In-vivo measurement of tri-axial loading at the head during the rugby tackle

Journal:	*Research in Sports Medicine*
Manuscript ID	GSPM-2017-0002.R2
Manuscript Type:	Original Research
Keywords:	rugby, accelerometry, head injuries, tackles

In-vivo measurement of tri-axial loading at the head during the rugby tackle

Abstract.

To investigate the anatomical distribution of linear and rotational forces during the tackle scenario, male rugby players performed a total of 48 trials, as ball carrier or tackler. Participants wore headgear accommodating three Global Positioning System units measuring uni-axial acceleration at the occipital region (OR), left tempero-parietal (LT-PR) and right tempero-parietal region (RT-PR). An additional unit was located at the cervico-thoracic spinal region (CSR) in a custom vest. There was a significant main effect for tackle condition ($P<0.001$), with the tackler exposed to significantly greater load than the ball carrier, supporting epidemiological observations. A repeated measures General Linear Model also revealed a significant ($P<0.001$) main effect for unit location upon 3D load, with significantly higher load at the CSR (1.63±0.54 a.u) and OR (1.67±0.94 a.u) units when compared to the LT-PR (1.23±0.39 a.u) and RT-PR (1.21±0.44 a.u) units. The anatomical specificity in loading supports epidemiological observations and provides an insight into potential concussion aetiology.

INTRODUCTION

The incidence of head injuries and concussions in rugby ranges from 6.6-14.6 and 4.1-9.1 per 1000 game hours respectively (Kemp, Hudson, Brooks, & Fuller, 2008; Brooks, Fuller, Kemp, & Reddin, 2005; Fuller, Sheerin, & Targett, 2013; Gardner, Iverson, Williams, Baker, & Stanwell, 2014; Tommasone & Valovich McLeod, 2006). Whilst catastrophic brain injury in rugby is rare (McCrory, Berkovic, & Cordner, 2000), concussive injury is frequent, accounting for up to 25% of all injuries (McIntosh, 2003). The concussive incidence rate equates to a concussion every 6 matches, with 15 concussions recorded during the 2011 rugby World Cup competition (Fuller et al., 2013). Concussion is a complex pathophysiological process resulting from a direct impact to the head, or to another region of the body causing an abrupt acceleration and/or deceleration to the craniocervical complex (Marshall, 2012). Repeated concussions and mild traumatic brain injury (MTBI) can result in chronic traumatic encephalopathy (CTE) (Roberts, Allsop, & Bruton, 1990; McKee, Cantu, Nowinski, Hedley-Whyte, Gavett, Budson, et al., 2009; Patricios and Kemp, 2014). The development of CTE can have symptoms of deterioration in attention, memory and concentration which can manifest to overt dementia (McKee et al. 2009). In previous research, at least 17% of repeated concussion or MTBI sufferers developed CTE (Roberts et al., 1990), and 90% of neuropathologically confirmed cases of CTE were athletes (90%).

The tackle is the most common facet of play in which head injuries occur within rugby, accounting for 56-64% (Bird, Waller, Marshall, Alsop, Chalmers, & Gerrard, 1998; Brooks et al., 2005; Kemp et al., 2008). The tackle scenario is unlikely to be linear; Broglio, Schnebel, Sosnoff, Shin, Fend & Zimmerman (2010) identified the presence of linear and rotational accelerations of the head, with rotational forces contributing to the mechanism of concussion (Thompson & Hagedorn, 2012). Video analysis of concussive events within Australian Rules Football, Rugby and Rugby league found that although the majority of concussions occurred as a result of a direct impact to the head, concussion also arose as result of a change in relative momentum of the head relative to the trunk (McIntosh, McCrory, & Comerford, 2000). The potential for concussive injury via the whiplash mechanism is attributed to the large degrees movement of the head relative to the neck (Ommaya & Hirsch, 1971; Shaw, 2002).

The relative anatomical accelerations and contribution of linear and rotational forces in concussions present an opportunity in the use of tri-axial accelerometry to investigate the mechanism of head injury in the rugby tackle scenario. GPS technology has been utilised previously in rugby to quantify the demands of playing and training (Reid, Cowman, Green, & Coughlan, 2013; Jones, West, Crewther, Cook, & Kilduff, 2015; Hartwig, Naughton, & Searl, 2011) and to quantify the intensity and frequency of collisions (Suarez-Arronez, Arenas, Lopez, Requena, Terrill, & Mendez-Villanueva, 2014; Cunniffe, Proctor, Barker, & Davies, 2009; Venter, Opperman, & Opperman, 2011). The contemporary development of GPS-based micro-technologies has established a greater degree of reliability due to the higher sampling frequencies (Boyd, Ball, & Aughey, 2011), and research has demonstrated the efficacy of incorporating tri-axial accelerometry in sports such as netball (Cormack, Smith, Mooney, Young, & O'Brien, 2014), basketball (Montgomery, Pyne, & Minahan, 2010) and Australian football (Boyd, Ball, & Aughey, 2013). The aim of the present study is to investigate the efficacy of tri-axial accelerometry in identifying risk factors for head injury during the rugby tackle event. To account for the whiplash mechanism associated with the relative movement of anatomical locations, units will be housed within a protective helmet in addition to the most common placement at the cervico-thoracic junction. Multiple sites at the head are considered to account for the linear and rotational forces which contribute to concussion.

MATERIALS AND METHOD

Participants

A total of 24 rugby tackle events were analysed to provide a total of 48 trials (24 as tackler and 24 as ball carrier). This data set comprised 12 male rugby union players (age 21.3 ±

2.2 years; weight 88.7 ± 5.6 kg; height 1.84 ± 0.06 m), recruited from a single semi-professional club. These 12 players represent a relatively homogeneous sample from within the club, and this was deemed beneficial given the potential impact of anthropometric variability on loading and tackle technique. Furthermore, during testing, matched pairs were established based on weight, height and playing position. All participants were made aware of the purposes and risks of the study prior to any data collection. All participants provided written informed consent, were health screened and reported to be injury free for at least six months prior to data collection. Additionally, each player had a minimum of 8 years of competitive rugby experience, and a current training status equivalent to four training sessions (two rugby-specific sessions) and one competitive match per week. Ethical consent was provided at a Departmental level in accord with the spirit of the declaration of Helsinki.

Experimental Design

A tackle scenario involving two participants, a tackler and ball carrier, was created using either the active shoulder or smother tackles based on their prominence in rugby (McIntosh, Savage, McCrory, Frechede, & Wolfe, 2010). During each tackle, both the ball carrier and tackler wore modified protective headgear designed to accommodate three Catapult MinimaxX S4 GPS units (Catapult Innovations, Victoria, Australia) with an incorporated tri-axial piezoelectric linear accelerometer (Kionix: KXP94) operating at 100Hz. The reliability of these accelerometers has been previously established within the literature as acceptable (CV= 0.91-1.05%) in dynamic movements (Boyd et al., 2011). Two units were positioned either side of the skull at the left tempero-parietal region (LT-PR) and right tempero-parietal region (RT-PR) and one was positioned to the rear, at the occipital region (OR) of the skull. A fourth unit was fitted in the customary position between the scapulae at the thoraco-cervical region (CSR) in the elasticised vests provided by the manufacturer.

Prior to data collection, participants engaged in a ten minute warm up incorporating dynamic stretches and standing tackle impacts. Participants were also required to perform ten submaximal tackles, progressing from a stationary crouched position to gradually increasing approach lengths up to the pre-determined experimental set-up of 5m. This progressive exercise was performed to gradually increase the velocity of contact, and to ensure a safe and ecologically valid technique was achieved by both participants. Player pairs were established prior to experimental trials, and all familiarisation trials were completed in these pairs to establish consistency.

Within the experimental pair, each participant completed the active shoulder and smother tackle scenarios as both ball carrier and tackler. These four experimental trials were completed in randomised order across the pairs. In the active shoulder tackle, the tackler's shoulder makes the first point of contact with the ball carrier's trunk region, this is followed by a leg drive and forward momentum to bring the ball carrier to the ground. The smother tackle involves the tackler wrapping his arms around the ball carrier and utilising their momentum to bring them to the ground, rotating with them in the process.

Each trial allowed the tackler and ball carrier a run-up sequence of 5m before the tackle was performed, in which both tackles resulted in the ball carrier being taken to the ground. The absolute and relative speeds of the ball carrier and tackler influence the incidence and severity of injury (Quarrie & Hopkins, 2008). In the current study the GPS unit placed at the CSR was used to quantify the forward velocity of both players immediately prior to impact. Familiarisation trials were utilised to establish a consistent expression of effort, and to attain a reliable approach speed by both players. Immediately after impact, the culmination of the tackle event was also standardised. Familiarisation trials identified that the majority of tackle events utilised a two stride effort to take the ball carrier to the ground. As a result, tacklers were instructed to complete the grounding of the ball carrier with a maximum of two strides: typically the first stride being to establish contact with the ball carrier, and the second stride used to drive the ball carrier to the ground and complete the tackle.

Data Analysis

All data was downloaded using Catapult Sprint software (Version 5.1.1, Catapult Innovations, Victoria, Australia). The forward velocity of the ball carrier and tackler immediately prior to impact were 5.6 ± 0.3 m·s^{-1} and 3.8 ± 0.2 m·s^{-1} respectively. During each tackle, each of the four tri-axial accelerometers (CSR, OR, LT-PR and RT-PR) were analysed for anterior-posterior (AP), medio-lateral (ML) and vertical (V) uni-axial PlayerLoad™. Uni-axial load was calculated using the equation as described by Boyd, Ball, & Aughey (2013), and defined using the instantaneous rate of change in acceleration: $\sqrt{[(a_{y1} - a_{y-1})^2/100]}$. This was done for each of the three discrete uni-axial vectors.

The cumulative tri-axial Total PlayerLoad was also calculated, defined as the sum of the three uni-axial vectors (rather than the square root of the sum as described by Boyd, Ball, & Aughey). This summative tri-axial value was subsequently used to calculate the relative contribution of each plane to total load.

Statistical Analysis.

Statistical analysis and the selected analysis parameters were determined *a* priori. The assumptions associated with a repeated measures general linear model (GLM) were assessed to ensure model adequacy, including the residual normality for each analysis parameter. Mauchly's test of sphericity was supplemented with a Greenhouse Geisser correction where appropriate. Subsequent inferential analyses were performed using a mixed method two-way (unit location*tackle condition) repeated measure GLM to examine differences in the loading between the tri-axial accelerometer locations (CSR, OR, LT-PR, RT-PR), and tackle condition (ball carrier, tackler). Where significant main effects or interactions were observed, post-hoc pairwise comparisons with a Bonferroni correction factor were applied. To further identify substantive significance associated with main effects and interactions, partial eta squared (η^2) values were calculated to estimate effect sizes. All data are presented as mean ± SD unless otherwise stated.

RESULTS

There was a significant main effect (P<0.001, η^2=0.72) for unit location with significantly higher (P≤0.001) 3D load at the CSR (1.63±0.54 a.u) and OR (1.67±0.94 a.u) units when compared to the LT-PR (1.23±0.39 a.u) and RT-PR (1.21±0.44 a.u) units. Further analysis revealed a significant main effect (P<0.001, η^2=0.59) for tackle condition and a significant interaction (P<0.001, η^2=0.46) between unit location and tackle condition.

The active shoulder tackler exhibited significantly (p≤0.001) greater Load at CSR (1.90±0.57 a.u) and OR (2.03±0.76 a.u) than LT-PR (1.50±0.40 a.u) and RT-PR (1.49±0.43 a.u) units. The ball carrier also exhibited significantly higher (P≤0.036) 3D load at CSR (1.90±0.41 a.u) and OR (1.69±0.52 a.u) than LT-PR (1.17±0.18 a.u) and RT-PR (1.16±0.21 a.u).

The ball carrier into the smother tackle also exhibited significantly greater (P≤0.001) Load at CSR (1.71±0.33 a.u) and OR (1.69±0.45 a.u) than LT-PR (1.25±0.19 a.u) and RT-PR (1.25±0.20 a.u). In contrast, the smother tackler exhibited significantly greater (P≤0.013)

Load at OR (1.28±0.15 a.u) than CSR (1.02±0.39 a.u), LT-PR (0.99±0.23 a.u) and RT-PR (0.95±0.27 a.u) units. The influence of tackle condition and unit placement is summarised in Figure 1.

** Insert Figure 1 near here **

Table 1 summarises the influence of unit location and tackle condition on the uni-axial Load. There was a significant main effect for unit location in each of the Anterio-Posterior (P=0.031, η^2=0.23), Medio-Lateral (P<0.001, η^2=0.87) and Vertical (P<0.001, η^2=0.66) planes. There was also a significant main effect for tackle condition (Anterio-Posterior: P<0.001, η^2=0.52; Medio-Lateral: P<0.001, η^2=0.55; Vertical: P<0.001, η^2=0.72) and a significant interaction effect between unit location and tackle condition in each plane (Anterio-Posterior: P<0.001, η^2=0.44; Medio-Lateral: P<0.001, η^2=0.48; Vertical: P<0.001, η^2=0.26).

Post-hoc analysis revealed that Anterio-Posterior loading was significantly higher for the ball carrier at the CSR when compared to the LT-PR and RT-PR in the active shoulder (P≤0.033) and smother tackles (P≤0.037). Conversely, AP loading at CSR was significantly less for the tackler during the smother tackle than at either parietal regions (P≤0.039).

Medio-Lateral loading was significantly higher at the CSR and OR than LT-PR and RT-PR in all tackle conditions (P≤0.001). For the tackler, loading at OR was significantly greater than at CSR in both conditions (AS: P=0.009: S: P=0.017). For the ball carrier, the active shoulder tackle elicited significantly greater ML loading at CSR than OR (P=0.003).

Vertical loading was significantly higher at the CSR and OR than the LT-PR and RT-PR regions in the AS-T ($P \leq 0.018$), AS-BC ($P \leq 0.002$), and S-BC ($P \leq 0.045$) tackle conditions. In the S-T condition, OR loading was significantly greater than at all other locations ($P \leq 0.026$), and LT-PR was significantly higher than RT-PR ($P = 0.032$).

** Insert Table 1 near here **

AP Load was significantly greater at the CSR than all other sites for the ball carrier in each condition. However the smother tackler exhibited significantly less Load at CSR than all other locations, whilst the active shoulder tackler exhibited no difference between unit locations.

ML Load was significantly greater at CSR and OR than at LT-PR and RT-PR in all tackle conditions, however there was a distinction between ball carrier and tackler. ML Load at CSR was significantly greater than OR for the tackler, but for the ball carrier Load at OR was significantly greater than CSR.

Vertical Load was also significantly greater at CSR and OR than LT-PR and RT-PR for the ball carrier in both conditions, and for the active shoulder tackler. However, for the smother tackler V Load was significantly greater at OR than all other sites, with a symmetry differential evident in LT-PR loading being significantly greater than RT-PR.

The relative contribution of each uni-axial vector to Total Load is summarised in Figure 2. There was a significant ($P < 0.001$) main effect for unit location in each axis. In the ML plane ($\eta^2 = 0.96$) the % contribution was significantly greater at the CSR and OR than the parietal regions. There was a compensatory greater increase in % contribution in the AP

(η^2=0.82) and V (η^2=0.49) planes at LT-PR and RT-PR than at CSR and OR. In the AP plane, the % contribution was significantly higher (*P*=0.032) at CSR than OR.

** Insert Figure 2 near here **

In relative axial loading, there was a significant main effect for tackle condition in the ML (*P*<0.001, η^2=0.76) and V (*P*<0.001, η^2=0.81) planes, but not in the AP plane (*P*=0.272, η^2=0.11). There was a significant interaction effect between unit location and tackle condition in the % contribution of all planes (ML: *P*<0.001, η^2=0.31; AP: *P*<0.001, η^2=0.33; V: *P*=0.001, η^2=0.24). This data is summarised in Table 2.

The tackler exhibited significantly greater (*P*≤0.001) AP % loading at the PR locations than CSR and OR. In the active shoulder tackle, relative AP loading was significantly higher (*P*=0.002) at CSR than OR. The ball carrier in the active shoulder tackle exhibited significantly greater AP % loading at RT-PR than at CSR and OR (*P*≤0.017), whereas this relative loading was significantly greater (*P*≤0.020) at LT-PR in the smother tackle.

The greater AP% contribution in the PR sites was also evident in the V plane. For the tackler, V % at LT-PR was significantly greater (*P*≤0.001) than OR in the active shoulder tackle, and significantly greater (*P*≤0.001) than CSR in the smother tackle. For the ball carrier, relative V loading was significantly higher at RT-PR than CSR and OR in the active shoulder (*P*=0.026) and smother (*P*≤0.001) tackle. In the active shoulder tackle, relative loading at OR was significantly greater (*P*≤0.001) than at CSR.

Conversely, the ML % contribution to total Load was significantly lower in the PR locations in all tackle conditions. In the active shoulder tackle, the relative loading was significantly higher at OR than CSR (*P*<0.001) for the tackler, but significantly higher at CSR than OR for the ball carrier (*P*=0.017). For the ball carrier, LT-PR exhibited higher relative loading than RT-PR (*P*=0.037). In the smother tackle, relative ML loading at CSR and OR were significantly greater (*P*<0.001) than at PR locations for tackler and ball carrier. The smother tackler exhibited significantly greater (*P*=0.019) loading at RT-PR than LT-PR.

** Insert Table 2 near here **

DISCUSSION

Placing wearable technology in helmets has informed understanding of the biomechanics of concussion (Broglio et al., 2010; Broglio, Eckner, Martini, Sosnoff, Kutcher, & Randolph, 2011). The aim of the present study was to assess the efficacy of incorporating multiple tri-axial accelerometers within protective headgear in identifying risk factors for injury. The neoprene headgear used has limited capacity to attenuate impact energy (McIntosh, McCrory, Finch, Best, Chalmers, & Wolfe, 2009; McIntosh et al., 2000) and thus negates the influence of the headgear itself on measures of accelerometry. The product used in this study was a commercially available scrum cap, carrying the IRB approval logo, and meeting the requirement that no part of the headgear is thicker than 10mm when uncompressed and with a density of no more than 45kg/m^3. Critical discussion of the load magnitudes is limited by a lack of similar research, but the implications of unit placement have been considered previously (Barrett, Midgley, &Lovell, 2014

The tempero-parietal region was identified by McIntosh et al. (2000) as the most frequent site of concussive injuries in rugby, informing placement in this study. Total load was significantly lower in the peripheral tempero-parietal regions when compared to the central occipital and cervico-thoracic regions. The greater magnitude of loading in the central regions might be attributed to the initial point of impact and the prevalence of linear (rather than rotational) forces in these tackle scenarios. This is indicative of the primary influence of linear forces where both players are moving forward. The front on tackle has greatest propensity to cause concussion (Kemp et al., 2008) due to the greater presence of linear forces, which are key contributors to concussive injury (Broglio et al., 2010; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003).

The loading pattern supports the epidemiological literature indicating the tackler is at the greatest risk of head injury (Kemp et al., 2008; Bird et al., 1998). The greater loading in central regions was observed in all conditions, but in the smother tackle the tackler was subjected to a significantly greater load at the OR. This tackle is performed front-on, in an upright position with the initial point of contact being the sternum. Analyses of AP load confirmed greater magnitudes in all units positioned within the headgear relative to the CSR, creating an impulse resulting in the head being set in motion relative to the trunk (Shaw, 2002). This whiplash mechanism contributes to concussion in contact sports (McIntosh et al., 2000).

In the active shoulder technique, the tackler is advised to position their head to the side of the ball carrier to reduce the likelihood of a direct head impact. The tackler using this technique was exposed to a greater absolute and relative medio-lateral load at OR. The initiation of rotational forces have been regarded a key risk factor to concussion in contact sport (Broglio et al., 2010, 2011; Guskiewicz, Mihalik, Shankar, Marshall, Crowell, Oliaro, et al., 2007; Broglio, Surma, & Ashton- Miller, 2010). The relative differences in ML load between anatomical sites suggest there is propensity for medio-lateral whiplash due to the large freedom of movement of the head. This could increase the propensity of a collision between the brain floating in the cerebrospinal fluid and the stiff walls of the skull, causing a concussion (Shaw, 2002; Wilberger, Ortega, & Slobounov, 2006). Conversely, the ball carrier into the active shoulder tackle exhibited significantly greater 3D load at the CSR region. The points of contact and transferal of kinetic energy differ between the tackler and ball carrier (Quarrie & Hopkins, 2008; Fuller, Brooks, Cancea, Hall, & Kemp, 2007b).

There was lower (absolute and relative) anterio-posterior load at the CSR than the OR in all tackle conditions, with a compensatory increase in medio-lateral and vertical loading contributions. Previous research investigating the biomechanics of head impacts has emphasised the importance of the role of both linear and rotational accelerations in concussive injury (Broglio et al., 2010, 2011) The proposed rotational component induced by the presence of lateral forces, has been suggested to have great propensity to cause concussion due to the increased strain on brain stem integrity (Guskiewicz et al., 2007; Broglio, Surma, & Ashton-Miller, 2010) which is derived from the anatomical linear alignment of the brain stem itself (Ommaya & Gennarelli, 1974).

The sensitivity of unit placement and the tri-axial nature of loading patterns suggests potential in head injury screening. For example, the significant difference in loading between the occipital skull and cervico-thoracic junction might inform analysis and identification of the whiplash mechanism. Up to 90% of sport related concussions occur without loss of consciousness (Cantu, 1996) and there is no "gold standard" for diagnosing concussion. Repeated concussions are usually more severe (Saffary, Chin, & Cantu, 2012) and the propensity of suffering a second concussion is increased by up to three-fold (Guskiewicz, Weaver, Padua, & Garrett, 2000). The efficacy of this tool is therefore encouraging as it could be incorporated alongside other assessment tools to improve diagnosis of concussive injury. The present study has demonstrated the efficacy of positioning micro-technology upon the head, which could be further utilised to determine whether a player has experienced too great a load upon the head in a game/ head injury incident to allow them to return to training or play too soon. This could protect players from repeated concussive injuries, decreasing the propensity of insidious long- term neuropathological conditions (McKee et al., 2009; Patricios & Kemp, 2014). In the present study such a threshold would relate to the magnitude of acceleration, but recently the potential of exposure thresholds based on frequency of heading in soccer has been considered (Catenaccio, Caccese, Wakschlag, Fleysher, Kim, Kim, et al., 2016). The authors describe HeadCount, a 2 week recall questionnaire that was used to quantify the product of number of games and average number of headers per game. Catenaccio et al. reported this inexpensive and logistically convenient instrument to be a valid means for monitoring frequency of exposure, and advocated applications in other sport. A combination of magnitude and frequency monitoring should therefore be considered.

Concerns of injury in youth sport being detrimental to physical development (Emery, 2010) and epidemiological studies still denoting high incidence and severity of head injuries and concussion in youth rugby (Bleakley, Tully, & O'Connor, 2011; Haseler, Carmont, & England, 2010; McIntosh et al., 2009) supports the use of this tool in youth rugby. Future research quantifying the biomechanics of concussive injuries could be correlated alongside other management protocols, such as investigation into clinical symptomology, neuropsychological function and postural stability, to establish this tool as another potential measure to monitor the concussive risk in collision sports. Rule changes present an alternate opportunity to influence injury risk. Caccese, Lamond, Buckley, & Kaminski (2016) recently advocated rule modifications for young soccer players to reduce heading in soccer in technical scenarios where ball velocity is greatest, specifically from goal kicks and punts. The authors utilised a triaxial accelerometer and gyro located at the back of the head around the nuchal line to quantify peak linear and rotational head accelerations during match-play. Interestingly, about a third of impacts which exceeded the predetermined 10g threshold for analysis were non-head impact events, with the authors identifying sliding to the ground and contact with another player as scenarios which also resulted in high head accelerations. Caccese et al. (2016) in advocating a restriction on high-velocity heading scenarios cite previous rule changes in sport designed to protect the athlete, including Yang & Baugh (2016) in soccer who placed age-specific restrictions on heading exposure, and modified kick-off rules (Ruestow, Duke, Finley, & Pierce, 2015) and full-contact practice restrictions (Reynolds, Patrie, Henry, Goodkin, Broshek, Wintermark, et al., 2016) in football.

Through comparison of the relative raw planar acceleration between units positioned on the head and CSR, it may be possible to quantify magnitudes of acceleration/deceleration of the head relative to the scapulae that initiate concussion via potential whiplash mechanisms. Figure 3 depicts an example of the relative difference in CSR and OR anterio-posterior acceleration during a tackle scenario. If these analyses were utilised in future ecological incidents of diagnosed head injury through systematic use of the technology, potential quantification and identification of the aetiology of concussion is possible. This could develop normative acceleration/deceleration thresholds to assist diagnostics of concussive injuries.

** Insert Figure 3 near here **

It must be acknowledged that the data presented in the current study cannot be generalised beyond this population and choice of tackle scenarios. In trying to establish a consistent experimental paradigm there are inevitably compensations in ecological validity. There are a number of factors which influence the tackle event, and ultimately the injury risk. Quarrie & Hopkins (2008) cited running speed as an aetiological risk factor, but qualified speed with descriptors such as jog, run, or sprint. In the current study a speed of ~20km/hr was attained prior to contact by the ball carrier, with a relatively lower speed attained by the tackler. It is difficult to directly compare these values with the literature, but they will inevitably influence loading magnitudes. An extension of the experimental paradigm to include a more diverse range of tackle techniques, impact speeds, and also mis-matched pairs of subjects would further enhance ecological validity. In ensuring a consistent tackle event, the random and unpredictable nature of this scenario is negated. The present study did not consider the influence of any evasive movements for example, and this might influence the velocity and loading at impact. Furthermore, the data presented more accurately represents the acceleration of the protective headgear rather than the head. There is potential for relative movement of the head within the headgear which is not accounted for, and this must be acknowledged in interpretation. The consideration of protective equipment beyond that used in the present study would also have merit.

In conclusion, unit location and tackle condition had a significant effect on the magnitude and tri-axial nature of loading. The relative acceleration of different anatomical regions has potential in quantifying the whiplash mechanism commonly cited in concussive events. The greater load elicited in centrally located CSR and OR units suggests that linear forces are most prominent in front on tackles, supporting epidemiological observations. The present study has also highlighted evident loading dissimilarities between players in alternative roles and tackle techniques, which supports epidemiological observations, denoting the tackler is of greatest risk of head injury. Variations in elicited load between altering unit placements, within different facets of play has provided an insight into the potential aetiology of head injuries sustained within specific areas of the game. This could provide a basis for the instigation of further passive interventions to increase the safety of the game. Considering the findings of the present study and the proposed practical applications, there is evident potential for further applications in certain wearable technologies for the assessment of concussion risk and/or management in rugby and other football codes.

ACKNOWLEDGEMENTS

No potential conflict of interest was reported by the authors.

REFERENCES.

1. Barrett, S., Midgley, A., & Lovell, R. (2014). PlayerLoad™: Reliability, convergent validity, and influence of unit position during 55 treadmill running. *International Journal of Sports Physiology and Performance*, *9(6)*, 945-952.
2. Bird, Y. N., Waller, A. E., Marshall, S. W., Alsop, J. C., Chalmers, D. J., & Gerrard, D. F. (1998). The New Zealand rugby injury and performance project V: Epidemiology of a season of rugby injury. *British Journal of Sports Medicine*. *32*, 319-325.
3. Bleakley, C., Tully, M., & O'Connor, S. (2011). Epidemiology of adolescent rugby injuries: A systematic review. *Journal of Athletic Training*. *46(5)*, 555-565.

4. Boyd, L. J., Ball, K., & Aughey, R. J. (2011). The reliability of minimaxX accelerometers for measuring physical activity in Australian football. *International Journal of Sports Physiology and Performance, 6,* 311-321.

5. Boyd, L. J., Ball, K., & Aughey, R. J. (2013). Quantifying external load in Australian football matches and training using accelerometers. *International Journal of Sports Physiology and Performance, 8,* 44-51.

6. Broglio, S. P., Eckner, J. T., Martini, D., Sosnoff, J. J., Kutcher, J. S., & RandolpH, C. (2011). Cumulative head impact burden in high school football. *Journal of Neurotrauma*, *28*, 2069-2078.

7. Broglio, S. P., Schnebel, B., Sosnoff, J. J., Shin, S., Fend, X., He, X., & Zimmerman, J. (2010). Biomechanical properties of concussions in high school football. *Medicine and Science in Sports and Exercise, 42,* 2064-2071.

8. Broglio, S. P., Surma, T., & Ashton- Miller, J. A. (2010). High school and collegiate football athlete concussions: A biomechanical review. *Annals of Biomedical Engineering, 40(1),* 37-46.

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

10. Caccese, J. B., Lamond, L. C., Buckley, T. A., & Kaminski, T. W. (2016). Reducing purposeful headers from goal kicks and punts may reduce cumulative exposure to head acceleration. *Research in Sports Medicine*, *24(4)*, 407-415.

11. Cantu, R. C. (1996). Head injuries in sport. *British Journal of Sports Medicine, 30,* 289-296.

12. Catenaccio, E., Caccese, J., Wakschlag, N., Fleysher, R., Kim, N., Kim, M., Buckley, T. A., Stewart, W. F., Lipton, R. B., Kamisnki, T., & Lipton, L. (2016). Validation

and calibration of HeadCount, a self-report measure for quantifying heading exposure in soccer players. *Research in Sports Medicine, 24(4)*, 416-425.

13. Cormack, S. J., Smith, R. L., Mooney, M. M., Young, W. B., & O'Brien, B. J. (2014). Accelerometer load as a measure of activity profile in different standards of netball match play. *International Journal of Sports Physiology and Performance, 9(2),* 283-291.

14. Cunniffe, B., Proctor. W., Barker, J. S. & Davies, B. (2009). An evaluation of the physiological demands of elite rugby union using global positioning system tracking system. *Journal of Strength and Conditioning Research, 23(4),* 1195-1203.

15. Emery, C. A. (2010). Injury prevention in paediatric sport-related injuries: A scientific approach. *British Journal of Sports Medicine, 44,* 64-69.

16. Fuller, C. W., Brooks, J. H., Cancea, R. J., Hall, J., & Kemp, S. P. (2007). Contact events in rugby union and their propensity to cause injury. *British Journal of Sports Medicine, 41(12),* 862-867.

17. Fuller, C. W., Sheerin, K., & Targett, S. (2013). Rugby World Cup 2011: International Rugby Board injury surveillance study. *British Journal of Sports Medicine, 47,* 1184-1191.

18. Gardner, A., Iverson, G., Williams, W., Baker, S., & Stanwell, P. (2014). A systematic review and meta-analysis of concussion in rugby union. *Sports Medicine, 44(12),* 1717-1731.

19. Guskiewicz, K. M., Weaver, N. L., Padua, D. A., & Garrett, W .E. (2000). Epidemiology of concussion in collegiate and high school football players. *American Journal of Sports Medicine, 28,* 643-650.

20. Guskiewicz, K. M., Mihalik, J. P., Shankar, V., Marshall, S. W., Crowell, D. H., Oliaro, S. M., Ciocca, M. F., & Hooker, D. N. (2007). Measurement of head impacts

in collegiate football players: relationship between head impact biomechanics and acute clinical outcome after concussion. *Neurosurgery, 61(6)*, 1244-1252.

21. Hartwig, T. B., Naughton, G., & Searl, J. (2011). Motion analyses of adolescent rugby union players: A comparison of training and game demands. *Journal of Strength and Conditioning Research, 25 (4),* 966-972.

22. Haseler, C. M., Carmont, M. R., & England, M. (2010). The epidemiology of injuries in English youth community rugby union. *British Journal of Sports Medicine, 44*, 1093-1099.

23. Jones, M. R., West, D. J., Crewther, B. T., Cook, C. J., & Kilduff, L. P. (2015). Quantifying positional and temporal movement patterns in professional rugby union using global positioning system. *European Journal of Sport Science, 12,* 1-9.

24. Kemp, S. P. T., Hudson, Z., Brooks, J. H. M., & Fuller, C. W. (2008). The epidemiology of head injuries in English professional rugby union. *Clinical Journal of Sports Medicine, 18(3),* 227-234.

25. Marshall, C. M. (2012). Sports-related concussion: A narrative review of the literature. *Journal of the Canadian Chiropractic Association, 56 (4)*, 299-310.

26. McCrory, P. R., Berkovic, S. F., & Cordner, S. M. (2000). Deaths due to brain injury among footballers in Victoria, 1968-1999. *The Medical Journal of Australia, 172 (5)*, 217-219.

27. McIntosh, A. S. (2003). Helmets and head protection for the athlete as a means to prevent injury. *Official Journal of the International Federation of Sports Medicine, 4 (1)*, 1-9.

28. McIntosh, A. S., McCrory, P., & Comerford, J. (2000). The dynamics of concussive head impacts in rugby and Australian rules football. *Medicine and Science in Sports and Exercise, 32 (12)*, 1980-1984.

29. McIntosh, A. S., McCrory, P., Finch, C. F., Best, J. P., Chalmers, D. J., & Wolfe, R. (2009). Does padded headgear prevent head injury in rugby union football? *Medicine and Science in Sports and Exercise, 41 (2)*, 306-313.

30. McIntosh, A. S., Savage, T. N., McCrory, P., Frechede, B. O., & Wolfe, R. (2010). Tackle characteristics and injury in a cross section of rugby union football. *Medicine and Science in Sports and Exercise, 42 (5)*, 977-984.

31. McKee, A. C., Cantu, R. C., Nowinski, C. J., Hedley-Whyte, E. T., Gavett, B. E., Budson, A. E, Santini, V. E., Lee, H., Kubilus, C. A., & Stern, R. A. (2009). Chronic traumatic encephalopathy in athletes: Progressive tauopathy following repetitive head injury. *Journal of Neuropathology and Experimental Neurology, 68(7)*, 709-735.

32. Montgomery, P. G., Pyne, D., & Minahan, C. L. (2010). The physical and physiological demands of basketball training and competition. *International Journal of Sports Physiology and Performance, 5,* 75-86.

33. Ommaya, A. K. & Hirsch, A. E. (1971). Tolerances for cerebral concussion from head impact and whiplash in primates. *Journal of Biomechanics, 4,* 13-21.

34. Ommaya, A. K., & Gennarelli, T. A. (1974). Cerebral concussion and traumatic unconsciousness: Correlation of experimental and clinical observations on blunt head injuries. *Brain, 97,* 633-654.

35. Patricios, J. S., & Kemp, S. P. T. (2014). Chronic traumatic encephalopathy: Rugby's call for clarity, data and leadership in the concussion debate. *British Journal of Sports Medicine, 48 (2)*, 76-79.

36. Pellman, E. J., Viano, D. C., Tucker, A. M., Casson, I. R., & Waeckerle, J. F. (2003). Concussion in professional football: Reconstruction of game impacts and injuries. *Neurosurgery, 35 (4)*, 799- 814.

37. Quarrie, K. L., & Hopkins, W. G. (2008). Tackle injuries in professional rugby union. *American Journal of Sports Medicine, 36(9),* 1705-1716.

38. Reid, L. C., Cowman, J. R., Green, B. S., & Coughlan, G.F. (2013). Return to play in elite rugby union: Application of global positioning system technology in return-to-running programs. *Journal of Sport Rehabilitation, 22,* 122-129.

39. Reynolds, B. B., Patrie, J., Henry, E. J., Goodkin, H.P., Broshek, D. K., Wintermark, M., & Druzgal, T. J. (2016). Practice type effects on head impact in collegiate football. *Journal of Neurosurgery, 124(2),* 501-510.

40. Roberts, G. W., Allsop, D., & Bruton C. (1990). The occult aftermath of boxing. *Journal of Neurology Neurosurgery and Psychiatry, 53,* 373-378.

41. Ruestow, P. S., Duke, T. J., Finley, B. L., & Pierce, J.S. (2015). Effects of the NFL's amendments to the free kick rule on injuries during the 2010 and 2011 seasons. *Journal of Occupational and Environmental Hygiene, 12(12),* 875-882.

42. Saffary, R., Chin, L. S., & Cantu, R. C. (2012). From concussion to chronic traumatic encephalopathy: A review. *Journal of Clinical Sport Psychology, 6,* 351-362.

43. Shaw, N. (2002). The neurophysiology of concussion. *Progress in Neurobiology, 67(4),* 281-344.

44. Suarez-Arrones, L., Arenas, C., López, G., Requena, B., Terrill, O., & Mendez-Villanueva, A. (2014). Positional differences in match running performance and physical collisions in men rugby sevens. *International Journal of Sports Physiology and Performance, 9,* 316-323.

45. Thompson, J. W. G. & Hagedorn, D. (2012). Multimodal analysis: New approaches to the concussion conundrum. *Journal of Clinical Sport Psychology, 6,* 22-46.

46. Tommasone, B. A. & Valovich Mcleod, T. C. (2006). Contact sport concussion incidence. *Journal of Athletic Training*, *41(4)*, 470-472.

47. Venter, R., Opperman, E., & Opperman, S. (2011). The use of global positioning system (GPS) tracking devices to access movement demands and impacts in under-19 rugby union match play. *African Journal of Physical, Health Education and Recreation and Dance*, *17 (1)*, 1-8.

48. Wilberger, J., Ortega, J., & Slobounov, S. (2006). *Foundations of Sport-Related Brain Injuries.* USA: Springer US.

49. Yang, Y. T., & Baugh, C. M. (2016). US Youth Soccer concussion policy: Heading in the right direction. *JAMA Pediatrics, 170(5),* 413-414.

LEGENDS TO TABLES & FIGURES

Table 1. The influence of tackle condition and unit location on uni-axial Load.

Table 2. The relative uni-axial contributions to Load.

Figure 1. The influence of tackle condition and unit location on Total PlayerLoad.

Figure 2. The influence of unit location on the relative uni-axial contributions to Load.

Figure 3. The relative acceleration of CSR and OR to quantify the whiplash mechanism.

Tackle Condition	Unit Location	Uni-Axial Player Load (a.u)		
		AP	ML	V
AS-T	CSR	0.56 ± 0.19	0.62 ± 0.21	0.71 ± 0.18
	OR	0.53 ± 0.22	0.76 ± 0.30 *	0.75 ± 0.25
	LT-PR	0.54 ± 0.14	0.37 ± 0.11 *^	0.60 ± 0.17 *^
	RT-PR	0.53 ± 0.18	0.38 ± 0.11 *^	0.58 ± 0.16 *^
AS-BC	CSR	0.59 ± 0.16	0.54 ± 0.14	0.77 ± 0.19
	OR	0.49 ± 0.18 *	0.42 ± 0.15 *	0.78 ± 0.20
	LT-PR	0.39 ± 0.06 *^	0.22 ± 0.06 *^	0.57 ± 0.10 *^
	RT-PR	0.40 ± 0.07 *^	0.20 ± 0.07 *^	0.56 ± 0.08 *^
S-T	CSR	0.30 ± 0.06	0.36 ± 0.07	0.36 ± 0.03
	OR	0.35 ± 0.11	0.47 ± 0.16 *	0.47 ± 0.14 *
	LT-PR	0.37 ± 0.07 *	0.24 ± 0.08 *^	0.39 ± 0.09 ^
	RT-PR	0.35 ± 0.09 *	0.24 ± 0.08 *^	0.36 ± 0.11 ^$
S-BC	CSR	0.52 ± 0.11	0.53 ± 0.12	0.67 ± 0.14
	OR	0.52 ± 0.16	0.52 ± 0.17	0.66 ± 0.16
	LT-PR	0.45 ± 0.06 *	0.28 ± 0.07 *^	0.52 ± 0.10 *^
	RT-PR	0.41 ± 0.08 *^	0.28 ± 0.08 *^	0.56 ± 0.06 *^

* denotes significantly different than CSR

^ denotes significantly different than OR

$ denotes significantly different than LT-PR

Tackle Condition	Unit Location	Uni-Axial Contribution (%)		
		AP	ML	V
AS-T	CSR	29.24± 3.09	32.38± 1.90	38.38± 4.38
	OR	25.44 ± 2.35 *	37.15 ± 2.38 *	37.41 ± 2.84
	LT-PR	35.70 ± 3.01 *^	24.64 ± 3.00 *^	39.66 ± 2.44 ^
	RT-PR	35.44 ± 3.32 *^	25.28 ± 2.05 *^	39.29 ± 4.34
AS-BC	CSR	30.85± 3.71	28.71± 4.41	40.44± 7.02
	OR	28.47 ± 3.02	24.73 ± 2.15 *	46.79 ± 4.13 *
	LT-PR	33.47 ± 3.29 ^	18.23 ± 3.29 *^	48.31 ± 4.86 *
	RT-PR	34.56 ± 2.71 *^	16.60 ± 3.39 *^$	48.85 ± 2.86 *^
S-T	CSR	29.18± 1.91	35.36± 2.60	35.46± 3.51
	OR	27.20 ± 3.81	36.30 ± 4.10	36.50 ± 3.74
	LT-PR	37.51 ± 4.65 *^	23.61 ± 3.13 *^	38.88 ± 3.16 *
	RT-PR	37.31 ± 2.83 *^	25.28 ± 2.31 *^$	37.41 ± 2.27
S-BC	CSR	30.24± 2.46	30.76± 3.69	39.00± 2.85
	OR	30.31 ± 3.25	30.23 ± 3.80	39.45 ± 3.72
	LT-PR	36.10 ± 3.68 *^	22.17 ± 3.78 *^	41.74 ± 4.06
	RT-PR	32.74 ± 2.14 ^$	21.88 ± 4.14 *^	45.38 ± 3.95 *^

* denotes significantly different than CSR

^ denotes significantly different than OR

$ denotes significantly different than LT-PR

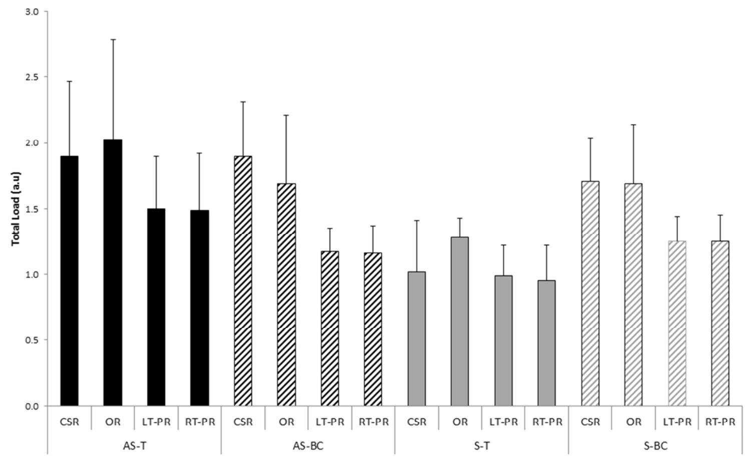

Figure 1. The influence of tackle condition and unit location on Total PlayerLoad.

338x190mm (96 x 96 DPI)

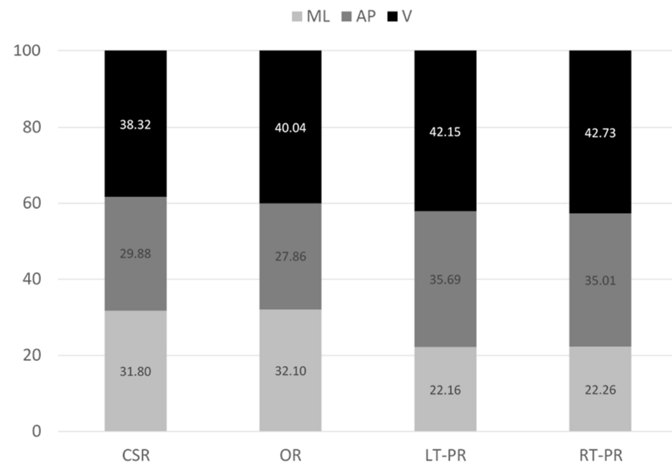

Figure 2. The influence of unit location on the relative uni-axial contributions to Load.

338x190mm (96 x 96 DPI)

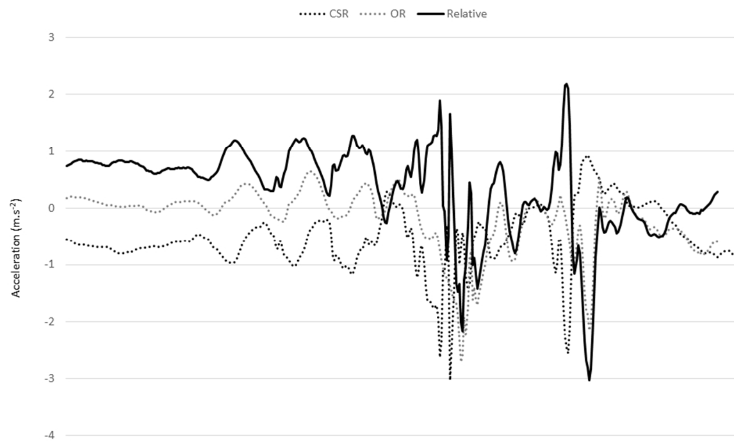

Figure 3. The relative acceleration of CSR and OR to quantify the whiplash mechanism.

338x190mm (96 x 96 DPI)