©Journal of Sports Science and Medicine (2014) **13,** 557-563
http://www.jssm.org

Research article

Momentum and Kinetic Energy before the Tackle in Rugby Union

Sharief Hendricks ✉, David Karpul and Mike Lambert
MRC/UCT Research Unit for Exercise Science and Sports Medicine, Department of Human Biology, Faculty of Health Sciences, the University of Cape Town and the Sports Science Institute of South Africa, Cape Town, South Africa

Abstract
Understanding the physical demands of a tackle in match situations is important for safe and effective training, developing equipment and research. Physical components such as momentum and kinetic energy, and it relationship to tackle outcome is not known. The aim of this study was to compare momenta between ball-carrier and tackler, level of play (elite, university and junior) and position (forwards vs. backs), and describe the relationship between ball-carrier and tackler mass, velocity and momentum and the tackle outcome. Also, report on the ball-carrier and tackler kinetic energy before contact and the estimated magnitude of impact (energy distributed between ball-carrier and tackler upon contact). Velocity over 0.5 seconds before contact was determined using a 2-dimensional scaled version of the field generated from a computer alogorithm. Body masses of players were obtained from their player profiles. Momentum and kinetic energy were subsequently calculated for 60 tackle events. Ball-carriers were heavier than the tacklers (ball-carrier 100 ± 14 kg vs. tackler 93 ± 11 kg, d = 0.52, p = 0.0041, n = 60). Ball-carriers as forwards had a significantly higher momentum than backs (forwards 563 ± 226 $Kg \cdot m \cdot s^{-1}$ n = 31 vs. backs 438 ± 135 $Kg \cdot m \cdot s^{-1}$, d = 0.63, p = 0.0012, n = 29). Tacklers dominated 57% of tackles and ball-carriers dominated 43% of tackles. Despite the ball-carrier having a mass advantage before contact more frequently than the tackler, momentum advantage and tackle dominance between the ball-carrier and tackler was proportionally similar. These findings may reflect a characteristic of the modern game of rugby where efficiently heavier players (particularly forwards) are tactically predetermined to carry the ball in contact.

Key words: Tackle, rugby union, contact sports, momentum, kinetic energy.

Introduction

The physical demands of rugby union are characterized by intermittent short duration, high intensity exercise with frequent physical collisions between players known as the tackle (Gabbett and Ryan, 2009; Hendricks and Lambert, 2010; Hendricks et al., 2012a). Understanding the physical demands of a tackle in real match situations is necessary for the design and development of proper training drills, equipment, planning and management of training, and in order to replicate the event in the laboratory for research (Austin et al., 2011; Frechede and McIntosh, 2009; McIntosh et al., 2000; Newman et al., 2005; Pellman et al., 2003b). Methods however, to determine kinematics and kinetics of collisions in real match situations without instrumentation of the player remain difficult. With that said, systems to estimate velocity, acceleration, momentum and energy transfer at impact, and its association with concussion in American football, Australian rules football, rugby league and rugby union have been developed (Frechede and McIntosh, 2009; McIntosh et al., 2000; Newman et al., 2005; Pellman et al., 2003b). These systems primarily make use of video analysis in combination with a computer-generated algorithm. Using known ground markings as references points, two-dimensional scaled versions of the field are constructed (Brewin and Kerwin, 2003; Edgecomb and Norton, 2006) allowing for accurate measures of linear distance over time. Moreover, the measurement is independent of camera set-up, enabling analysis of televised footage (Alcock et al., 2009; Kwon and Casebolt, 2006).

Difference in momentum between the ball-carrier and tackler is postulated to contribute to the risk of injury and play a part in predicting the outcome the tackle (Brooks et al., 2005; Eaton and George, 2006; Fuller et al., 2010; Garraway et al., 1999; Headey et al., 2007; Hendricks and Lambert, 2010; McIntosh et al., 2010; Quarrie and Hopkins, 2008; Sundaram et al., 2011; Takarada, 2003). The hypothesis is that the player with the lower momentum is at higher risk of injury and also less likely to dominate the tackle contest. Understandably, these hypotheses are largely based on basic physical principles of collisions (Blazevich, 2007; Burkett, 2010). Related to momentum, players entering the tackle also have kinetic energy. In inelastic collisions, like most completed tackle events, the sum kinetic energy of the ball-carrier and tackler before the tackle is equal to the total kinetic energy after the tackle (when the ball-carrier and tackler are in full contact, and have become one system). Upon contact, energy is redistributed or dispersed between the players (Takarada, 2003). The amount of energy redistributed within the system can be calculated, and may provide an indication of the physical demand of the contact in the tackle. With all that said, momentum before the tackle is yet to be quantified for the tackle.

Considering all the external and internal forces acting on live bodies during a collision in a real match situation, the measurement of physical components in a biomechanically complex situation like the tackle is virtually impossible. However, an approach to the problem is to simplify real match contact situations and apply basic physical principles of collisions, conservation of momentum and energy. Furthermore, the necessary assumptions that are associated with these estimations are needed to understand match demands and collision dynamics (Frechede and McIntosh, 2009; McIntosh et al., 2000; Newman et al., 2005; Pellman et al., 2003b). Indeed, this

Received: 20 January 2014 / Accepted: 24 March 2014 / Published (online): 01 September 2014

type of match analysis has proved valuable in reconstructing and modelling collisions in the laboratory for further analysis (Frechede and McIntosh, 2009; McIntosh et al., 2000; Pellman et al., 2003a; Pellman et al., 2003b). Although velocity, acceleration, momentum and energy transfer at impact, and their association with concussion have been reported in rugby union and other collision sports (McIntosh et al., 2000), little is known about the tackle in rugby union. Studies that have reported on the kinetics of contact situations in rugby union matches however, did not report the type of contact (tackle, ruck, collision) or indicate role of the players in the contact (i.e. ball-carrier or tackler)(McIntosh et al., 2000).

From the current literature on the tackle, it is evident that tackle characteristics and tackle injury risk profiles differ for the type of tackle (front-on vs side-on), position (forwards and backs), and playing level (Fuller et al., 2010; McIntosh et al., 2010; Quarrie and Hopkins, 2008). In view of this, it may be assumed then that the momentum of the ball-carrier and tackler will be different for each of these factors. Therefore, the purpose of this study was to firstly report the mass and velocity of the ball-carrier and tackler for 3 different levels of play. Secondly, to quantify and compare momenta between ball-carrier and tackler, level of play and position. Thereafter, describe the relationship between the difference in mass, velocity and momentum (between ball-carrier and tackler) before contact in the tackle and the outcome of the tackle. Finally, report on the ball-carrier and tackler kinetic energy before contact and the estimated magnitude of impact (energy distributed between ball-carrier and tackler upon contact).

Methods

Participants

A total of nine rugby union matches from Super 14 2010 (3 matches) – an elite international level consisting of teams of full-time professional rugby players from provincial franchises in Australia, South Africa and New Zealand; Varsity Cup, South Africa 2010 (2 matches) – a highly competitive national university level consisting of semi-professional players; and Under 19 Currie Cup, South Africa 2010 (4 matches) – a level consisting of highly trained junior players, were randomly selected and analysed for this study. Televised recordings were used for the Super 14 and Under 19 Currie Cup and self-recorded video footage was used for Varsity Cup matches.

Front-on and side-on tackles that occurred during each match were then coded using Sportscode Elite (Version 6.5.1, Sportstec, Australia). Tackles were identified when *'when ball-carrier was contacted (hit and/or held) by an opponent (primary tackler) without reference to whether the ball-carrier went to ground* (Quarrie and Hopkins, 2008). Tackles were further classified into front-on and side-on tackles. Front-on tackles were coded when the anterior body parts of the ball-carrier were contacted first by the primary tackler (Quarrie & Hopkins 2008), whereas side-on tackles were identified when the lateral body parts (on either side) of the ball-carrier were contacted first by the primary tackler (Quarrie and Hopkins, 2008). Apart from identifying front-on and side-on tackles, tackles were randomly selected irrespective of team, playing position, field location, set piece/breakdown that preceded the tackle, or any other tackle characteristic. The ball-carriers' and tacklers' playing position were identified and categorised into either forward or back. Thereafter, the mass of the identified ball-carrier and tackler were recorded from their publically available player profiles either from their National Union, Super 14 franchise or Provincial Union website. This study was approved by the University Research Ethics Committee.

Velocity measurement

The velocity measurement for this study is described elsewhere (Hendricks et al., 2012b). In brief, the video footage of the tackle event had to fulfil the following visibility criteria i) Visual of 4 locations with known distances represented by the lines on the field, ii) Clear running path for at least 0.5 seconds of the ball-carrier and primary tackler pre-tackle, iii) Camera had to remain fixed over this period. Tackle events that fulfilled these criteria (10 tackles x 3 levels x 2 types of tackles = 60 tackles) were subsequently imported into Dartfish Team-pro (Version 4.0.9.0 Switzerland).

Figure 1. **Actual analysed imaged of a tackle event (image magnified).**

Using Dartfish Analyser, a timer was set to zero at the point of contact between the ball-carrier and primary tackler. The ball-carrier and tackler were then retracted for 0.5 seconds (25 frames) from the point of contact. This period is considered the pre-tackle phase (Fuller et al., 2010). Thereafter, the ball-carrier and tackler were tracked forward to the point of contact for the 0.5 seconds. Ball-carriers were generally tracked from mid-section (hip area) and tacklers on the upper body (Figure 1). The rationale for this is that during most tackles, tacklers enter the tackle with their upper body as the first point of contact. Once the body region was selected, the tracking of the player was meticulously observed to confirm that the tracked path was indeed the movement path of the body region in question (i.e. mid-section for ball-carriers and upper body for tacklers), as the tracking software may be confounded by elements such as similar playing kit colours to opposition, video footage clarity, surrounding players etc. In cases where the tracking software lost the selected point on the player, and deviated from the obvious movement path, the tracking software was returned to the point on the body and the tracking path re-established. A line was then drawn with the software through the tracked path of both the ball-carrier and tackler, and divided into 0.1 second intervals (Five 0.1 second intervals, six markings). An image of the analysed tackle, with the marked 0.1 seconds intervals, was subsequently imported into Matlab (Version 6.5, Mathworks Inc, United States of America).

An algorithm to determine the planar location of a single point determined by pixel co-ordinates within an image was developed in Matlab (Version 6.5, Mathworks Inc, United States of America). As mentioned earlier, one of the inclusion criteria for analysis of the tackle event was a visual of 4 locations with known distances represented by the lines on the field. This made it possible to enter four known x and y co-ordinates on the field. The program then created a 2D-axis (x; y) system in the plane of the field shown in the imported image from Dartfish. Once the 4 known co-ordinates were entered, and the 2D-axis system created, it was possible to obtain x; y co-ordinates of any point on the field. To obtain the co-ordinates, the analyser had to simply select any point on the field, and the algorithm would calculate the co-ordinates despite the projective distortion to the image created by the camera (Given that each tackle event was analysed individually and a scaled version of the field was reconstructed for each tackle event based on the visual and knowledge of distances between field markings, the projected distortion was accounted for). For every tackle event, a new image and a new 2D-axis system was created, according to the known distances. Before a tackle was analysed, and to further validate the 2D-axis system, co-ordinates produced by the 2D-axis system had to correspond to the known distances of the playing field from the imported image.

The centre of the field (on the half-way line at the mid-point between the two touchlines) was chosen as the point of origin on the field (x = 0; y = 0). After the additional validation, the co-ordinates of the marked 0.1 second intervals were obtained for both the ball-carrier and the tackler. The distance between 2 co-ordinates (x and y) was calculated and divided by 0.1 seconds to produce the average velocity ($m \cdot s^{-1}$) over that interval. This was repeated for the five 0.1 second intervals up to the point of contact for both ball-carrier and tackler. Average velocity over the 0.5 seconds was subsequently calculated.

Validation

The validity of the methods are described in detail by Hendricks et al. (Hendricks et al., 2012b). Validity was tested by comparing the velocity measurement described above to a criterion velocity measurement. In summary, the velocity measurement showed an acceptable reproducibility and agreement when compared to a criterion velocity for both the ball-carrier and tackler (Hendricks et al., 2012b).

Momentum

Assuming all external forces acting on the ball-carrier and tackler are zero, momentum (P) before the tackle was calculated using the momentum formula:

$$P = m.v, \qquad \text{Eq. 1}$$

where *m* is mass of player *v* is average velocity over the 0.5 seconds.

Given that momentum is a vector quantity, the direction of the ball-carrier and tackler were described in relation to their opponent. Front-on tackles were described in the opposite direction to their opponent, and side-on tackles described approximately perpendicular to the direction of their opponent.

Tackle dominance

The outcome of the tackle for this study was indicated by the direction of progression the tackler and ball-carrier made (as a single unit) towards the opposition try-line from the point of contact to the point where both players went to ground. This was considered an indication of the physical dominance of the tackler or ball-carrier in the contact.

Estimated magnitude of impact (energy distributed between ball-carrier and tackler upon contact)

Assuming all external forces acting on the ball-carrier and tackler are zero, kinetic energy (KE) before the tackle was calculated using the formula:

$$KE = \frac{1}{2} m.v^2, \qquad \text{Eq. 2}$$

Thereafter, magnitude of impact was calculated by subtracting the kinetic energy before the collision (KE_{before}) from the kinetic energy after the collision (KE_{after}). KE_{before} was calculated by adding the $KE_{ball\text{-}carrier\ and}$ $KE_{tackler}$. KE_{after} was calculated using the following formula:

$$KE = \frac{1}{2}(m_{ball\ carrier} + m_{tackler})v^2_{after\ collision}, \qquad \text{Eq. 3}$$

where $v^2_{after\ collision}$ *is velocity after contact, calculated from conservation of momentum. Given that all tackles analysed in this study were complete tackles where the ball-carrier and tackler became one system and moved in the same direction after contact, it was assumed that momentum after the collision was conserved (inelastic collisions).*

Statistical analysis

Mass, Velocity, Momentum and Kinetic Energy before contact: T-tests and Cohen's effect size (*d*) statistics were used to compare mass, velocity, and absolute momentum between the type of tackles (front-on vs. side-on), positions (forward vs. back), and ball-carrier vs. tackler. Analysis of variance (ANOVA) and Cohen's effect size (*d*) statistics were also used to compare differences between levels. A Tukey *post-hoc* test was used to further analyse any differences when the F value was significant. T-tests and Cohen's effect size (*d*) statistics were also used to compare kinetic energy differences between the ball-carrier and tackler, and the magnitude of impact between types of tackles, and between tackles outcomes for each type of tackle. A two-tailed p-value was used for all tests, with the *a priori* alpha level of significance set at $p < 0.05$. Effect sizes of <0.09, 0.10-0.49, 0.50-0.79, and >0.80 were considered trivial, small, moderate, and large, respectively (Batterham and Hopkins, 2006). All analyses were conducted using STATA 11.1 (StataCorp LP, USA). Data reported as mean±standard deviations (SD).

Results

Body mass

Super 14 backs were heavier than Varsity Cup ($p = 0.05$, $d = 0.68$) and Under 19 backs ($p = 0.002$, $d = 0.92$). Similarly, Super 14 and Varsity Cup forwards were heavier than Under 19 forwards (Super 14 $p = 0.01$, $d = 0.98$; Varsity Cup $p = 0.004$, $d = 0.96$). There was an overall significant difference between ball-carrier and tackler masses (ball-carrier 100.1±13.7 kg vs. tackler 93.4 ± 10.9 kg, $p = 0.0041$, $d = 0.52$, $n = 60$) within the study's sample (Table 1). More specifically, the ball-carriers were heavier than the tacklers in Super 14 ($p = 0.008$, $d = 0.8$) and Under 19 ($p = 0.051$, $d = 0.6$) levels. Furthermore, overall ($p < 0.001$, $n = 60$, $d = 1.48$) and within each competition ($p < 0.01$, $n = 20$), forwards were significantly heavier than backs whether as a ball-carrier or tackler. Also, ball-carriers were heavier than tacklers in 68% of all tackles.

Table 1. Average body mass for ball-carrier and tacklers in Super 14, Varsity Cup and Under 19. Data reported as mean (±SD).

	n	Ball-carrier	n	Tackler
Super 14	20	105.3 (9.9)	20	95.9 (11.5)
Backs	8	96.1 (4.6)	14	90.8 (8.5)
Forwards	12	111.4 (7.4)	6	107.8 (8.6)
Varsity Cup	20	97.3 (16.1)	20	93.9 (12.5)
Backs	13	87.9 (3.9)	15	88.6 (5.4)
Forwards	7	114.7 (15.9)	5	109.8 (14.7)
Under 19	20	97.6 (13.6)	20	90.4 (8.2)
Backs	8	85.6 (7.2)	8	84.5 (7.4)
Forwards	12	105.6 (10.6)	12	94.3 (6.3)

Velocity

Table 2 shows the velocity for forwards and backs during front-on and side-on tackles. Backs executing side-on tackles were significantly faster than forwards executing side-on tackles ($p < 0.05$, $d = 0.89$). In 45% of all tackles, ball-carriers had a higher velocity than their counterparts.

Table 2. Average velocity for the ball-carrier and tackler by position (forward and backs). Data reported as mean (±SD).

	n	Ball-carrier	n	Tackler
Velocity before Front-on Tackle ($m\cdot s^{-1}$)				
All Forwards	16	5.2 (2.4)	13	5.6 (1.9)
All Backs	14	4.7 (1.3)	17	5.8 (2.3)
All Positions	30	5.0 (2.0)	30	5.7 (2.1)
Velocity before Side-on Tackle ($m\cdot s^{-1}$)				
All Forwards	15	5.2 (1.9)	10	3.7 (1.1)
All Backs	15	5.1 (1.7)	20	5.5 (2.1)
All Positions	30	5.1 (1.8)	30	4.9 (2.0)

Momentum

In the sample of tackles analysed in this study, the differences in ball-carrier momenta between the three levels were small (Table 3). In contrast, differences in tackler momenta were moderate between Varsity Cup and Super 14 front-on tackles ($d = 0.6$, $p > 0.05$), and large between Super 14 and Under 19 ($d = 0.95$, $p = 0.089$), and Varsity Cup and Under 19 ($d = 0.94$, $p > 0.05$). No differences in momenta were evident between ball-carrier and tackler, and between front-on and side-on tackles. Overall, ball-carriers as forwards had a significantly higher momentum than backs (forwards 563 ± 226 $Kg\cdot m\cdot s^{-1}$ $n = 31$ vs. backs 438 ± 135 $Kg\cdot m\cdot s^{-1}$ $n = 29$, $d = 0.63$, $p = 0.001$).

Table 3. Average momentum for the ball-carrier and tackler in Super 14, Varsity Cup and Under 19. Average momentum for forwards and backs are also included. Data reported as mean (±SD).

	n	Ball-carrier (in the opposite direction to the tackler)	n	Tackler (in the opposite direction to the ball-carrier)
Momentum before Front-on Tackle ($Kg\cdot m\cdot s^{-1}$)				
Super 14	10	508 (321)	10	471 (212)
Varsity Cup	10	529 (80)	10	620 (268)
Under 19	10	479 (174)	10	517 (148)
All Forwards	16	523 (266)	13	566 (222)
All Backs	14	486 (125)	17	513 (217)
All Positions and Levels	30	505 (209)	30	536 (217)
Momentum before Side-on Tackle ($Kg\cdot m\cdot s^{-1}$)				
Super 14	10	519 (241)	10	523 (209)
Varsity Cup	10	522 (162)	10	503 (181)
Under 19	10	459 (156)	10	347 (106)
All Forwards	15	523 (210)	10	384 (133)
All Backs	15	473 (158)	20	494 (197)
All Positions and Levels	30	500 (186)	30	458 (183)
All Backs	15	473 (158)	20	494 (197)
All Positions and Levels	30	500 (186)	30	458 (183)

Mass, velocity and momentum difference between ball-carrier and tackler before contact in front-on tackles

In the 30 front tackles analysed for this study, tacklers dominated 57% of tackles and ball-carriers dominated 43% of tackles (Figure 2). Ball-carriers had a mass advantage over their opponent in 77% of all front on tackles, and tacklers entered the tackle with a higher velocity than the ball-carrier 67% of the time. Tacklers entered the tackle with a superior estimated momentum to that of the ball-carrier 60% of all front-on tackles.

Kinetic Energy before contact and magnitude of impact (energy distributed between ball-carrier and tackler upon contact)

The kinetic energy before contact in the tackle for both ball-carrier and tackler, and magnitude of impact for each tackle outcome is shown in Table 4. For outcomes where the ball-carrier dominated the tackle (both front-on and side-on) and during tackler dominated front-on tackles, kinetic energy was not different between the ball-carrier and tackler. In tackler dominated side-on tackles however, the difference between ball-carrier and tackler was large ($d = 0.94$, $p > 0.05$). Furthermore, the difference in the magnitude of impact between ball-carrier dominated side-on tackles, and tackler dominated side tackles was large ($d = 0.87$, $p > 0.05$).

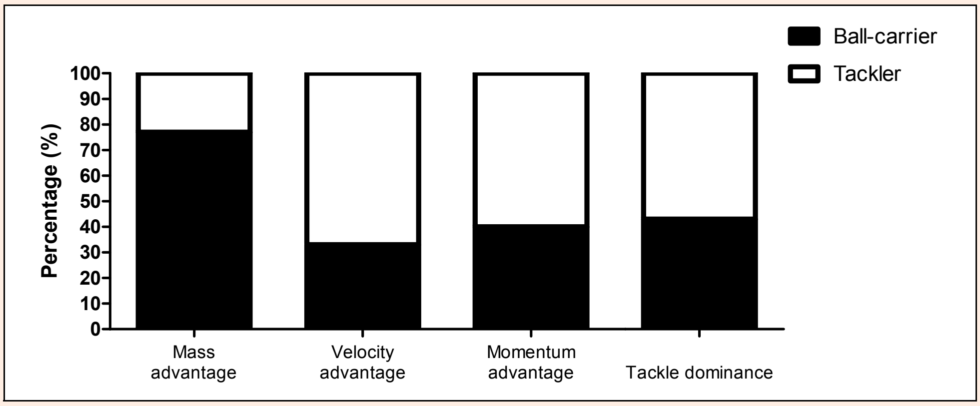

Figure 2. Percentage proportion of ball-carrier and tackler mass advantage, velocity advantage, momentum advantage and tackle dominance for the front on tackle (Data reported as percentage frequency, n=30)

Table 4. Kinetic Energy before contact and magnitude of impact (energy distributed between ball-carrier and tackler upon contact). Data reported as mean (±SD).

	n	Ball-carrier Kinetic Energy (Joules)	Tackler Kinetic Energy (Joules)	Energy (magnitude of impact) (Joules)
		Front-on		
Contact dominated by Ball-carrier	13	1417 (628)	1519 (1077)	2754 (1075)
Contact dominated by Tackler	17	1464 (1815)	1911 (1395)	3063 (1911)
		Side-on		
Contact dominated by Ball-carrier	27	1463 (1030)	1389 (1055)	2705 (1462)
Contact dominated by Tackler	3	1058 (862)	435 (283)	1431 (1078)

Discussion

The purpose of this study was to quantify momentum before contact in the tackle, and using the basic physical principles of conservation of momentum and energy (and the associated assumptions), calculate the magnitude of impact during real match situations for the ball-carrier and tackler. Furthermore, describe the momentum and magnitude of impact for three different levels of play, playing position, and the relationship between tackle dominance and magnitude of impact. In support of previous studies (Duthie et al., 2003; Sedeaud et al., 2012), forwards were generally heavier than backs whether as a ball-carrier or tackler. Interestingly, ball-carriers tended to be heavier than tacklers. In the tackles analysed for this study, tackle situations where ball-carriers were heavier also presented itself more frequently (68% of all tackles, and 77% of all front on tackles) than tackles situations where tacklers were at a mass disadvantage. Furthermore, forwards carrying the ball into contact had a significantly higher momentum than backs taking the ball into contact. Collectively, these findings may reflect a characteristic of the modern game of rugby where efficiently heavier players (particularly forwards) are tactically predetermined to carry the ball in contact. Indeed, heavier teams have been associated with team success in rugby union (Olds, 2001; Sedeaud et al., 2012).

In the sample of front on tackles studied, despite the mass advantage ball-carriers had over tacklers before contact, momentum before front tackles were proportionally even between ball-carriers and tacklers, and the frequency of tackle dominance was just under 50%. Seemingly, tacklers entered front-on tackles with a higher velocity more frequently than ball-carriers, which may be a contributing factor to the distribution of relative momentum and tackle dominance. In a laboratory setting, Usman et al. found no significant association between the force produced by a tackler during a front on shoulder tackle, and their body mass index (Usman et al., 2011). In our study, tacklers were frequently at a mass disadvantage, yet dominated 57% of all tackles. This supports the findings of Usman et al. (2011) and may suggest, from a tackler perspective, mass may not be a significant contributor to forceful tackles. Admittedly, the definition of tackle outcome described for this study was limited to the direction of progression the tackler and ball-carrier made (as a single unit) towards the opposition try-line from the point of contact to the point where both players went to ground. The aim of the tackle outcome definition for this study was to relate physical components such as mass, velocity, and momentum to tackle dominance, and not necessarily tackle success. Undoubtedly, after entering a tackle, maintaining, or re-gaining possession is probably the primary objective of any player, and in this regard, player size (mass and height) may aid in protecting the ball from the opponent. However, the physical characteristics measured in this study alone would not have sufficiently explained a tackle success definition where ball possession was measured as an outcome since other factors, for example tackle and contact skills (Wheeler and Sayers, 2009; Wheeler et al., 2010), contribute to this result.

When the ball-carrier and tackler engage in contact, the physical demand of contacting another moving body was determined by calculating the amount of energy distributed between the ball-carrier and tackler upon contact. This excess of energy may cause muscle damage and injury to the musculoskeletal system (Takarada, 2003). The tackles analysed in this study were all injury-free, and therefore may provide evidence for the physical tolerance levels of rugby players during the tackle. However, the ability of a player to repeatedly engage in tackle contests within in a match and over a competitive season, and remain injury-free remains unanswered. Presumably, technique may play a role in reducing the energy load on the musculoskeletal system.

The analysis of tackles in this study represents a highly simplified, but ultimately practical measure for calculating velocity, momentum, and energy transfer during a complex tackle event in real match situations. Indeed, previous work using a similar analysis during real match concussive head impacts proved successful in reconstructing and modelling head impacts in the laboratory (Frechede and McIntosh 2009; McIntosh et al., 2000; Pellman et al., 2003a; 2003b). A key distinction, and noteworthy limitation of the present study in comparison to previous work on concussive head impacts, is the mass used to estimate momentum and energy transfer. Because head impacts were measured, momentum and energy transfer were measured using the mass of the head only. In contrast, the present study utilised whole body mass for the calculation of momentum and energy transfer. In addition, the motion path of the ball-carrier and tackler towards contact was assumed linear by a point above field level. Although a linear path was a necessary assumption for the calculation of velocity, we acknowledge the position measurements will inevitably contain a small amount of artefact dependent on how much vertical motion of the measurement point occurs during the measurement period. Consequently, subtle changes in movement before contact were obscured. Arguably, a sample size of 10 for each grouping variable may be too small to make any tenacious conclusions about differences in mass, velocity and momentum. With that said, considering all three playing groups were high level, the lacks of statistically significant differences are not surprising. Given one of the objectives of this study was to report mass, velocity, and momentum at the different playing levels, using a sample of high level players, albeit different competitions, highlights a caveat of the study.

Conclusion

In summary, ball-carriers were observed to be heavier than tacklers in the tackles analysed in this study. Plausibly, this may be a reflection of the modern game of where heavier players, in particular forwards, are used tactically to cross the advantage line. In front on tackles, despite the ball-carrier having a mass advantage before contact more frequently, the momentum advantage was proportionally similar between ball-carriers and tacklers. This finding was echoed for the relative frequency of tackle dominance. The estimated magnitude of impact during the 60 completed injury free tackles in this study provides evidence for the tolerance to impact loads during the tackle contest. The 2D-axis is favourable since it does not require the instrumentation of the player. An alternative method for measuring distance, velocity and magnitude of impact would be to attach some form of measuring device such as a global position system (GPS) or accelerometer to the body of the player. To accomplish this, access to, and consent of the players is needed. To date, studies using a GPS device to characterise velocity and impacts in collision team sports have been limited to classifying impacts within a range instead of reporting actual values (McLellan and Lovell, 2012). Having said that, the advancements of team GPS devices (Varley et al., 2012) and instrumented body systems, such as the head impact telemetry (HIT) system in American football (Duma et al., 2005), has the potential to allow for more precise measurements. In view of this, a comparison between the 2D analysis, latest team GPS devices and instrumented body systems in rugby union will be worthwhile.

Acknowledgments

The authors of this paper would like to thank the National Research Foundation/German Academic Exchange Service, Medical Research Council of South Africa, Frank Foreman Scholarship, Glickman/Elliot Scholarship, University of Cape Town Equity Scholarship, Doctoral Research Scholarship, and the Exercise Science and Sports Medicine Scholarship for support during the study.

References

Alcock, A., Hunter, A. and Brown, N. (2009) Determination of football pitch locations from video footage and official pitch markings. *Sports Biomechanics* **8(2)**, 129-140.

Austin, D., Gabbett, T. and Jenkins, D. (2011) The physical demands of Super 14 rugby union. *Journal of Science and Medicine in Sport* **14(3)**, 259-263.

Batterham, A.M. and Hopkins, W.G. (2006) Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance* **1**, 50-57.

Blazevich, A. (2007) *Sports Biomechanics: The Basics: Optimising Human Performance* London, A&C Black Publishers Ltd.

Brewin, M. and Kerwin, D. (2003) Accuracy of scaling and DLT reconstruction techniques for planar motion analyses. *Journal of Applied Biomechanics* **19**, 79-88.

Brooks, J.H., Fuller, C.W., Kemp, S.P. and Reddin, D.B. (2005) Epidemiology of injuries in English professional rugby union: part 1 match injuries. *British Journal of Sports Medicine* **39(10)**, 757-766.

Burkett, B. (2010) *Sport Mechanics for Coaches.* 3rd edition. Champaign, IL, Human Kinetics.

Duma, S.M., Manoogian, S.J., Bussone, W.R., Brolinson, P.G., Goforth, M.W., Donnenwerth, J.J., Greenwald, R.M., Chu, J.J. and Crisco, J.J. (2005) Analysis of real-time head accelerations in collegiate football players. *Clinical Journal Sport Medicine* **15(1)** 3-8.

Duthie, G., Pyne, D. and Hooper, S. (2003) Applied physiology and game analysis of rugby union. *Sports Medicine* **33(13)** 973-991.

Eaton, C. and George, K. (2006) Position specific rehabilitation for rugby union players. Part II: Evidence -based examples. *Physical Therapy in Sport* **7**, 30-35.

Edgecomb, S.J. and Norton, K.I. (2006) Comparison of global positioning and computer-based tracking systems for measuring player movement distance during Australian football. *Journal of Science and Medicine in Sport* **9**, 25-32.

Frechede, B. and McIntosh, A.S. (2009) Numerical reconstruction of real-life concussive football impacts. *Medicine & Science in Sports & Exercise* **41(2)**, 390-398.

Fuller, C.W., Ashton, T., Brooks, J.H., Cancea, R.J., Hall, J. and Kemp, S.P. (2010) Injury risks associated with tackling in rugby union. *British Journal of Sports Medicine* **44(3)**, 159-167.

Gabbett, T. and Ryan, P. (2009) Tackling Technique, Injury Prevention, and Playing Performance in High-Performance Collision Sport Athletes. *International Journal of Sports Science and Coaching* **4(4)**, 521-533.

Garraway, W.M., Lee, A.J., Macleod, D.A., Telfer, J.W., Deary, I.J. and Murray, G.D. (1999) Factors influencing tackle injuries in rugby union football. *British Journal of Sports Medicine* **33(1)**, 37-41.

Headey, J., Brooks, J.H. and Kemp, S.P. (2007) The epidemiology of shoulder injuries in English professional rugby union. *The American Journal of Sports Medicine* **35(9)**, 1537-1543.

Hendricks, S., Jordaan, E. and Lambert, M. (2012a) Attitude and behaviour of junior rugby union players towards tackling during training and match play. *Safety Science* **50**, 266-284.
Hendricks, S., Karpul, D., Nicolls, F. and Lambert, M. (2012b) Velocity and acceleration before contact in the tackle during rugby union matches. *Journal of Sports Sciences*, **30(12)**, 1215-1224
Hendricks, S. and Lambert, M. (2010) Tackling in Rugby: Coaching Strategies for Effective Technique and Injury Prevention. *International Journal of Sports Science and Coaching*, **5(1)**, 117-135.
Kwon, Y.H. and Casebolt, J.B. (2006) Effects of light refraction on the accuracy of camera calibration and reconstruction in underwater motion analysis. *Sports Biomechanics* **5(1)**, 95-120.
McIntosh, A.S., McCrory, P. and Comerford, J. (2000) The dynamics of concussive head impacts in rugby and Australian rules football. *Medicine & Science in Sports & Exercise*, **32(12)**, 1980-1984.
McIntosh, A.S., Savage, T.N., McCrory, P., Frechede, B.O. and Wolfe, R. (2010) Tackle characteristics and injury in a cross section of rugby union football. *Medicine & Science in Sports & Exercise* **42(5)**, 977-984.
McLellan, C.P. and Lovell, D.I. (2012) Neuromuscular responses to impact and collision during elite rugby league match play. *Journal of Strength and Conditioning Research* **26(5)**, 1431-1440.
Newman, J.A., Beusenberg, M.C., Shewchenko, N., Withnall, C. and Fournier, E. (2005) Verification of biomechanical methods employed in a comprehensive study of mild traumatic brain injury and the effectiveness of American football helmets. *Journal of Biomechanics* **38(7),** 1469-1481.
Olds, T. (2001) The evolution of physique in male rugby union players in the twentieth century. *Journal of Sports Science* **19(4)** 253-262.
Pellman, E.J., Viano, D.C., Tucker, A.M. and Casson, I.R. (2003a) Concussion in professional football: location and direction of helmet impacts-Part 2. *Neurosurgery* **53(6)**, 1328-1340.
Pellman, E.J., Viano, D.C., Tucker, A.M., Casson, I.R. and Waeckerle, J.F. (2003b) Concussion in professional football: reconstruction of game impacts and injuries *Neurosurgery* **53(4)**, 799-812.
Quarrie, K.L. and Hopkins, W.G. (2008) Tackle injuries in professional Rugby Union. *The American Journal of Sports Medicine* **36(9),** 1705-1716.
Sedeaud, A., Marc, A., Schipman, J., Tafflet, M., Hager, J.P. and Toussaint, J.F. (2012) How they won Rugby World Cup through height, mass and collective experience. *British Jouranl of Sports Medicine* **46(8)**, 580-584.
Sundaram, A., Bokor, D.J. and Davidson, A.S. (2011) Rugby Union on-field position and its relationship to shoulder injury leading to anterior reconstruction for instability. *Journal of Science and Medicine in Sport* **14(2)**, 111-114.
Takarada, Y. (2003) Evaluation of muscle damage after a rugby match with special reference to tackle plays. *British Journal of Sports Medicine* **37(5)**, 416-419.
Usman, J., McIntosh, A.S. and Frechede, B. (2011) An investigation of shoulder forces in active shoulder tackles in rugby union football. *Journal of Science and Medicine in Sport* **14(6)**, 547-552.
Varley, M.C., Fairweather, I.H. and Aughey, R.J. (2012) Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *Journal of Sports Sciences* **30(2)**, 121-127.
Wheeler, K. and Sayers, M. (2009) Contact Skills Predicting Tackle-Breaks in Rugby Union. *International Journal of Sports Science and Coaching* **4(4)**, 535-544.
Wheeler, K.W., Askew, C.D. and Sayers, M.G. (2010) Effective attacking strategies in rugby union. *European Journal of Sport Science* **10(4)**, 237-242.

✉ **Dr Sharief Hendricks**
MRC/UCT Research Unit for Exercise Science and Sports Medicine, Department of Human Biology, Faculty of Health Sciences, the University of Cape Town and the Sports Science Institute of South Africa, Cape Town, South Africa

Key points

- First study to quantify momentum, kinetic energy, and magnitude of impact in rugby tackles across different levels in matches without a device attached to a player.
- Physical components alone, of either ball-carrier or tackler, are not good predictors of tackle dominance.
- The range of magnitudes of impact of injury free tackles observed in this study provides evidence for the physical tolerance of players during the tackle.

AUTHORS BIOGRAPHY

Sharief HENDRICKS
Employment
Research Fellow at the UCT/MRC Research Unit for Exercise Science and Sports Medicine at the University of Cape Town.
Degree
PhD
Research interest
Technical and tactical skill development, long-term participation development, injury prevention, science communication, strength and conditioning, concussion, video and performance analysis, health promotion and physical activity, social media.
E-mail: sharief.hendricks01@gmail.com

Mike LAMBERT
Employment
Professor at the UCT/MRC Research Unit for Exercise Science and Sports Medicine at the University of Cape Town.
Degree
PhD
Research interest
Training-induced fatigue, adaptation to exercise, particularly the maladaptation which occurs after the exposure to chronic exercise, monitoring training status and research on improving performance and health of rugby players.
E-mail: mike.lambert@uct.ac.za

Davis KARPUL
Employment
Researcher in the MRC/UCT Research Unit for Exercise Science and Sports Medicine at the University of Cape Town.
Degree
MSc
Research interest
The numerical analysis of sport, biomechanics, and instrumentation.