SE∽NZ
SPORT & EXERCISE SCIENCE
NEW ZEALAND

The Journal of Sport and Exercise Science, Vol. 5, Issue 3, 179-187 (2021)

www.sesnz.org.nz

JSES
ISSN: 2703-240X

Collision monitoring in elite male rugby union using a new instrumented mouth-guard

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ARTICLE INFO

Received: 17.11.2020
Accepted: 10.03.2021
Online: 16.04.2021

Keywords:
Contact
Tackle
Accelerometer
Gyroscope
Inertial

ABSTRACT

An instrumented mouth-guard and data analytics platform (PROTECHT) was used to compare collision metrics derived from linear and rotational accelerations of elite rugby union players according to position (forwards and backs), match role (starters and non-starters), match halves (first- and second-half) and six contact types. Analyses were performed at the level of individual collisions and across whole-matches. Fifteen male players from one elite-level rugby union team wore instrumented mouth-guards during 10 matches. Collision metrics were analysed using the PROTECHT system. At the level of individual contacts, linear ($P = 0.034$) and rotational accelerations ($P = 0.049$) were larger in the second-half of matches. Rotational accelerations were highest for ball-carries ($P < 0.05$) compared to aerial challenges and rucks. Analysis of matches demonstrated no differences ($P > 0.05$) between backs and forwards, across all variables, while non-starters had higher mean rotational intensity ($P = 0.006$) and moderate-intensity collisions/min ($P = 0.011$; $d = 0.69$) compared to starters. Linear load/min ($P = 0.041$) and moderate collision counts/min ($P = 0.031$) were also higher in the second-half when comparing all match performances but there were no differences ($P > 0.05$) among those playing both halves. The intensity of collisions increased in the second-half of matches and is likely explained by replacement players. This information can be used to support the utilisation of replacement players. The lower magnitude of head accelerations compared to previous studies requires further research to establish the accuracy of head impact thresholds in rugby union.

1. Introduction

Rugby union is an intermittent team sport, with frequent bouts of static and dynamic collisions (i.e., tackles, contested carries, rucks, mauls), combined with movements of varying intensity (Delaney et al., 2017). While the movement demands of rugby union have been well-characterised (Lindsay et al., 2015; Cunningham et al., 2016; Roe et al., 2016; Tee et al., 2016; Delaney et al., 2017; Reardon et al., 2017; Read et al., 2018), objectively monitoring the frequency, magnitude and type of collisions between players has been historically problematic. This is unfortunate, since physical collisions, by definition, mandate external mechanical loading, leading to tissue trauma, post-match muscle soreness and impaired muscle function among rugby players (Smart et al., 2008; Twist et al., 2012). Furthermore, the majority of injuries sustained in the rugby codes are related to collisions (Fuller et al., 2008; Quarrie & Hopkins, 2008) and the capacity to successfully execute collision-based actions in matches can improve match outcome (Woods et al., 2017; Schoeman & Schall, 2019), and the probability of being selected (Waldron et al., 2014a).

Collisions in the rugby codes have been most commonly identified via description of match video footage (Twist et al., 2012; Waldron et al., 2014a; 2014b; Hendricks et al., 2014; Schoeman & Schall, 2019). These approaches have identified that between 0.3 and 1.1 collisions occur per minute of match-play during contact team sports (Gray et al., 2018). While this

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approach can be considered as a gold-standard for recording collision frequencies and gathering other contextual data, such as the collision type, it does not quantify collision intensity, nor does it provide real-time data and can be labour-intensive for researchers and rugby practitioners (Naughton et al., 2020). To address these limitations, automated tackle and collision detection algorithms have been developed based on signals derived from inertial measurement systems (accelerometers, gyroscopes and magnetometers), which are integrated into Global Positioning System (GPS) devices and worn in an elasticated vest between the scapula of players during training and matches (Kelly et al., 2012; Hulin et al., 2017; Chambers et al., 2019). The intention of these approaches has been to quantify both the frequency and intensity of collision events. However, the materials used to mount and house the inertial measurement devices on players lack the necessary integrity and can lead to signal artefact (McLean et al., 2018). Subsequently, the resulting signal received using this form of micro-technology may be greatly influenced by external noise, thus affecting the reliability of raw accelerations (Waldron et al., 2011), leading to erroneous collision recordings (Reardon et al., 2017).

To overcome the limitations of previous approaches, protective mouth-guards, worn by players in matches, can be instrumented with inertial measurement devices (King et al., 2015). This type of technology can be used to determine raw accelerations (via accelerometers) and angular velocities (via gyroscopes) experienced at the head, with six degrees of freedom. Coupling the sensor to movement of the skull is crucial for accurate detection of linear accelerations and rotational velocities (Wu et al., 2016), thus overcoming errors caused by non-adherence to skin or clothing. While this approach has been more recently adopted to detect head-related impacts in amateur rugby union (King et al., 2015), the same technology has potential to be used to detect whole-body collision events in rugby. The PROTECHT system (https://swa.one/, United Kingdom) is a new analytics platform, which embeds inertial sensors into custom-fit mouth-guards, with potential to provide real-time linear and rotational acceleration data to players and coaches. Therefore, we used the PROTECHT system to monitor the collision frequency and intensity of elite rugby union players, across 10 competitive fixtures. Given the reported collision differences between positional groups (Grainger et al., 2018; Macleod et al., 2018; Yamamoto et al., 2020), contact types (Macleod et al., 2018), and fatigue-induced changes in tackling frequency across match periods (Tee et al., 2016), we also compared collision characteristics between: 1) forwards and backs, 2) starter and non-starters, 3) first and second-halves and 4) six distinct contact types. Therefore, the overall aim was to evaluate metrics derived from linear and rotational accelerations, recorded via the PROTECHT system, at the level of individual collisions and across whole matches according to these factors.

2. Methods

2.1. Subjects

Fifteen elite male rugby union players (mean ± SD: age = 26 ± 4 years; body mass = 104.3 ± 12.4 kg; stature = 1.86 ± 0.05 m) provided written, informed consent to take part in this study. Institutional ethical approval was provided for this study, which was conducted in accordance with the 2013 Helsinki Declaration.

2.2. Design

An observational cohort study was conducted on fifteen elite rugby union players, across 10 competitive matches in the 2019-2020 season. Players wore custom-fitted instrumented mouth-guards during matches (PROTECHT system), from which collision metrics were recorded and analysed post-hoc. Data were characterised at two levels; per contact (n = 978) and per match performance (n = 43). Comparisons were made between 1) positions (forwards (n = 9) vs. backs (n = 6)), 2) match halves (first *vs.* second), 3) starters vs. non-starters and 4) six contact types. The contact types were: aerial collisions, rucks, tackles, carries, scrum/mauls and unavoidable collisions (see Schoeman & Schall 2019, for definitions). Aerial collisions defined as a collision that occurred from a player competing to catch a ball from a kick which resulted in an impact meeting the system's collision criteria. Unavoidable impacts were defined as a collision that a player received undertaking a number of activities not defined or measured in OPTA. These could be a player hitting the floor after a tackle, a player being bumped by another player in defence or attack or a kick chase, which resulted in an impact meeting the system's collision criteria. The selected comparisons and sample sizes varied according to the level of analysis (i.e., per contact or match performance). An additional comparison of match halves was performed among those performing in both halves of matches (n = 22).

2.3. Procedure

The PROTECHT system includes an iMG containing a tri-axial accelerometer (H3LIS331DL, STMicroelectronics, Genova, Switzerland) and a tri-axial gyroscope (LSM9DS1, STMicroelectronics, Genova, Switzerland). The former was sampled at 1 kHz (± 200 g, 16-bit resolution) and the latter at 952 Hz (± 35 rad/s, 16-bit resolution). Each recorded collision event was video-verified using OPTAPRO (OPTAPRO, www.optaprorugby.com, London, United Kingdom) to determine contact type, in addition to assessing the sensitivity (91%), specificity (95.7%) and accuracy (95.1%) of the PROTECHT system in identifying all collision events in rugby union, which is consistent with data from other activities (Mcnamara et al., 2015; Macleod et al., 2018). The device has been technically validated and closely compares (95% Limits of Agreement: peak linear acceleration = -2.6 ± 9.2 g, peak rotational acceleration = 230 ± 492 rad/s/s) to criterion measures (unpublished data), with intra-class correlation coefficient values of 0.91 for peak linear acceleration and 0.95 for peak rotational acceleration.

2.4. Measurement

Collisions recorded by the PROTECHT system were identified as meeting set criteria, as follows: 1) the mouth-guard was in players' mouths, as determined by an infrared sensor embedded within the mouth-guard and 2) any linear acceleration value exceeding 10 g

was transmitted. If it did not exceed 10 *g* the data were removed, except from those that were video-verified. This threshold level was chosen based on a review of previous studies (King et al., 2015). The impacts below the threshold level were considered to negligible and, therefore, eliminated non-impacts events, such as running and jumping (Ng et al., 2006). If it did not exceed 10 *g* the data were removed, except from those that were video-verified. This threshold level was chosen based on a review of previous studies (King et al., 2015). The impacts below the threshold level were considered to negligible and, therefore, eliminated non-impacts events, such as running and jumping (Ng et al., 2006).

For each collision, the inertial sensors collected 104 ms of data, for linear acceleration and rotational velocity. Rotational accelerations were derived from the rotational velocity time-series using a five-point stencil. Spectral analysis on the linear acceleration-time series data, which identified no obvious high frequency (i.e., > 200 Hz) components in the signal. Therefore, the data were not filtered. The measured rotational velocity was filtered on-chip via an anti-aliasing filter at 105 Hz and a low-pass filter with a cut-off of 100 Hz. Peak values reported were defined as the maximum numerical value of the vector-norm of the respective time-series data. Collision intensity was categorized based on the average z-score for peak linear and rotational value from the collision event. Intensity bandings were determined through standard deviation values: weak ⩽ -1, Light -1-0, moderate 0-1, strong 1-2 and very strong >2 SD. The remaining variables are described in Table 1.

2.5. Statistical analysis

Analyses were conducted at two levels; model 1) all individual collisions and model 2) total match-collision profiles (model 2). In model 1, after log-transformation of data, a fully factorial linear mixed model was used to identify differences in individual collision metrics (across 978 separate collision events) between positional groups (backs vs. forwards), halves of the match (first or second), match role (starters vs. non-starters) and collision type (aerial, tackle, carry, scrum, maul, unavoidable collisions). Each of the above variables were treated as fixed factors and each individual player was included as a random effect. In model 2, a linear mixed model was also used to assess differences between positions, match halves and match roles, across 20 separate collision metrics. Differences between halves of the match were assessed on all match files and on players only completing both halves of the whole match. The same organization of fixed and random factors was used. Fixed effects and interactions were followed up with Bonferroni *post-hoc* tests to identify pairwise differences. Statistical significance was recognised when $P < 0.05$. Cohen's *d* effect sizes were calculated, with thresholds set as: ≤ 0.2 small; ≤ 0.6 moderate; ≤ 1.2 large; ≥ 2.0 very large (Hopkins et al., 2009). Statistical analyses were performed using SPSS version 24 (IBM SPSS Statistics Inc, Armonk, USA).

Table 1: Collision variable and definition

Variable	**Definition**
Count (*n*)	Number of all collision events recorded for the player in a match
Mean linear intensity (*g*)	The mean peak linear acceleration value attained for all collisions in a match
Mean rotational intensity (rad/s/s)	The mean peak rotational acceleration value attained for all collisions in a match
Peak linear intensity (*g*)	The highest linear acceleration value attained from an collision in a match
Peak rotational intensity (rad/s/s)	The highest rotational acceleration value attained from an collision in a match
Linear load (AU)	Accumulated sum of peak linear acceleration values for all collisions in a match
Rotational load (AU)	Accumulated sum of peak rotational acceleration values for all collisions in a match
Weak count (*n*)	Number of z-score derived weak collisions an athlete receives for a match
Light count (*n*)	Number of z-score derived light collisions an athlete receives for a match
Moderate count (*n*)	Number of z-score derived moderate collisions an athlete receives for a match
Strong count (*n*)	Number of z-score derived strong collisions an athlete receives for a match
Very strong count (*n*)	Number of z-score derived very strong collisions an athlete receives for a match

Note: all variables are also expressed per minute of match time (n/min).

3. Results

3.1. Collision characteristics by contact

Both linear ($P = 0.515$; $d = 0.12$) and rotational accelerations ($P = 0.216$; $d = 0.11$) during each collision were not different between backs and forwards (Figure 1A). Similarly, linear ($P = 0.101$; $d = 0.23$) and rotational ($P = 0.078$; $d = 0.20$) accelerations were not different between starters and non-starters (Figure 1C). However, linear ($P = 0.034$; $d = 0.25$) and rotational accelerations ($P = 0.049$; $d = 0.21$) were larger in the second-half of matches (Figure 1B). Lastly, there was a main effect of collision type for both linear ($P = 0.045$) and rotational accelerations ($P = 0.018$), with *post-hoc* tests demonstrating differences between carries and aerial challenges ($P = 0.008$; $d = 0.59$) or carries and rucks ($P = 0.045$; $d = 0.35$) for rotational accelerations only (Figure 2A).

3.2. Collision characteristics by match

Analysis of match profiles demonstrated no differences ($P > 0.05$) between backs and forwards, across all variables (Table 2). However, non-starters had higher mean rotational intensity ($P = 0.006$; $d = 0.75$) and moderate-intensity collisions/min ($P = 0.011$; $d = 0.69$), while total collision counts ($P = 0.011$; $d = 0.93$) and total linear load was higher in the starters ($P = 0.019$; $d = 0.85$) (Table 2). Linear load/min ($P = 0.041$; $d = 0.42$) and moderate collision counts/min ($P = 0.031$; $d = 0.52$) were higher in the second-half when comparing all match performances but there were no differences ($P > 0.05$) among those playing both halves of the match (Table 3).

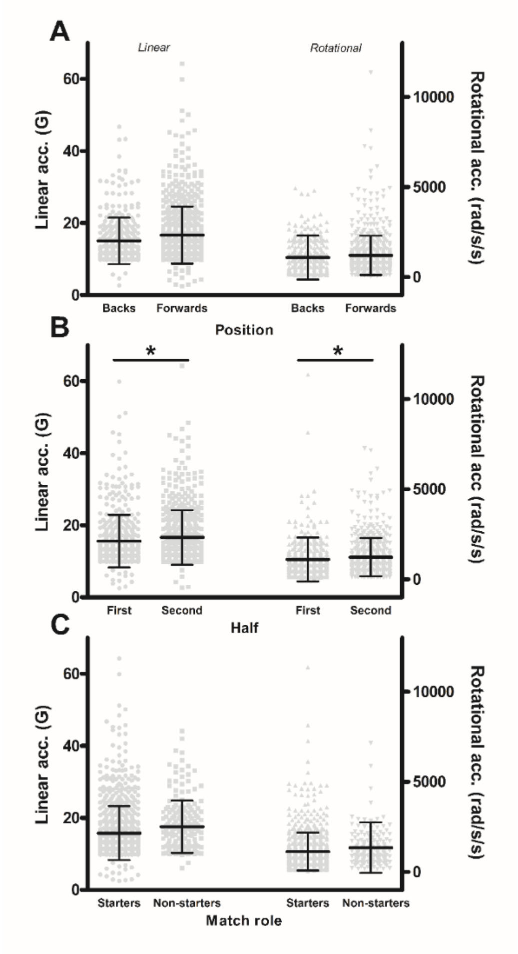

Figure 1: Linear (left) and rotational (right) accelerations measured via the PROTECHT system during elite rugby matches and comparisons of position (A; forwards vs. backs), match halves (B; first vs. second) and match role (C; starters vs. non-starters). * = difference ($P < 0.05$) between first- and second-half.

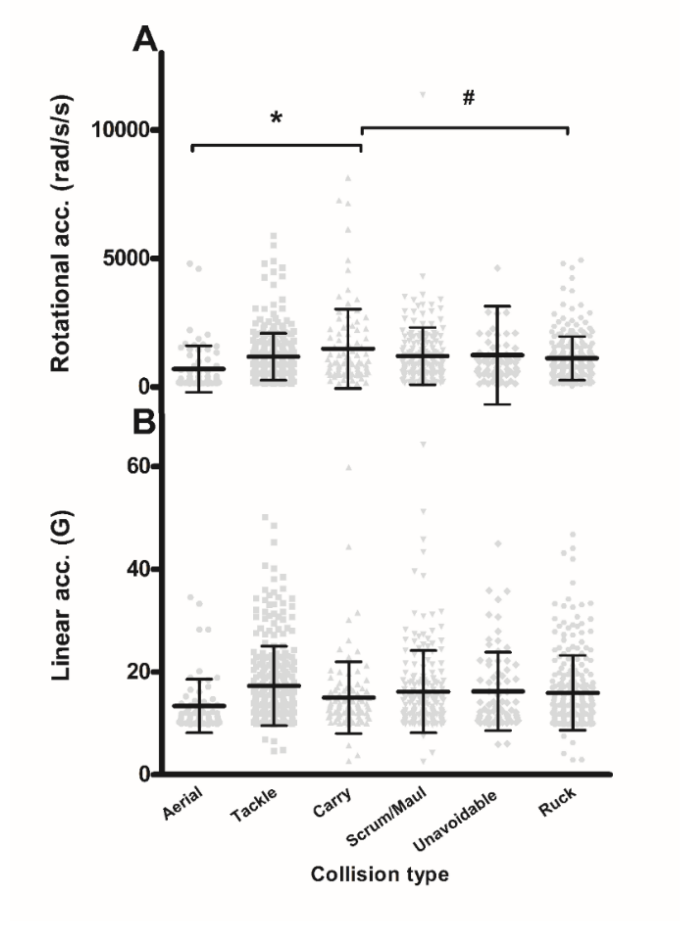

Figure 2: Rotational (A) and linear (B) accelerations measured via the PROTECHT system during elite rugby matches by collision type. * = difference ($P < 0.05$) between carry and aerial collisions; # = difference ($P < 0.05$) between carry and unavoidable collisions. Acc. = acceleration.

Table 2: Collision characteristics (mean ± SD) of backs *vs.* forwards and starters *vs.* non-starters

	Backs *vs.* Forwards		**Starters *vs.* Non-starters**	
	***n* = 13**	***n* = 30**	***n* = 27**	***n* = 16**
Count (*n*)	25.1 ± 25.5^{S}	21.5 ± 17.2	29.5 ± 22.3^{L*}	12.3 ± 8.2
Count/min (*n*/min)	0.34 ± 0.33^{M}	0.51 ± 0.34	0.42 ± 0.29^{M}	0.51 ± 0.41
Mean linear intensity (*g*)	16.1 ± 3.1^{M}	17.1 ± 2.7	16.3 ± 3.1^{M}	17.5 ± 2.2
Mean rotational intensity (rad/s/s)	1308.3 ± 540.1^{M}	1186.9 ± 393.3	1106.2 ± 296.4^{L*}	1421.7 ± 568.1
Peak linear intensity (*g*)	30.6 ± 9.3^{M}	34.2 ± 12.1	34.5 ± 12.5^{M}	30.8 ± 9.2
Peak rotational intensity (rad/s/s)	4113.9 ± 3757.4^{S}	3564.4 ± 2427.1	3742.9 ± 2329.2^{S}	3708.9 ± 3669.8
Linear load (AU)	376.9 ± 359.9^{S}	358.3 ± 271.1	451.9 ± 327.8^{L*}	215.6 ± 149.3
Rotational load (AU)	26749.1 ± 22666.4^{S}	25816.3 ± 22705.4	31642.6 ± 24766.5^{M}	16743.1 ± 14013.1
Linear load/min (AU/min)	5.08 ± 4.8^{L}	8.6 ± 6.1	6.6 ± 4.4^{M}	9.1 ± 7.6
Rotational load/min (AU/min)	361.6 ± 298.1^{M}	604.6 ± 464.4	458.6 ± 326.3^{M}	653.5 ± 559.7
Weak count (*n*)	0.23 ± 0.43^{S}	0.23 ± 0.67	0.29 ± 0.72^{M}	0.12 ± 0.34
Light count (*n*)	15.2 ± 19.2^{M}	12.1 ± 11.7	17.5 ± 16.1^{L*}	5.5 ± 5.1
Moderate count (*n*)	7.6 ± 5.6^{S}	6.8 ± 5.3	8.2 ± 5.9^{M}	5.1 ± 3.7
Strong count (*n*)	1.7 ± 1.9^{S}	2.1 ± 2.1	2.2 ± 2.2^{M}	1.4 ± 1.6
Very strong count (*n*)	0.23 ± 0.59^{M}	0.76 ± 1.3	0.81 ± 1.3^{M}	0.25 ± 0.44
Weak count/min (*n*/min)	0.01 ± 0.01^{S}	0.01 ± 0.01	0.01 ± 0.01^{S}	0.01 ± 0.01
Light count/min (*n*/min)	0.2 ± 0.25^{M}	0.27 ± 0.22	0.25 ± 0.21^{S}	0.25 ± 0.26
Moderate count/min (*n*/min)	0.11 ± 0.07^{M}	0.17 ± 0.12	0.12 ± 0.07^{L*}	0.19 ± 0.14
Strong count/min (*n*/min)	0.03 ± 0.02^{M}	0.05 ± 0.06	0.03 ± 0.03^{M}	0.05 ± 0.07
Very strong count/min (*n*/min)	0.004 ± 0.009^{M}	0.02 ± 0.03	0.01 ± 0.02^{S}	0.01 ± 0.02

Note: * = sig. different ($P < 0.05$) to comparison group. Cohens *d*: S = small, M = moderate, L = large.

Table 3: Collision characteristics (mean ± SD) of the first and second-half of matches

	First-half vs. Second-half *All matches*		**First-half *vs.* Second-half** *Whole-matches*	
	n = 28	***n = 37***	***n = 22***	***n = 22***
Count (*n*)	16.1 ± 11.5^{S}	14.1 ± 11.8	16.1 ± 11.7^{S}	16.2 ± 13.4
Count/min (*n*/min)	0.41 ± 0.28^{M}	0.51 ± 0.41	0.41 ± 0.28^{M}	0.51 ± 0.38
Mean linear intensity (*g*)	15.8 ± 3.1^{M}	16.8 ± 4.1	15.6 ± 3.1^{S}	16.2 ± 5.1
Mean rotational intensity (rad/s/s)	1184.8 ± 628.7^{S}	1253.4 ± 442.3	1233.6 ± 682.3^{S}	1245.6 ± 470.9
Peak linear intensity (*g*)	29.1 ± 10.8^{S}	31.1 ± 11.7	28.9 ± 11.1^{M}	31.9 ± 12.9
Peak rotational intensity (rad/s/s)	3548.2 ± 3297.3^{S}	3331.1 ± 2507.2	3740.6 ± 3480.9^{S}	3532.2 ± 1835.4
Linear load (AU)	252.3 ± 177.1^{S}	231.9 ± 183.2	252.6 ± 183.2^{S}	260.4 ± 204.3
Rotational load (AU)	17600.1 ± 12733.2^{S}	17011.2 ± 14033.4	18082.2 ± 13392.2^{S}	20032.1 ± 15833.5
Linear load/min (AU/min)	6.3 ± 4.2^{M*}	8.7 ± 6.8	6.4 ± 4.4^{M}	8.3 ± 6.1
Rotational load/min (AU/min)	466.5 ± 340.2^{M}	610.6 ± 486.8	489.3 ± 361.6^{M}	613.1 ± 415.3
Weak count (*n*)	0.25 ± 0.64^{M}	0.08 ± 0.27	0.31 ± 0.71^{M}	0.09 ± 0.29
Light count (*n*)	9.7 ± 9.2^{M}	7.7 ± 8.2	9.5 ± 8.8^{S}	9.4 ± 9.4
Moderate count (*n*)	4.6 ± 2.9^{S}	4.6 ± 3.6	4.7 ± 3.1^{S}	4.8 ± 4.1
Strong count (*n*)	1.1 ± 1.4^{M}	1.4 ± 1.3	1.2 ± 1.4^{M}	1.6 ± 1.4
Very strong count (*n*)	0.5 ± 1.2^{M}	0.3 ± 0.6	0.41 ± 1.01^{S}	0.36 ± 0.78
Weak count/min (*n*/min)	0.01 ± 0.01^{S}	0.01 ± 0.01	0.01 ± 0.02^{S}	0.01 ± 0.02
Light count/min (*n*/min)	0.24 ± 0.22^{S}	0.27 ± 0.27	0.23 ± 0.22^{S}	0.27 ± 0.27
Moderate count/min (*n*/min)	0.11 ± 0.07^{M*}	0.17 ± 0.14	0.12 ± 0.07^{M}	0.15 ± 0.13
Strong count/min (*n*/min)	0.03 ± 0.04^{M}	0.05 ± 0.06	0.03 ± 0.05^{M}	0.05 ± 0.04
Very strong count/min (*n*/min)	0.01 ± 0.03^{S}	0.01 ± 0.02	0.01 ± 0.02^{S}	0.01 ± 0.02

Note: * = sig. different ($P < 0.05$) to comparison group. Cohens *d*: S = small, M = moderate, L = large. 'Whole- matches are those where players completed the entire game on the field, while 'All' matches encompass those where players were substituted on or off the field.

4. Discussion

We investigated, for the first time, the characteristics of individual and total match collisions, using the validated PROTECHT system. The frequency of collisions recorded for each player/match (~30 collisions or 0.42/min) is in accordance with that reported across rugby codes using video, GPS-housed inertial sensors (Naughton et al., 2020). However, the mean intensity (linear ~16-17 vs. ~22 *g*; rotational ~1,100 - 1,400 *vs*. ~3,600 - 4,400 rad/s/s) and frequency of collisions (~30 vs. ~50-95) were markedly smaller than reported from other instrumented mouth-guards used in amateur rugby union (King et al., 2015). A detailed discussion of these discrepancies is beyond the remit of the current study but it appears to relate to hardware and signal processing differences between devices, resulting in the PROTECHT system reporting systematically lower frequency and intensity of collisions compared to others (X2Biosystems Inc). The 'bulky fit' and technical error of the previous instrumented mouth-guard was noted by the authors (King et al., 2015), which may have been improved by the custom-fit of the PROTECHT system mouth-guards. This raises some cause for concern, given that data from the older system (X2Biosystems Inc.) has been used to determine concussion risk thresholds in rugby union (King et al., 2015) and could be overestimating head collision frequency and intensity. Further work is required to compare the performance of the two systems in order to validate the concussion risk thresholds.

The initial analysis of individual collisions, which removes the match context, showed that both linear and rotational accelerations did not differentiate positional groups or starters/non-starters, but were larger in the second-half of matches. Carries had the descriptively largest collision intensities, with aerial challenges and unavoidable collisions the smallest in comparison. Analysis of match-collision profiles showed a similar pattern of results, with first-to-second half differences in linear load and moderate collisions (expressed relative to playing time) only apparent when all match files were considered, rather than those playing both halves. Analysis of playing role showed that non-starters had higher mean rotational intensities and relative moderate collisions compared to starters, thus explaining the increase in collision metrics between match halves.

We anticipated that there would be a decline in collision metrics between the first- and second-half of matches. However, both the individual and match-level analyses performed questioned this, demonstrating that most variables were unchanged between halves of the match, with some collision characteristics actually increasing. Indeed, our refined analysis of players performing in both halves of matches also showed no differences in any measured variable. This indicates that the primary reason for second-half increases is the introduction of replacement players (non-starters) and that the effect of fatigue (Tee et al., 2016) does not appear to manifest in collision measurements of this type. The reasons for this are not entirely clear but the different technological approaches between this and previous studies might be partly attributable. For example, collision detection algorithms based on data from inertial sensors housed within GPS devices have been recently criticised, owing to their poor validity and insufficient sensitivity for measuring collision frequency and/or intensity (Chambers et al., 2019; Naughton et al., 2020). This has been suggested to partly relate to the placement and mounting surfaces of the device, which is subject to movement artifact. It is feasible that erroneous collision recordings (i.e., false positives/negatives) lead to misinterpretation of between-half changes, particularly when collisions are low-intensity or short duration (Hulin et al., 2017). This is overcome by the iMG used herein, which couples the movement of the skull and is sufficiently sensitive to stratify on-field collisions into intensity bands. Furthermore, given the importance of intensity in determining 'load' (intensity x volume or frequency), the current system offers greater understanding of collision characteristics. This was supported by the variables that increased in the second-half or were higher among starters (linear load or moderate collisions/min), which rely upon accurate quantification of collision magnitude (intensity). For example, linear load summates all linear collisions performed, and when expressed relative to playing time (linear load/min), provides an indication of the collision 'density' and could be adopted by rugby coaches when using the PROTECHT system.

Irrespective of the analyses performed (i.e., individual contacts or match files), we did not find any positional differences across the 10 matches (involving 15 players). This was somewhat surprising, given the consistency of reported higher collision frequencies among forwards compared to backs using other technologies (Grainger et al., 2018; Macleod et al., 2018; Yamamoto et al., 2020). The preliminary nature of the current analysis could partly explain these results, as the dispersion of data was large relative to the mean values, which might preclude the identification of significant differences, despite effect sizes ranging from small to large (Table 3). Furthermore, the use of only one team limits the generalisability of the results to the wider elite rugby population and precluded further positional categorisation. Nevertheless, previous analyses of similar samples to the current study have identified differences between forwards and backs in collision metrics (Reardon et al., 2017), which raises the possibility that collisions measured at the head using mouth-guard technology are more homogenous across positions than previously considered. In support of this, differences in the intensity of head collisions (using alternative mouth-guard technology) between forwards and backs were not as clearly identifiable (King et al., 2015). Collisions in matches can often be contests between players from any positional group, thus, it is feasible all have equal probability of being co-involved in high-impact collisions. It is also possible that the alternative methods (GPS-housed or video) used for detecting collisions include contacts that are unrecognised at the head (i.e., contact anatomically inferior to the head) or are filtered from the PROTECHT system's recordings (i.e., < 10 *g*). This will alter the identification of collisions and consequent interpretation of group differences. Therefore, our preliminary data suggest that players of all positions have equal probability of being involved in collisions of varying intensity when measured using mouth-guard technology.

Analysis of the six collision types demonstrated that aerial balls and unavoidable collisions had less rotational intensity compared to carries. Ball-carrying is an important rugby-specific skill that can positively affect the outcome of matches (Schoeman

& Schall, 2019) or team selection (Waldron et al., 2014a) Carrying the ball into opposition contact with high-intensity increases the force and momentum of the player at the point of collision, which relates to successful collision outcomes (Hendricks et al., 2014; Waldron et al., 2014b). This also makes ball-carriers a natural target for impactful challenges from the opposition, who also contribute an external application of force to the ball-carriers measured impact (Hendricks et al., 2014). Carrying the ball into contact typically involves three phases; the approach (or 'entry'), an initial collision and a final static or quasi-static exertion. The nature of each phase (and therefore the entire collision) is unpredictable, which leads to a multitude of outcomes and resultant forces. For example, the energetic contribution of a player tackling the ball-carrier from a wide angle, while rapidly accelerating and targeting the upper-body, is likely to elicit a large rotational acceleration on the ball-carrier. Indeed, this type of contact is fairly common in rugby and could explain the higher rotational demands of ball-carriers (Figure 2A). This is noteworthy, since rotational head accelerations have been associated with diffuse head injury (Rowson et al., 2016). Although the exact timing of the rotational acceleration was not determined in the current study, exposure to high rotational forces, particularly during the final stationary phase of a collision could pose a risk to player safety. In this scenario, the player's capacity to re-direct energy of the contact is constrained, and the common involvement of second tacklers or secondary impacts from support players may exacerbate these risks. Of further note, the analysis of non-starters demonstrated higher mean rotational intensity and more than a three-fold reduction in light contacts in favour of higher moderate contacts/min (Table 3). Thus, replacement players choose to exert their influence on the match by adopting strategies that preferentially increased the magnitude of rotational accelerations. Further research is required to understand how this is achieved.

This study provides preliminary evidence that the PROTECHT system could be used by coaches to assess the 'impact' of their replacement players in the second-half of matches. Indeed, if the tactical intention is for the non-starters to increase the collision demands of the match when being introduced, then our data confirm that this is often achieved. The ability to determine this is currently not afforded by GPS-housed inertial sensors. Our data also has implications for the performance of the ball-carrier, who will need to develop the skill and physical ability to maintain ball possession, while receiving the highest rotational forces in a short period of time. The lowest rotational collision accelerations found during aerial balls probably relates to the intentional withdrawal of tackling players in accordance with rugby union laws, thus providing some evidence of its efficacy in reducing collision loads of air-borne players.

In conclusion, using the PROTECHT system, we have demonstrated that the intensity of collisions in elite rugby union matches tends to increase in the second-half of matches and is captured by linear load/min and moderate counts/min. Given that players completing both halves of matches do not change their collision metrics, the increased collision intensity was likely to be explained by the introduction of replacement players to the match. Players carrying the ball showed the largest rotational collision intensities, with aerial challenges and unavoidable collisions the smallest in comparison. Forwards and backs were not different across any collision metric. This information can be used to support rugby coaches' decisions to utilise replacement players in the second-half, if their intention is to increase the collision intensity. Our data also demonstrates how the ball-carrying players experience the largest collisions measured at the head and that this is more likely to occur in the second-half when fatigue typically ensues. Specific skills training and physical conditioning can be adopted to account for this occurrence and does not appear to require position-specific focus. The rather large differences between other mouth-guard systems raises some concerns and further work is required to understand the reasons for these disparate findings.

Conflict of Interest

There was no financial support provided for this study; however, a financial relationship exists between Sports and Wellbeing analytics Limited (SWA) and Swansea University. The PROTECHT system has been developed by SWA and authors from both SWA and Swansea University are included in this current paper. The authors from Swansea University had full access to all of the data in this study and take full responsibility for their integrity and analysis. The results of the current study do not constitute endorsement of the product by the authors or the journal.

Acknowledgment

Thank you to the rugby staff and players involved in this study for their cooperation.

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