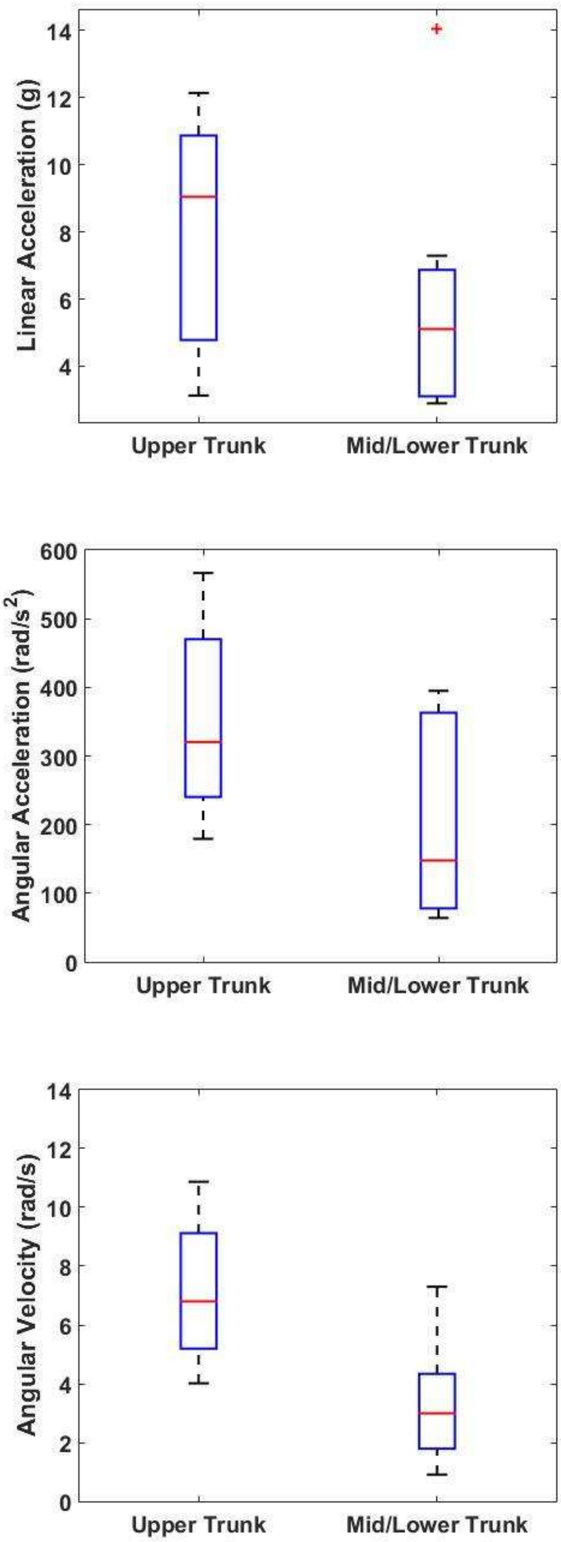

Fig. 7. Human volunteer tackles: the median ball carrier peak resultant head linear acceleration, angular acceleration and change in head angular velocity (red line) with upper and lower quartiles (blue box) and outliers (red cross) for upper trunk and mid/lower trunk tackles.

Impact Speed	Upper Trunk	Mid/Lower Trunk	p-value	Effect Size	Interpretation
Ball Carrier	1.7 (±0.5)	1.4 (±0.6)	0.176	0.63	Moderate
Tackler	2.5 (±0.6)	2.1 (±0.5)	0.125	0.72	Moderate

Table 1. Human volunteer tackles: the mean (±1 SD) ball carrier and tackler impact speeds for upper trunk and mid/lower trunk tackles with p-values and effect size.

DISCUSSION

General

The trends from the multibody simulations and human volunteer tackles presented in this study both indicate that tackle height has a considerable effect on the inertial head kinematics for the ball carrier. In both the modelling and staged rugby tackles, increasing the tackle height caused inertial head kinematics to rise substantially, particularly when the impact occurred above the chest of the ball carrier. Given the exploratory nature of this study, it is difficult to assess the effect on long-term brain health. Therefore, further real world data is needed to support these findings such as on-field measurements using wearable head sensors (Wu et al., 2016b).

The issue with tackling high can be two-fold. Firstly, studies have found that upper body tackles (Tierney et al., 2016b), particularly when the intended primary contact is with the ball carrier's upper trunk (Tierney and Simms, 2017a), were the main cause of direct head impacts in rugby union for the tackler. For the ball carrier, the current study implies that higher tackle heights can also cause greater repetitive inertial head loading even when executed in accordance with current rules. Inertial loading of the head is determined by forces transmitted through the neck (Tierney and Simms, 2017b). These forces are much higher when the tackler makes principal contact with the ball carrier's upper trunk in comparison to lower down on the body (Tierney and Simms, 2017b). The laws of mechanics explain that the energy transmitted during an impact is attenuated along a damped/deformable linkage system through viscous dissipation (Kim et al., 1994). Thus, the kinematics of the head that result directly from an impact to the body will be inversely related to the distal distance of the impact with regard to these segments (Tierney and Simms, 2017b). Also, in a front-on shoulder tackle (Tierney and Simms, 2017c), most ball carrier rotation occurs in the sagittal plane (Wu et al., 2016b). The overall ball carrier angular momentum about the point of contact is conserved in the tackle resulting in greater head rotations when the tackle height is greater (Tierney and Simms, 2017b). This was observed both in the multibody model simulations and the staged tackles.

The predicted kinematic values from this study suggest that repeated upper trunk tackles in comparison to mid/lower trunk tackles, based on the McIntosh injury model (McIntosh, 2005), may contribute to the development of the cognitive deficits reported for rugby players (Shuttleworth-Edwards and Radloff, 2008, Hume et al., 2016, Alexander et al., 2015). However, this cannot be concluded from the current study. Future biomechanical research should be combined with clinical research to further evaluate this. Further biomechanical research on tackle heights using methods such as wearable head sensors (King et al., 2015) and video analysis techniques (Tierney et al., 2016a, Tierney et al., 2017c, Tierney et al., 2015) could advance our understanding of tackle height on inertial head kinematics, in real match scenarios. This in turn can help to develop player protection strategies and reassess the maximum allowable tackle height law.

Multibody Modelling

By lowering the tackle height laws to below the chest (based on the peak ratios of upper trunk tackles to mid/lower trunk tackles in the multibody model simulations), average ball carrier peak head linear acceleration, angular acceleration and change in angular velocity values could be reduced in the tackle by 35%, 61% and 40%, respectively. The results reported in this study are within the range of reported head kinematic values from general rugby play (King et al., 2015). However, the numerical results must be considered preliminary since the model validity for use in rugby impacts must be further evaluated.

Staged Rugby Tackles

The principal findings and trends of the multibody modelling are strongly supported by the results of the staged rugby tackles. The head kinematics values from the staged rugby tackles are lower than that reported for general play (King et al., 2015). The tackle intensity was significantly lower than during competitive play: the impact speeds of the ball carrier and tackler (Table 1) are around 2-3 times lower than average impact speeds in elite game environments (Hendricks et al., 2012). Thus, substantially higher ball carrier head kinematics are likely to occur during competitive play tackles. Also, the ball carriers in this study had high awareness levels of the tackle allowing them to fully brace for the tackle impact. This should reduce head kinematics as neck muscle are more likely to be highly activated. However, further research is required to support these two abovementioned points. The outlier in Fig. 7 shows the variability of actual collisions, with high relative head kinematics also possible during a mid/lower trunk tackle. Overall, however, the head kinematics for the mid/lower trunk tackles are significantly less than for upper trunk tackles.

Limitations

The computational model used in this study has not been fully evaluated for rugby tackle reconstruction. A further challenge with the model is that realistic muscle activation is difficult to represent with a passive model. Nonetheless, the simplistic approach used in this study still gives an initial insight into the effect of tackle height on head kinematics. The principal findings are also supported by the staged rugby impacts. The ball carriers in these simulations and staged tackles did not exhibit evasive manoeuvres or fending into contact (Tierney et al., 2017b, Tierney et al., 2017a. This might reduce head kinematics in the tackle by compromising the tackler's ability to execute a high proficiency tackle (Tierney et al., 2017b). These aspects should be the focus of future work. Only a small sample size was utilised in the staged rugby tackles (4 players). A greater sample size would have improved the statistical power of the results. The small sample size was due to limited professional player recruitment and ethical constraints (only ten tackles per player-pair). The sampling frequency used in the staged rugby tackles may be too low for capturing accurate head acceleration data (Wu et al., 2016a). However, the frequency of inertial head acceleration is likely to be lower than for direct contact. The results of this study provide biomechanical support for the proposition of lowering the tackle height in rugby union. However, the changing of laws in sport is a complex process and will require further research, collaborations and discussions between players, coaches, referees, sports scientists and biomechanists etc.

CONCLUSIONS

This exploratory study shows that tackle height strongly affects the head kinematics experienced by the ball carrier in front-on shoulder tackles in rugby union, even without direct contact to the head. In particular, higher ball carrier head kinematic values were identified for upper trunk tackles compared to mid/lower trunk tackles. In the multibody simulations, average ball carrier peak resultant head linear acceleration, angular acceleration and change in angular velocity values for upper trunk tackles were greater than for mid/lower trunk tackles by a factor of 1.5, 2.5 and 1.7, respectively. Model validation is a limitation of this aspect of the study. However, the trends reported by the models are supported by the staged rugby tackle impacts. In these tackles, median ball carrier peak resultant head linear acceleration, angular acceleration and change in angular velocity values for upper trunk tackles were greater than for mid/lower trunk tackles by a factor of 1.8 ($p=0.102$), 2.2 ($p=0.025$) and 2.3 ($p=0.004$), respectively. The results of the study support the proposition of lowering the current tackle height laws to below the chest. However, real match data is required to support this.

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APPENDIX A

Table A: Design matrix of the 45 simulations based on ball carrier (BC) and tackler trunk angle with corresponding impact location on the ball carrier (Fig. 2).

Tackler Angle / BC Angle	0	10	20	30	40	50	60	70	80	90
40	7	3	2	1	1	-	-	-	-	-
50	7	5	3	2	1	1	-	-	-	-
60	7	5	4	3	2	1	1	-	-	-
70	7	5	4	3	2	2	1	1	-	-
80	7	6	5	4	3	2	2	1	1	-
90	7	6	5	4	3	3	2	2	1	1