ASSOCIATION OF DYNAMIC BALANCE WITH SPORTS RELATED CONCUSSION: A PROSPECTIVE COHORT STUDY

Abstract

Background: Concussion is one of the most common sports-related injuries, with little understood about the modifiable and non-modifiable risk factors. Researchers have yet to evaluate the association between modifiable sensorimotor function variables and concussive injury.

Purpose: Investigate the association between dynamic balance performance, a discrete measure of sensorimotor function, and concussive injuries.

Study Design: Prospective Cohort Study

Methods: One-hundred and nine elite male Rugby Union players were baseline tested in dynamic balance performance while wearing an inertial sensor, and prospectively followed during the 2016/2017 Rugby Union season. The sample entropy of the inertial sensor gyroscope magnitude signal was derived to provide a discrete measure of dynamic balance performance. Logistic regression modelling was then used to investigate the association between the novel digital biomarker of balance performance, known risk factors of concussion (concussion history, age and playing position) and subsequent concussive injury.

Results: Participant demographic data (mean ± SD) was as follows: age: 22.6±3.6 years; height: 185±6.5 cm; weight: 98.9±12.5 Kg; BMI: 28.9±2.9 kg/m^2; leg length: 98.8±5.5 cm. Of the 109 players, 44 (40.3%) had a previous history of concussion, while 21 (19.3%) sustained a concussion during the follow-up period. The receiver operatic curve analysis for the anterior sample entropy demonstrated a statistically significant area under the curve (0.64; 95%CI = 0.52 to 0.76; $p < 0.05$), with the cut-off score of anterior sample entropy ≥ 1.2, that maximized the sensitivity (76.2%) and specificity (53.4%) for identifying individuals who subsequently sustained a concussion. Players with sub-optimal balance performance at baseline were at a 2.81 greater odds (95% CI = 1.02-7.74) of sustaining a concussion during the Rugby Union season than those with optimal balance performance, even when controlling for concussion history.

Conclusion: Rugby Union players who possess poorer dynamic balance performance as measured by a wearable inertial sensor during the Y Balance Test have a three-times higher relative risk of sustaining

a sports-related concussion, even when controlling for previous history of concussion. These findings have important implications for future research and clinical practice, as it identifies a potential modifiable risk-factor. Further research is required to investigate this association in a large cohort, consisting of males and females, across a range of sports.

Clinical Relevance: This study has identified a modifiable risk-factor for concussion in Rugby Union players, suggesting movement control and balance training interventions may help reduce the incidence of concussion in this population.

Key Terms: Concussion; Traumatic brain injury Inertial sensor; Balance; Postural stability; Y Balance Test; Risk-factor.

What is known about the subject?

Sport-related concussion is a traumatic brain injury defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces. To date, the only risk-factor identified to have a high level of evidence for increasing an individual's risk of concussion is previous history of concussion. In recent times, evidence has emerged suggesting that a movement control training intervention implemented in community and high-school Rugby Union players led to a 60% and 59% reduction in concussion rates, respectively (Hislop et al, 2017 and Attwood et al, 2017). While the mechanism behind these reductions is unclear, we have hypothesised that improvements in sensorimotor control may have reduced the risk of a player entering a vulnerable position, and subsequently sustaining a concussion. However, no studies have investigated the association between sensorimotor control and concussion.

What this study adds to existing knowledge?

This is the first study to identify a discrete measure of dynamic balance performance as a modifiable risk-factor for sport-related concussion. These findings add significant value to the current literature in sport-related concussion; contributing an increased understanding surrounding why individuals may be at risk of concussion, post-concussion. Additionally, these findings help explain the reduced rates of concussion following movement control interventions reported in two recent cluster-randomised control studies.

This study has significant implications for both research and clinical practice as our results have demonstrated that Rugby Union players with sub-optimal dynamic balance performance, as measured using a wearable inertial sensor, are three-times more likely to sustain a concussion. Furthermore, a single inexpensive and accessible inertial sensor may be leveraged to help identify those at an increased risk. These findings would suggest that target movement control interventions may reduce individuals risk of sustaining a subsequent concussion injury, decreasing the burden of injury and protecting player welfare.

Introduction

Concussion is a significant health concern facing all those involved in sport. The Centre for Disease Control estimates that approximately 1.6-3.8 million concussions occur annually in the USA alone[27], with 19.5% of American adolescents reporting sustaining at least one concussion[43]. It is one of the most commonly reported injuries across a myriad of sports, such as American Football, Ice Hockey, Wrestling, and Rugby Union[12, 37, 39, 44]. Recently, concussion has become a priority for injury prevention in sport due to the growing concern surrounding its medium and long-term consequences. An increasing body of evidence suggests that following a concussion, athletes possess a higher risk of sustaining both concussion[1] and musculoskeletal injuries[4, 8, 34]. Additionally, emerging evidence suggests that there may be a potential long-term relationship between repeated concussive injuries and the development of Chronic Traumatic Encephalopathy and its associated neurological conditions[33].

This has driven researchers and sports governing bodies to attempt to identify risk-factors that may increase an individual's propensity for injury. A systematic review carried out by Abrahams and colleagues[1] reported that there was a high level of certainty that concussion history increases an athletes risk of sustaining a subsequent concussion, while ~~and~~ matches carry a higher risk of concussion than practices, across a range of collegiate and elite sports. In addition, it has been established that body-checking increases the risk of players sustaining a concussion in youth Ice-hockey[10, 11]. While Tucker and colleagues[42] have proposed that in Rugby Union, the tackler, with the most head-to-head contacts resulting in concussive injuries, should be the focus of interventions, including law (as the rules are referred to in Rugby Union) changes and tackle technique education. Identification of such risk-factors has resulted in interventions designed to target these modifiable risk factors. For example, the Ontario Ice-Hockey Federation introduced a ban on body-checking in youth ice-hockey, resulting in a threefold reduction in concussion rates[3].

It has been hypothesised that the increased risk of injury post-concussion may arise because of sensorimotor control deficits, which become exacerbated during more demanding physical activities[4, 24]. Additionally, Hislop and colleagues[18] and Attwood and colleagues[2] demonstrated that a structured preventative movement control intervention resulted in 59% (high school) and 60% (senior community) fewer concussions, respectively. The mechanism surrounding the reduction in concussion rates has not been established. We hypothesise that improvements in sensorimotor control may have reduced the risk of a player entering a vulnerable position, and subsequently sustaining a concussion. However, no studies have investigated the association between sensorimotor control and concussion.

The Y Balance Test (YBT) is one of the most commonly used clinical dynamic balance assessments[14]. It provides a valid and reliable discrete measure of sensorimotor control, requiring the individual to maintain their balance, while completing a maximal excursion outside of their base of support[14]. However, the traditional YBT reach distance does not capture detailed information pertaining to an individual's balance control during the task. Recent work has established that inertial sensor technology can capture valuable biomechanical information relating to the control of an individual's balance, not measured by the traditional YBT reach distances, providing a more sensitive measure of balance control changes[20-22]. This research has demonstrated the excellent within-session test-retest reliability (ICC = 0.76-0.92) and the discriminant validity of the inertial sensor instrumented YBT in a laboratory based setting[22]. To date, no research has been published investigating the inter-session test-retest reliability or the role of such a system in a clinical population.

The aim of this study is to investigate the association between dynamic balance performance, quantified using inertial sensor technology, and concussive injury in an elite Rugby Union cohort. It is hypothesised that individuals who possess poorer dynamic balance performance during the YBT will have a greater risk of sustaining a concussion.

Methods

Study Population

Two-hundred and eighty-seven elite male Rugby Union players, a sample of convenience, were recruited from the four senior Irish provincial Rugby Union teams and the Irish National Under-20 squad as part of a large multicentre study. Only two of the five teams participated in the inertial sensor based screening. As such, of the 287 elite Rugby Union players that met eligibility criteria, 178 (62%) players were excluded from the analysis as they did not undergo balance screening using the inertial sensor instrumented YBT, leaving 109 players included in the final analysis. Participants were eligible to take part if they were over the age of 18, an Irish Rugby Football Union (IRFU) affiliated elite Rugby Union player and provided informed consent. Participants were excluded from this study if they had any self-reported vestibular, visual or balance impairment or any neurological disease. Participants were also excluded if they had sustained a concussion in the preceding four-month period to ensure that they did not present with residual balance deficits because of a recent injury. Figure 1 presents a flow diagram illustrating those considered in the final analysis. Ethical approval was obtained from the University College Dublin Human Research Ethics Board. All participants read the information leaflet, provided informed consent and were informed of their right to withdraw from the study at any point.

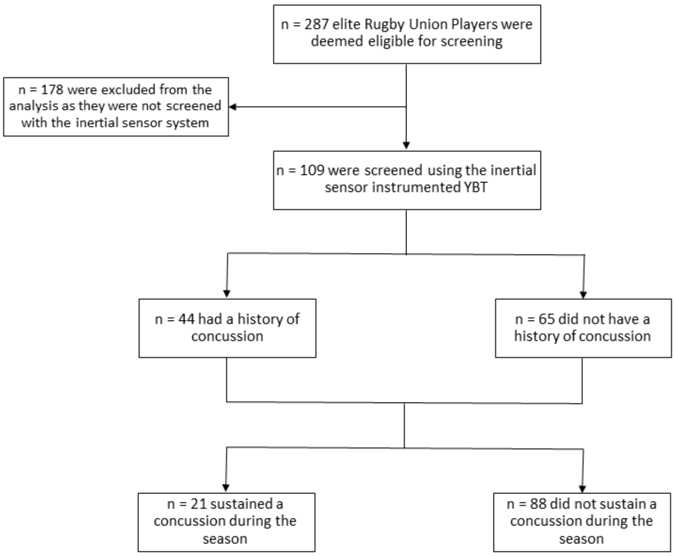

Figure 1: Number of participants considered eligible for the wider study protocol, and those who were included in the final analysis.

Study Protocol

Participants were recruited during one of two baseline testing sessions (pre-season or mid-season). Prior to commencement of the balance testing protocol, participants age, height, weight, bilateral leg length and self-reported concussion injury history were recorded.

A single inertial sensor (Shimmer3, Dublin, Ireland) was mounted at the level of the fourth lumbar vertebra (Figure 2) and secured using a custom made elastic belt to closely match the acceleration of the body’s centre of mass during the YBT excursions. The inertial sensor was connected via Bluetooth to an Android tablet (Galaxy Tab 2, Samsung) operating a custom-made application and configured to collect tri-axial gyroscope (±500 ◦/s) data at a frequency of 51.2 Hz during each YBT excursion. These data acquisition parameters were defined based on pilot testing and previous work investigating the utility of inertial sensors in the evaluation of exercise technique and balance [21, 22, 45]. Data were analysed offline using MATLAB (2014, Mathworks, Natwick, USA). The Shimmer3 inertial sensor is a commercially available product (costing approximately €250) which can be paired via Bluetooth to an Android tablet for data acquisition using Multishimmer Sync (Shimmer, Dublin, Ireland) or custom developed software. Such inertial sensor technology provides a means to capture detailed biomechanical data without the need for expensive laboratory constrained motion capture systems. The development of custom made software applications has the potential to allow for the instant automated online processing of this data, removing the need for the time consuming and expertise intensive offline processing required with laboratory based systems. As such, this technology provides an inexpensive and accessible means to objectively quantify dynamic balance performance in an unconstrained environment, addressing many of the limitations of laboratory based systems[13].

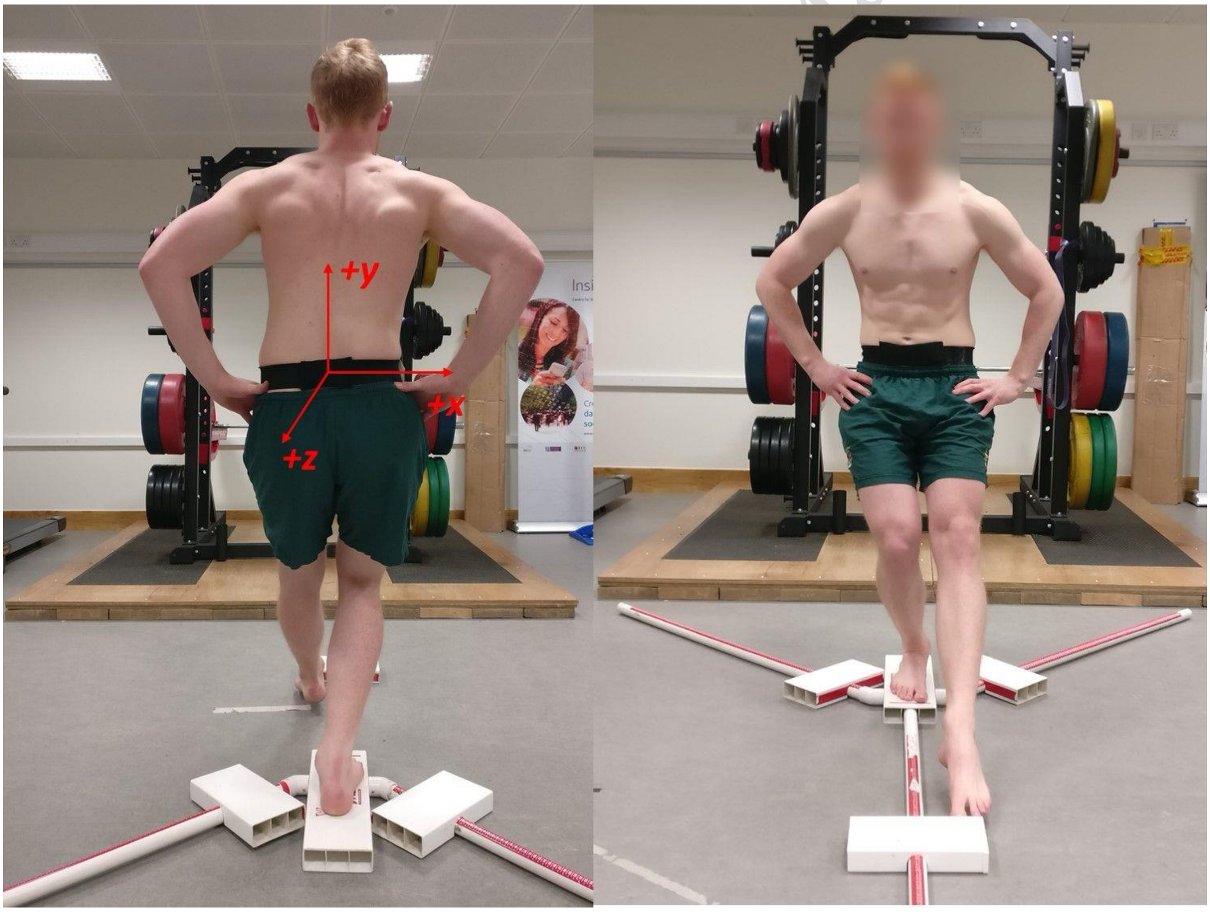

Figure 2: The sensor mounting location and orientation of the inertial sensor axis during the anterior reach of the YBT.

Individuals completed four practice trials and three recorded trials in the three defined directions of the YBT; anterior (ANT), posteromedial (PM) and posterolateral (PL) [14, 15]. Analogue YBT scores were obtained by recording the maximal reach distance, while the inertial sensor data was captured for the period the individual was in unilateral stance during the reach excursion. Reach distances were normalised in relation to the individuals leg length using the following formula[14]:

$$\text{Normalised Reach Distance} = \frac{\text{Reach distance (cm)}}{\text{Leg Length (cm)}} \text{ x } \frac{100}{1} \quad (1)$$

The mean of the three trials (reach distances and inertial sensor variables) were obtained to ensure measurement reliability. All baseline balance testing was completed by WJ and CD, two chartered physiotherapists experienced in the inertial sensor instrumented YBT testing. The total testing protocol, including setup and practice trials took approximately 10 minutes per athlete.

Outcome Variable

The outcome variable of interest for this study was diagnosis of concussion during the 2016/2017 Rugby Union season. Participants were followed from the time of recruitment (August 2016 or January 2017), to the end of the Rugby Union season (June 2017). The incidence of any training or match concussion was recorded by the team's medical staff, and reported centrally to the IRFU medical co-ordinator and the lead study investigator. Clinical diagnosis of concussion was made by the team physician and/or match-day physician using the Head Injury Assessment Tool (HIA), in compliance with the World Rugby guidelines on concussion management[46] and the fourth International Consensus Statement on Concussion in Sport[30]. The HIA involves a three-stage diagnostic process, centred around the international consensus statements definition of concussion and the sports concussion assessment tool (SCAT)[16]. This process involves a multifactorial assessment immediately post injury (HIA 1), a repeated assessment within 3-hours of the injury (HIA 2) and a follow-up assessment 36-48 hours post injury (HIA 3). These guidelines indicate that a concussion is a brain injury, defined as a "complex pathophysiological process affecting the brain, induced by biomechanical forces", resulting in a variety of non-specific signs and/or symptoms, not always involving a loss of consciousness. While the medical staff were not blinded to the players enrolled in the study, the medical staff and players were not provided with feedback of the individual players balance test results during the duration of the study.

Predictor Variables

Independent predictor variables considered as part of this analysis included traditional clinical variables; self-reported concussion history, playing-position, age-group, and dynamic balance variables (YBT reach distances and the Sample Entropy (SEn) of the gyroscope magnitude (GM) signal during each of the YBT excursions). Concussion history (which occurred outside of the 4-month exclusion criteria period) was defined according to the criteria outlined by in the 4th International Consensus Statement on Concussion in Sport[30].

GM represents the magnitude of the angular velocity, independent of direction, and was calculated using the following formula:

$$Gyroscope\ Magnitude = \sqrt{x^2 + y^2 + z^2}$$

Where *x*, *y* & *z* represent the rotational velocity in the sagittal (x), transverse (y) and frontal (z) planes. SEn is a measure developed from non-linear dynamics, designed to quantify the regularity/irregularity of a time series. Entropy based approaches are commonly applied to physiological signals, ranging from electrocardiography [26, 40] and electromyography [47], to biomechanical data [7, 38]. SEn is a unitless measure of the complexity of a signal, that can be appropriately applied to inertial sensor data to quantify sensorimotor function during tasks ranging from static balance [31, 35] to dynamic tasks such as gait [6, 32, 36]. Previous research has established that SEn measures of balance provide a means to quantify alterations in sensorimotor activity, capturing changes in severity of pathology [35]. As such, the SEn of the gyroscope magnitude signal provides a means to objectively quantify the complexity of the gyroscope magnitude signal, providing a measure of the individual's balance performance while completing the dynamic balance task. A low SEn score would be indicative of low complexity of balance control (optimal balance), while a high SEn score would indicate a high complexity of balance control (sub-optimal balance) (Figure 3). The SEn of the GM signal, of length $\boldsymbol{N} = \{\boldsymbol{x_1}, \boldsymbol{x_2}, \boldsymbol{x_3}, \dots, \boldsymbol{x_N}\}$, was calculated using the following formula:

$$Sample\ Entropy = -\log\left(\frac{A}{B}\right)$$

$\boldsymbol{A}$ was the number of template vector pairs having a Chebyshev distance $\boldsymbol{d}[\boldsymbol{X_{m+1}}(\boldsymbol{i}), \boldsymbol{X_{m+1}}(\boldsymbol{j})] < \boldsymbol{r}$ of length $\boldsymbol{m+1}$ and $\boldsymbol{B}$ was the number of template vectors pairs having $\boldsymbol{d}[\boldsymbol{X_m}(\boldsymbol{i}), \boldsymbol{X_m}(\boldsymbol{j})] < \boldsymbol{r}$ of length $\boldsymbol{m}$, where the embedding dimension, $\boldsymbol{m}$, was equal to 2 and the tolerance, $\boldsymbol{r}$**,** was equal to 0.1. The template vectors were defined such that $\boldsymbol{X_m}(\boldsymbol{i}) = \{\boldsymbol{x_i}, \boldsymbol{x_{i+1}}, \boldsymbol{x_{i+2}}, \dots \dots, \boldsymbol{x_{i+m-1}}\}$.

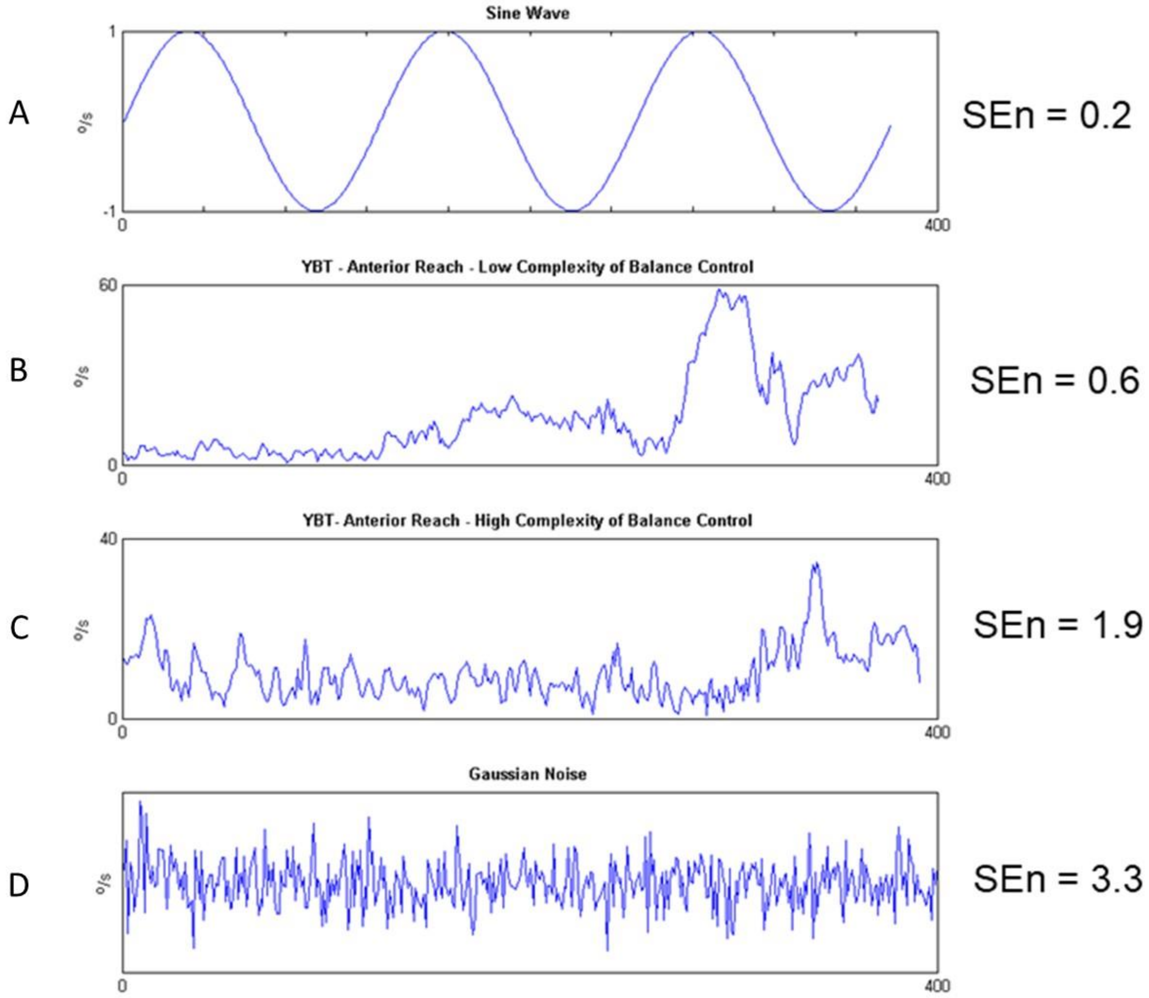

Figure 3: Illustrates the SEn score for four corresponding signals. The Sinusoid (a) possess a low SEn due to its low complexity, while Gaussian Noise signal (D) has a high SEn, indicating high signal complexity. Additionally, the SEn score for two individuals, one with a low complexity of balance control (B), and one with a high complexity of balance control (C) is presented.

Statistical Analysis

Descriptive statistics (means, standard deviations and frequencies) were used to describe the population. Mann-Whitney U tests were used to compare the concussed and non-concussed groups for the YBT reach distance measures and inertial sensor derived SEn, for all three reach directions. Variables and reach directions that demonstrated statistically significant differences between the concussed and non-concussed groups were considered for further analysis. Receiver operating characteristic (ROC) curves were performed to determine the area under the curve (AUC) and cut-off score that maximises the sensitivity and specificity for any of the statistically significant balance variables. Binary logistic regression models were used to estimate odds ratios (ORs), adjusted odds ratios (AORs), relative risk ratios (RR) and their respective 95% confidence intervals (95% CI) and Nagelkerke R^2. As previous history of concussion is considered a risk factor for future concussion, self-reported history of concussion was included in the regression modelling. Additionally, as playing position and age have been cited in the literature as potentially contributing to an individual's risk of sustaining a concussion, models were used to investigate the association of these factors with concussion [1]. Additional regression models were used to determine any potential confounding effects of concussion history, testing-point, playing-position and age-group on the estimates of association. Statistical analysis was carried out using SPSS Statistics [IBM], version 22.

Results

One-hundred and nine ~~287~~ elite Rugby Union players met eligibility criteria and were baseline tested using the inertial sensor instrumented YBT. These athletes had a mean ± SD age (22.6±3.6 years), height (185±6.5 cm), weight (98.9±12.5 Kg), BMI (28.9±2.9 kg/m^2) and leg-length (98.8±5.5 cm). Forty percent (44/109) of players reported a previous history of concussion, while 19.3% (21/109) of baselined players went on to sustain a concussive head injury during the 2016/2017 Rugby Union season. Sixty-two percent (13/21) of the individuals who went on to sustain a concussion during the season reported a previous history of concussion. Thirty-five percent (31/88) of individuals who did not go on to sustain a concussion reported a previous history of concussion. No participants had any missing data.

The Mann-Whitney U test analysis demonstrated that there was no statistically significant difference ($p > 0.05$) between the concussed and non-concussed group when considering the traditional reach-direction distances. However, the group that went on to sustain a concussion demonstrated statistically significantly greater SEn of the gyroscope magnitude signal in the ANT reach direction ($p < 0.05$), when compared to the non-concussed group (Table 1). As such, the only variable considered for further analysis was ANT SEn. The ROC analysis for the ANT SEn demonstrated a statistically significant AUC (AUC = 0.64; 95%CI = 0.52 to 0.76; $p < 0.05$), with the cut-off score of ANT SEn ≥ 1.2, that maximised the sensitivity (76.2%) and specificity (53.4%) for identifying individuals who subsequently sustained a concussion. As such, ANT SEn of the GM signal was considered in the binary logistic regression modelling. Regression models are presented in Table 2, demonstrating the estimates of association between concussion diagnosis and concussion history (model 1), playing-position (model 2), age-group (model 3), ANT SEn (model 4), concussion history and ANT SEn (model 5). Regression model 5 demonstrates that when controlling for concussion history, players with poor balance performance were at a 3.63 greater odds (95%CI = 1.20 to 10.97) of sustaining a concussion than players with optimal balance performance, indicating that poor balance performance at baseline is significantly associated with players sustaining a subsequent concussion. Furthermore, model 6 demonstrates that there ~~with~~ was no significant interaction effect observed between concussion history and ANT SEn, signifying that the relationship between concussion diagnosis and ANT SEn is independent, and not modified by history of concussion. Additional multivariable binary logistic regression models established that controlling for testing-point (model 7), playing-position (model 8) and age-group (model 9) did not significantly alter the estimates of association (Table 3). When the regression models are viewed together, they suggest that the dynamic balance performance, as measured using the inertial sensor, is associated with concussion independently of number of potential confounding factors. The RR of sustaining a concussion for those who possessed sub-threshold dynamic balance performance was 3.03 times greater (95%CI = 1.19 to 7.69) than for those with optimal balance performance, as measured by the wearable inertial sensor. Players with a previous history of concussion were at a ~~and~~ 2.36 times greater RR (95%CI = 1.07 to 5.22) of sustaining a concussion than those who did not report a previous history of concussion.

Table 1: The mean (SD) for the traditional and inertial sensor instrumented balance variables for the two groups (concussion and no concussion). Significant differences ($p < 0.05$) between the two groups are highlighted in bold.

Balance Variables		**Concussed (n = 21)**	**Not Concussed (n = 88)**
		Mean (SD)	**Mean (SD)**
Normalised Reach Distance	**ANT**	58.1 (6.1)	58.3 (5.2)
	PM	102.7 (6.5)	103.2 (6.7)
	PL	99.3 (6.8)	99.9 (6.9)
Sample Entropy	**ANT**	**1.32 (0.2)**	**1.19 (0.3)**
	PM	0.78 (0.3)	0.78 (0.3)
	PL	0.72 (0.3)	0.73 (0.3)

Table 2: The estimates of association for each of the predictor variables of interest and concussion diagnosis. Constant refers to the expected mean value of Y when X = 0 in a linear model.

Regression Model	Predictors	R^2	P Value	Odds Ratio	Lower CI	Upper CI
Model 1	**Concussion History**	0.07	0.03	2.94	1.10	7.85
	Constant		<0.01	0.14		
Model 2	**Playing Position**	0.04	0.12	2.33	0.82	6.63
	Constant		<0.01	0.13		
Model 3	**Age Group**	0.03	0.20	1.91	0.70	5.19
	Constant		<0.01	0.13		
Model 4	**ANT SEn**	0.10	0.015	3.84	1.29	11.40
	Constant		<0.01	0.104		
Model 5	**Concussion History**	0.15	0.045	2.81	1.02	7.74
	ANT SEn		0.023	3.63	1.20	10.97
	Constant		<0.01	0.07		
Model 6	**Concussion History**	0.15	0.27	2.91	0.44	19.2
	ANT SEn		0.13	3.71	0.69	20.10
	Interaction (ANT SEn* Concussion History)		0.97	0.96	0.10	8.9
	Constant		<0.01			

Table 3: The adjusted estimates of association for the two key predictor variables (concussion history and ANT SEn) and concussion diagnosis. Constant refers to the expected mean value of Y when X = 0 in a linear model.

Regression Model	Predictors	R^2	P Value	Odds Ratio	Lower CI	Upper CI
Model 7	**Concussion History**	0.17	0.07	2.56	0.91	0.72
	ANT SEn		0.02	3.74	1.23	11.38
	Testing Time		0.39	1.58	0.56	4.43
	Constant		<0.01	0.05		
Model 8	**Concussion History**	0.17	0.04	3.02	1.06	8.64
	ANT SEn		0.06	3.03	0.97	9.46
	Position		0.37	1.72	0.57	5.20
	Constant		<0.01	0.05		
Model 9	**Concussion History**	0.17	0.05	2.80	1.010	7.74
	ANT SEn		0.02	3.65	1.198	11.137
	AGE Group		0.28	1.79	0.63	5.13
	Constant		<0.01	0.05		

DISCUSSION

This is the first study to prospectively evaluate the association between dynamic balance performance and concussive injuries. Our results demonstrate that in an elite male Rugby Union population, there is an association between reduced dynamic balance performance and risk of sustaining a concussion. These findings may have significant implications for future research and clinical practice, suggesting that poor dynamic balance may be a modifiable risk-factor for sports related concussion.

The Mann-Whitney U test analysis demonstrated that there were no significant differences in the YBT reach distances between the non-concussed group and those who went on to sustain a concussion. These findings may be expected as the traditional YBT reach distances do not provide detailed information relating to balance performance[22]. When considering the SEn measures derived from the inertial sensor data, it was seen that there was a statistically significant difference between the non-injured and injured group for the ANT direction. As such, the cohort was categorised into two groups using the optimal cut-off for sensitivity and specificity from the ROC curve analysis, with individuals with sub-threshold ANT SEn deemed to have a greater irregularity and complexity in the GM signal during the ANT reach direction, indicating poorer dynamic balance.

The logistic regression analysis suggests that individuals who possessed a greater complexity in their balance control (GM SEn) during the ANT reach of the YBT were three-times more likely to sustain a concussion than the players who possessed lower balance control complexity. A multivariable logistic regression model investigating the relationship between concussion history and ANT SEn demonstrated that there was no significant change in the AORs for both concussion history and ANT SEn (Table 2, model 3). While there was no significant change in the AORs for both concussion history and ANT SEn, the measure of model fit (Nagelkerke R^2) increased from 0.10 (ANT SEn – model 4) and 0.07 (concussion history – model 1) when considering the predictor variables independently, to 0.15 (model 5 – concussion history and ANT SEn) when considering them together. This would suggest that when considering concussion history and balance performance together, the regression model can explain approximately 5% more (ANT SEn) and 8% more (concussion history) of the variability in the data when considering the predictor variables alone. This suggests that both variables (ANT SEn and concussion history) have value as predictors of concussion independently, but have increased predictive value when considered together. Additionally, when investigating the interaction between concussion history and ANT SEn (model 4), it was seen that there was no significant interaction between the two predictor variables; indicating that both clinical features were independent from each other, with no confounding or interaction effect altering their association with concussion diagnosis. These findings suggest that both concussion history and inertial sensor quantified balance performance (ANT SEn) independently show promise as predictive clinical features for concussion in a Rugby Union population. Additional multivariable logistic regression models were used to control for factors such as testing-point, playing-position and age-group. The AORs in Table 3 indicate that testing-time (model 7), playing-position (model 8) and age-group (model 9) did not have a significant effect on the estimates of association for both concussion history and ANT SEn. These findings are significant as they demonstrate that the inertial sensor derived measure of dynamic balance performance is associated with concussion independently from several potential key confounding factors. While the AOR 95% CI presented in model 6 are relatively wide for the three predictor variables, a likely explanation for this is the modest sample size recruited in the study, coupled with the inclusion of multiple predictors (concussion history, ANT SEn and the interaction variable). This would likely reduce the degrees of freedom of the model, leading to a decrease in the precision of the estimates of association. Importantly, when considering the model 4 (ANT SEn), a single variable regression model, the 95% CI are relatively small (95% CI = 1.29-11.40), despite the modest sample size.

The prevalence of concussion in this study cohort was 19.3%, similar to the previously published 17% reported by the English Rugby Football Union during the 2015/2016 season[23]. Twenty-seven percent more of the individuals who had a previous history of concussion went on to sustain a concussion during the season than those who did not report a history of concussion. The logistic regression model 1 results (Table 2) demonstrate that previous history of concussion increased the odds of an individual sustaining a concussion by 2.94, a RR of 2.36 times, extending previous findings, across a range of sports[1]. No significant association was observed between playing-position and concussion, supporting previously published findings which demonstrated that playing-position had no effect on concussion risk in professional Rugby Union[25]. Similarly, no significant association was found between age-group and concussion for the age range included in this study. While no research has investigated this in an elite cohort, previous studies have presented mixed findings, with Hollis and colleagues[19] reporting that senior community Rugby Union players had a higher risk of concussion than high-school players, while Lee and Garraway[28] concluded that there was no effect on risk between high-school and senior club rugby players. While the findings of this study contradict those of Hollis and colleagues, these findings may differ due to the different study populations and age ranges investigated in our study, and thus should be compared with caution. A possible explanation for this discrepancy is that because the under-20 cohort are training and playing in professional academy settings, there is less heterogeneity between the two age-groups than would be observed between high-school and senior club groups, resulting in a similar risk across the group.

No previous research has investigated the relationship between dynamic balance performance and concussion. There is one key explanation as to why individuals with poorer dynamic balance performance demonstrated a three-times greater risk of sustaining a concussion. It is well established that the tackler is at a higher risk of sustaining a concussion than the ball-carrier[9], with poor tackle technique associated with concussive injuries in elite junior Rugby Union[5, 17]. If an individual possesses reduced balance performance, they may have poorer control and awareness of their body, and thus sub-optimal tackle technique, increasing their risk of entering a vulnerable position and sustaining a head injury. This hypothesis is supported by the recent findings of two cluster-randomised control trials completed in a cohort of high-school and senior-community Rugby Union players, where it was demonstrated that a movement control intervention significantly reduced concussion rates[2, 18]. While the major theory surrounding these findings is related to changes in neck strength, it may be hypothesised that alteration in sensorimotor control through movement control and tackle technique training may have contributed to the reduced injury rates.

Limitations

There are three main limitations relating to this study. Firstly, while the sample recruited is relatively small and homogeneous, the study was exploratory in nature, requiring further research leveraging a larger and more representative sporting population (male/female, across a range of sports). Secondly, baseline testing took place at two separate time points; pre-season (August 2016) and mid-season (January 2017), resulting in two different lengths of follow-up. The different follow-up periods had the potential to influence the estimates of association between the dynamic balance and concussion. However, the statistical modelling implemented in this study controlled for testing time-point, demonstrated that testing point had no significant effect on the estimations of association between dynamic balance and concussive injuries. Thirdly, history of concussion was self-reported and as such may be an under-estimation, thus should be interpreted with caution. Additionally, the study team did not have information relating to the number of past-concussions or the length of time between past-concussions. As such, history of concussion was a binary variable that may have included individuals who had a history of one or multiple concussions. As a result, there could be potential confounding or interacting variables (number of past concussions or length of time between concussions) that were not included in the analysis presented in this paper. However, the results presented in this paper provide an exploratory investigation into the effect a history of concussion (one or multiple) may have on balance performance, and how this may confound and/or interact with risk of future concussion. Further research should be conducted to investigate the relationship between a history of single or multiple concussions, length of time between multiple past-concussions, balance performance and the association this may have with risk of future concussion.

Conclusions

This is the first study to investigate the association between dynamic balance performance and concussion in elite Rugby Union. The results demonstrate that poor balance performance is significantly associated with subsequent concussion injury, even when controlling for concussion history. Thus, individuals with sub-threshold dynamic balance control, as measured by a wearable internal sensor, are three-times more likely to sustain a concussive head injury. The findings of this exploratory study are significant as dynamic balance is a modifiable risk factor, with balance and motor control training interventions frequently demonstrating their efficacy in improving balance and reducing musculoskeletal injury risk[2, 18, 29, 41]. As such, early identification of such modifiable risk factors may allow medical teams to introduce appropriate targeted interventions to reduce player’s risk of sustaining a concussion in Rugby Union. Further research is required, leveraging a larger cohort, representing males and females across a range of sports.

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