



Title	Association of dynamic balance with sports related concussion: a prospective cohort study
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- 1 **ASSOCIATION OF DYNAMIC BALANCE WITH SPORTS RELATED CONCUSSION: A**
- 2 **PROSPECTIVE COHORT STUDY**

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3 **Abstract**

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

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

9 **Study Design:** Prospective Cohort Study

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

17 **Results:** Participant demographic data (mean \pm SD) was as follows: age: 22.6 \pm 3.6 years; height:
18 185 \pm 6.5 cm; weight: 98.9 \pm 12.5 Kg; BMI: 28.9 \pm 2.9 kg/m²; leg length: 98.8 \pm 5.5 cm. Of the 109 players,
19 44 (40.3%) had a previous history of concussion, while 21 (19.3%) sustained a concussion during the
20 follow-up period. The receiver operatic curve analysis for the anterior sample entropy demonstrated a
21 statistically significant area under the curve (0.64; 95% CI = 0.52 to 0.76; $p < 0.05$), with the cut-off
22 score of anterior sample entropy ≥ 1.2 , that maximized the sensitivity (76.2%) and specificity (53.4%)
23 for identifying individuals who subsequently sustained a concussion. Players with sub-optimal balance
24 performance at baseline were at a 2.81 greater odds (95% CI = 1.02-7.74) of sustaining a concussion
25 during the Rugby Union season than those with optimal balance performance, even when controlling
26 for concussion history.

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

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

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

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

38 **What is known about the subject?**

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

50 **What this study adds to existing knowledge?**

51 This is the first study to identify a discrete measure of dynamic balance performance as a modifiable
52 risk-factor for sport-related concussion. These findings add significant value to the current literature in
53 sport-related concussion; contributing an increased understanding surrounding why individuals may be
54 at risk of concussion, post-concussion. Additionally, these findings help explain the reduced rates of

55 concussion following movement control interventions reported in two recent cluster-randomised
56 control studies.

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

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64 **Introduction**

65 Concussion is a significant health concern facing all those involved in sport. The Centre for Disease
66 Control estimates that approximately 1.6-3.8 million concussions occur annually in the USA alone²⁷,
67 with 19.5% of American adolescents reporting sustaining at least one concussion⁴³. It is one of the most
68 commonly reported injuries across a myriad of sports, such as American Football, Ice Hockey,
69 Wrestling, and Rugby Union^{12, 37, 39, 44}. Recently, concussion has become a priority for injury prevention
70 in sport due to the growing concern surrounding its medium and long-term consequences. An increasing
71 body of evidence suggests that following a concussion, athletes possess a higher risk of sustaining both
72 concussion¹ and musculoskeletal injuries^{4, 8, 34}. Additionally, emerging evidence suggests that there may
73 be a potential long-term relationship between repeated concussive injuries and the development of
74 Chronic Traumatic Encephalopathy and its associated neurological conditions³³.

75 This has driven researchers and sports governing bodies to attempt to identify risk-factors that may
76 increase an individual's propensity for injury. A systematic review carried out by Abrahams and
77 colleagues¹ reported that there was a high level of certainty that concussion history increases an athletes
78 risk of sustaining a subsequent concussion, while ~~and~~ matches carry a higher risk of concussion than
79 practices, across a range of collegiate and elite sports. In addition, it has been established that body-
80 checking increases the risk of players sustaining a concussion in youth Ice-hockey^{10, 11}. While Tucker
81 and colleagues⁴² have proposed that in Rugby Union, the tackler, with the most head-to-head contacts
82 resulting in concussive injuries, should be the focus of interventions, including law (as the rules are
83 referred to in Rugby Union) changes and tackle technique education. Identification of such risk-factors
84 has resulted in interventions designed to target these modifiable risk factors. For example, the Ontario
85 Ice-Hockey Federation introduced a ban on body-checking in youth ice-hockey, resulting in a threefold
86 reduction in concussion rates³.

87 It has been hypothesised that the increased risk of injury post-concussion may arise because of
88 sensorimotor control deficits, which become exacerbated during more demanding physical activities⁴.
89 ²⁴. Additionally, Hislop and colleagues¹⁸ and Attwood and colleagues² demonstrated that a structured
90 preventative movement control intervention resulted in 59% (high school) and 60% (senior community)

91 fewer concussions, respectively. The mechanism surrounding the reduction in concussion rates has not
92 been established. We hypothesise that improvements in sensorimotor control may have reduced the risk
93 of a player entering a vulnerable position, and subsequently sustaining a concussion. However, no
94 studies have investigated the association between sensorimotor control and concussion.

95 The Y Balance Test (YBT) is one of the most commonly used clinical dynamic balance assessments¹⁴.
96 It provides a valid and reliable discrete measure of sensorimotor control, requiring the individual to
97 maintain their balance, while completing a maximal excursion outside of their base of support¹⁴.
98 However, the traditional YBT reach distance does not capture detailed information pertaining to an
99 individual's balance control during the task. Recent work has established that inertial sensor technology
100 can capture valuable biomechanical information relating to the control of an individual's balance, not
101 measured by the traditional YBT reach distances, providing a more sensitive measure of balance control
102 changes²⁰⁻²². This research has demonstrated the excellent within-session test-retest reliability
103 (ICC = 0.76-0.92) and the discriminant validity of the inertial sensor instrumented YBT in a
104 laboratory based setting²². To date, no research has been published investigating the inter-
105 session test-retest reliability or the role of such a system in a clinical population.

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

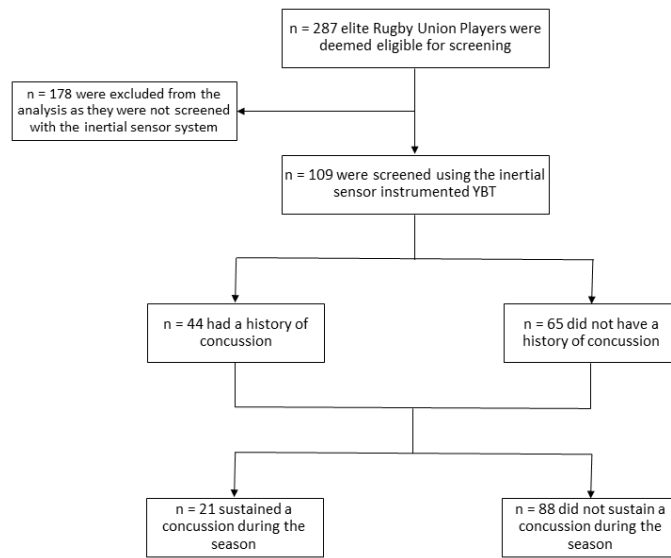
110 **Methods**

111 **Study Population**

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

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

131

132 **Study Protocol**

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

136 A single inertial sensor (Shimmer3, Dublin, Ireland) was mounted at the level of the fourth lumbar
 137 vertebra (Figure 2) and secured using a custom made elastic belt to closely match the acceleration of
 138 the body's centre of mass during the YBT excursions. The inertial sensor was connected via Bluetooth
 139 to an Android tablet (Galaxy Tab 2, Samsung) operating a custom-made application and configured to
 140 collect tri-axial gyroscope (± 500 °/s) data at a frequency of 51.2 Hz during each YBT excursion. These
 141 data acquisition parameters were defined based on pilot testing and previous work investigating the
 142 utility of inertial sensors in the evaluation of exercise technique and balance^{21, 22, 45}. Data were analysed

143 offline using MATLAB (2014, Mathworks, Natwick, USA). The Shimmer3 inertial sensor is a
144 commercially available product (costing approximately €250) which can be paired via Bluetooth to an
145 Android tablet for data acquisition using Multishimmer Sync (Shimmer, Dublin, Ireland) or custom
146 developed software. Such inertial sensor technology provides a means to capture detailed
147 biomechanical data without the need for expensive laboratory constrained motion capture systems. The
148 development of custom made software applications has the potential to allow for the instant automated
149 online processing of this data, removing the need for the time consuming and expertise intensive offline
150 processing required with laboratory based systems. As such, this technology provides an inexpensive
151 and accessible means to objectively quantify dynamic balance performance in an unconstrained
152 environment, addressing many of the limitations of laboratory based systems¹³.



153
154 **Figure 2: The sensor mounting location and orientation of the inertial sensor axis during the**
155 **anterior reach of the YBT.**

156

157 Individuals completed four practice trials and three recorded trials in the three defined directions of the
158 YBT; anterior (ANT), posteromedial (PM) and posterolateral (PL) ^{14, 15}. Analogue YBT scores were
159 obtained by recording the maximal reach distance, while the inertial sensor data was captured for the
160 period the individual was in unilateral stance during the reach excursion. Reach distances were
161 normalised in relation to the individuals leg length using the following formula¹⁴:

$$162 \quad \text{Normalised Reach Distance} = \frac{\text{Reach distance (cm)}}{\text{Leg Length (cm)}} \times \frac{100}{1} \quad (1)$$

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

167 **Outcome Variable**

168 The outcome variable of interest for this study was diagnosis of concussion during the 2016/2017 Rugby
169 Union season. Participants were followed from the time of recruitment (August 2016 or January 2017),
170 to the end of the Rugby Union season (June 2017). The incidence of any training or match concussion
171 was recorded by the team's medical staff, and reported centrally to the IRFU medical co-ordinator and
172 the lead study investigator. Clinical diagnosis of concussion was made by the team physician and/or
173 match-day physician using the Head Injury Assessment Tool (HIA), in compliance with the World
174 Rugby guidelines on concussion management⁴⁶ and the fourth International Consensus Statement on
175 Concussion in Sport³⁰. The HIA involves a three-stage diagnostic process, centred around the
176 international consensus statements definition of concussion and the sports concussion assessment tool
177 (SCAT)¹⁶. This process involves a multifactorial assessment immediately post injury (HIA 1), a
178 repeated assessment within 3-hours of the injury (HIA 2) and a follow-up assessment 36-48 hours post
179 injury (HIA 3). These guidelines indicate that a concussion is a brain injury, defined as a "complex
180 pathophysiological process affecting the brain, induced by biomechanical forces", resulting in a variety
181 of non-specific signs and/or symptoms, not always involving a loss of consciousness. While the medical

182 staff were not blinded to the players enrolled in the study, the medical staff and players were not
183 provided with feedback of the individual players balance test results during the duration of the study.

184 **Predictor Variables**

185 Independent predictor variables considered as part of this analysis included traditional clinical variables;
186 self-reported concussion history, playing-position, age-group, and dynamic balance variables (YBT
187 reach distances and the Sample Entropy (SEn) of the gyroscope magnitude (GM) signal during each of
188 the YBT excursions). Concussion history (which occurred outside of the 4-month exclusion criteria
189 period) was defined according to the criteria outlined by in the 4th International Consensus Statement
190 on Concussion in Sport³⁰.

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

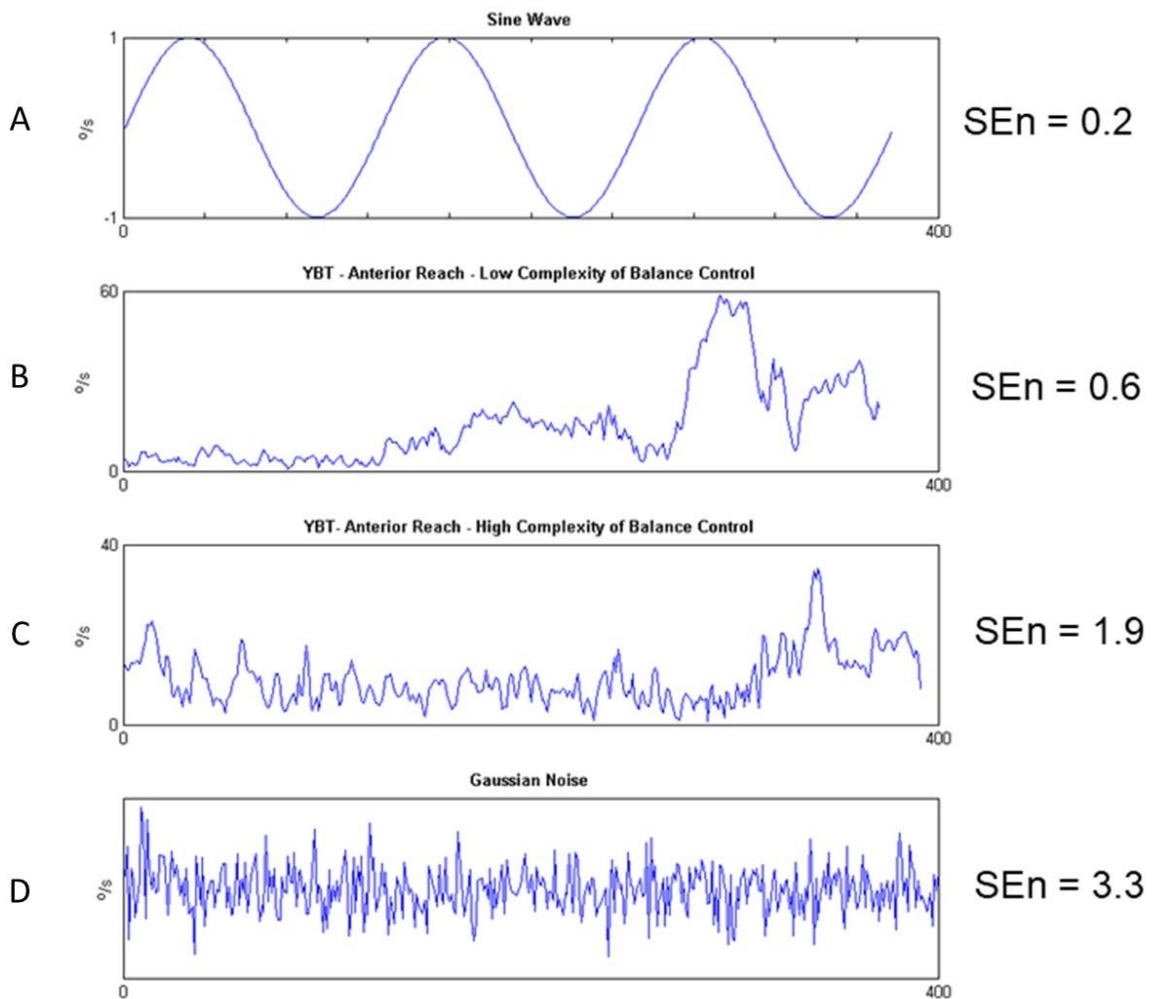
$$193 \quad \text{Gyroscope Magnitude} = \sqrt{x^2 + y^2 + z^2}$$

194 Where x , y & z represent the rotational velocity in the sagittal (x), transverse (y) and frontal (z) planes.
195 SEn is a measure developed from non-linear dynamics, designed to quantify the regularity/irregularity
196 of a time series. Entropy based approaches are commonly applied to physiological signals, ranging from
197 electrocardiography^{26,40} and electromyography⁴⁷, to biomechanical data^{7,38}. SEn is a unitless measure
198 of the complexity of a signal, that can be appropriately applied to inertial sensor data to quantify
199 sensorimotor function during tasks ranging from static balance^{31,35} to dynamic tasks such as gait^{6,32},
200³⁶. Previous research has established that SEn measures of balance provide a means to quantify
201 alterations in sensorimotor activity, capturing changes in severity of pathology³⁵. As such, the SEn of
202 the gyroscope magnitude signal provides a means to objectively quantify the complexity of the
203 gyroscope magnitude signal, providing a measure of the individual's balance performance while
204 completing the dynamic balance task. A low SEn score would be indicative of low complexity of
205 balance control (optimal balance), while a high SEn score would indicate a high complexity of balance
206 control (sub-optimal balance) (Figure 3). The SEn of the GM signal, of length $N =$
207 $\{x_1, x_2, x_3, \dots, x_N\}$, was calculated using the following formula:

208

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

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



213

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

219

220 **Statistical Analysis**

221 Descriptive statistics (means, standard deviations and frequencies) were used to describe the population.
222 Mann-Whitney U tests were used to compare the concussed and non-concussed groups for the YBT
223 reach distance measures and inertial sensor derived SEn, for all three reach directions. Variables and
224 reach directions that demonstrated statistically significant differences between the concussed and non-
225 concussed groups were considered for further analysis. Receiver operating characteristic (ROC) curves
226 were performed to determine the area under the curve (AUC) and cut-off score that maximises the
227 sensitivity and specificity for any of the statistically significant balance variables. Binary logistic
228 regression models were used to estimate odds ratios (ORs), adjusted odds ratios (AORs), relative risk
229 ratios (RR) and their respective 95% confidence intervals (95% CI) and Nagelkerke R². As previous
230 history of concussion is considered a risk factor for future concussion, self-reported history of
231 concussion was included in the regression modelling. Additionally, as playing position and age have
232 been cited in the literature as potentially contributing to an individual's risk of sustaining a concussion,
233 models were used to investigate the association of these factors with concussion¹. Additional regression
234 models were used to determine any potential confounding effects of concussion history, testing-point,
235 playing-position and age-group on the estimates of association. Statistical analysis was carried out using
236 SPSS Statistics [IBM], version 22.

237 **Results**

238 One-hundred and nine ~~287~~ elite Rugby Union players met eligibility criteria and were baseline tested
239 using the inertial sensor instrumented YBT. These athletes had a mean \pm SD age (22.6 \pm 3.6 years),
240 height (185 \pm 6.5 cm), weight (98.9 \pm 12.5 Kg), BMI (28.9 \pm 2.9 kg/m²) and leg-length (98.8 \pm 5.5 cm).
241 Forty percent (44/109) of players reported a previous history of concussion, while 19.3% (21/109) of
242 baselined players went on to sustain a concussive head injury during the 2016/2017 Rugby Union
243 season. Sixty-two percent (13/21) of the individuals who went on to sustain a concussion during the
244 season reported a previous history of concussion. Thirty-five percent (31/88) of individuals who did not

245 go on to sustain a concussion reported a previous history of concussion. No participants had any missing
246 data.

247 The Mann-Whitney U test analysis demonstrated that there was no statistically significant difference (p
248 > 0.05) between the concussed and non-concussed group when considering the traditional reach-
249 direction distances. However, the group that went on to sustain a concussion demonstrated statistically
250 significantly greater SEn of the gyroscope magnitude signal in the ANT reach direction ($p < 0.05$),
251 when compared to the non-concussed group (Table 1). As such, the only variable considered for further
252 analysis was ANT SEn. The ROC analysis for the ANT SEn demonstrated a statistically significant
253 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
254 maximised the sensitivity (76.2%) and specificity (53.4%) for identifying individuals who subsequently
255 sustained a concussion. As such, ANT SEn of the GM signal was considered in the binary logistic
256 regression modelling. Regression models are presented in Table 2, demonstrating the estimates of
257 association between concussion diagnosis and concussion history (model 1), playing-position (model
258 2), age-group (model 3), ANT SEn (model 4), concussion history and ANT SEn (model 5). Regression
259 model 5 demonstrates that when controlling for concussion history, players with poor balance
260 performance were at a 3.63 greater odds (95% CI = 1.20 to 10.97) of sustaining a concussion than players
261 with optimal balance performance, indicating that poor balance performance at baseline is significantly
262 associated with players sustaining a subsequent concussion. Furthermore, model 6 demonstrates that
263 there ~~with~~ was no significant interaction effect observed between concussion history and ANT SEn,
264 signifying that the relationship between concussion diagnosis and ANT SEn is independent, and not
265 modified by history of concussion. Additional multivariable binary logistic regression models
266 established that controlling for testing-point (model 7), playing-position (model 8) and age-group
267 (model 9) did not significantly alter the estimates of association (Table 3). When the regression models
268 are viewed together, they suggest that the dynamic balance performance, as measured using the inertial
269 sensor, is associated with concussion independently of number of potential confounding factors. The
270 RR of sustaining a concussion for those who possessed sub-threshold dynamic balance performance
271 was 3.03 times greater (95% CI = 1.19 to 7.69) than for those with optimal balance performance, as

272 measured by the wearable inertial sensor. Players with a previous history of concussion were at a ~~and~~
 273 2.36 times greater RR (95% CI = 1.07 to 5.22) of sustaining a concussion than those who did not report
 274 a previous history of concussion.

275 **Table 1: The mean (SD) for the traditional and inertial sensor instrumented balance variables for the two groups**
 276 **(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	ANT	58.1 (6.1)	58.3 (5.2)
	PM	102.7 (6.5)	103.2 (6.7)
Reach Distance	PL	99.3 (6.8)	99.9 (6.9)
	ANT	1.32 (0.2)	1.19 (0.3)
Sample Entropy	PM	0.78 (0.3)	0.78 (0.3)
	PL	0.72 (0.3)	0.73 (0.3)

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

Regression Model	Predictors	R²	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			

280

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

Regression Model	Predictors	R²	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		

283

284 **DISCUSSION**

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

290 The Mann-Whitney U test analysis demonstrated that there were no significant differences in the YBT
291 reach distances between the non-concussed group and those who went on to sustain a concussion. These
292 findings may be expected as the traditional YBT reach distances do not provide detailed information
293 relating to balance performance²². When considering the SEn measures derived from the inertial sensor
294 data, it was seen that there was a statistically significant difference between the non-injured and injured
295 group for the ANT direction. As such, the cohort was categorised into two groups using the optimal
296 cut-off for sensitivity and specificity from the ROC curve analysis, with individuals with sub-threshold
297 ANT SEn deemed to have a greater irregularity and complexity in the GM signal during the ANT reach
298 direction, indicating poorer dynamic balance.

299 The logistic regression analysis suggests that individuals who possessed a greater complexity in their
300 balance control (GM SEn) during the ANT reach of the YBT were three-times more likely to sustain a
301 concussion than the players who possessed lower balance control complexity. A multivariable logistic
302 regression model investigating the relationship between concussion history and ANT SEn demonstrated
303 that there was no significant change in the AORs for both concussion history and ANT SEn (Table 2,
304 model 3). While there was no significant change in the AORs for both concussion history and ANT
305 SEn, the measure of model fit (Nagelkerke R²) increased from 0.10 (ANT SEn – model 4) and 0.07
306 (concussion history – model 1) when considering the predictor variables independently, to 0.15 (model
307 5 – concussion history and ANT SEn) when considering them together. This would suggest that when
308 considering concussion history and balance performance together, the regression model can explain
309 approximately 5% more (ANT SEn) and 8% more (concussion history) of the variability in the data
310 when considering the predictor variables alone. This suggests that both variables (ANT SEn and

311 concussion history) have value as predictors of concussion independently, but have increased predictive
312 value when considered together. Additionally, when investigating the interaction between concussion
313 history and ANT SEn (model 4), it was seen that there was no significant interaction between the two
314 predictor variables; indicating that both clinical features were independent from each other, with no
315 confounding or interaction effect altering their association with concussion diagnosis. These findings
316 suggest that both concussion history and inertial sensor quantified balance performance (ANT SEn)
317 independently show promise as predictive clinical features for concussion in a Rugby Union population.
318 Additional multivariable logistic regression models were used to control for factors such as testing-
319 point, playing-position and age-group. The AORs in Table 3 indicate that testing-time (model 7),
320 playing-position (model 8) and age-group (model 9) did not have a significant effect on the estimates
321 of association for both concussion history and ANT SEn. These findings are significant as they
322 demonstrate that the inertial sensor derived measure of dynamic balance performance is associated with
323 concussion independently from several potential key confounding factors. While the AOR 95% CI
324 presented in model 6 are relatively wide for the three predictor variables, a likely explanation for this is
325 the modest sample size recruited in the study, coupled with the inclusion of multiple predictors
326 (concussion history, ANT SEn and the interaction variable). This would likely reduce the degrees of
327 freedom of the model, leading to a decrease in the precision of the estimates of association. Importantly,
328 when considering the model 4 (ANT SEn), a single variable regression model, the 95% CI are relatively
329 small (95% CI = 1.29-11.40), despite the modest sample size.

330 The prevalence of concussion in this study cohort was 19.3%, similar to the previously published 17%
331 reported by the English Rugby Football Union during the 2015/2016 season²³. Twenty-seven percent
332 more of the individuals who had a previous history of concussion went on to sustain a concussion during
333 the season than those who did not report a history of concussion. The logistic regression model 1 results
334 (Table 2) demonstrate that previous history of concussion increased the odds of an individual sustaining
335 a concussion by 2.94, a RR of 2.36 times, extending previous findings, across a range of sports¹. No
336 significant association was observed between playing-position and concussion, supporting previously
337 published findings which demonstrated that playing-position had no effect on concussion risk in

338 professional Rugby Union²⁵. Similarly, no significant association was found between age-group and
339 concussion for the age range included in this study. While no research has investigated this in an elite
340 cohort, previous studies have presented mixed findings, with Hollis and colleagues¹⁹ reporting that
341 senior community Rugby Union players had a higher risk of concussion than high-school players, while
342 Lee and Garraway²⁸ concluded that there was no effect on risk between high-school and senior club
343 rugby players. While the findings of this study contradict those of Hollis and colleagues, these findings
344 may differ due to the different study populations and age ranges investigated in our study, and thus
345 should be compared with caution. A possible explanation for this discrepancy is that because the under-
346 20 cohort are training and playing in professional academy settings, there is less heterogeneity between
347 the two age-groups than would be observed between high-school and senior club groups, resulting in a
348 similar risk across the group.

349 No previous research has investigated the relationship between dynamic balance performance and
350 concussion. There is one key explanation as to why individuals with poorer dynamic balance
351 performance demonstrated a three-times greater risk of sustaining a concussion. It is well established
352 that the tackler is at a higher risk of sustaining a concussion than the ball-carrier⁹, with poor tackle
353 technique associated with concussive injuries in elite junior Rugby Union^{5,17}. If an individual possesses
354 reduced balance performance, they may have poorer control and awareness of their body, and thus sub-
355 optimal tackle technique, increasing their risk of entering a vulnerable position and sustaining a head
356 injury. This hypothesis is supported by the recent findings of two cluster-randomised control trials
357 completed in a cohort of high-school and senior-community Rugby Union players, where it was
358 demonstrated that a movement control intervention significantly reduced concussion rates^{2,18}. While
359 the major theory surrounding these findings is related to changes in neck strength, it may be
360 hypothesised that alteration in sensorimotor control through movement control and tackle technique
361 training may have contributed to the reduced injury rates.

362 **Limitations**

363 There are three main limitations relating to this study. Firstly, while the sample recruited is relatively
364 small and homogeneous, the study was exploratory in nature, requiring further research leveraging a

365 larger and more representative sporting population (male/female, across a range of sports). Secondly,
366 baseline testing took place at two separate time points; pre-season (August 2016) and mid-season
367 (January 2017), resulting in two different lengths of follow-up. The different follow-up periods had the
368 potential to influence the estimates of association between the dynamic balance and concussion.
369 However, the statistical modelling implemented in this study controlled for testing time-point,
370 demonstrated that testing point had no significant effect on the estimations of association between
371 dynamic balance and concussive injuries. Thirdly, history of concussion was self-reported and as such
372 may be an under-estimation, thus should be interpreted with caution. Additionally, the study team did
373 not have information relating to the number of past-concussions or the length of time between past-
374 concussions. As such, history of concussion was a binary variable that may have included individuals
375 who had a history of one or multiple concussions. As a result, there could be potential confounding or
376 interacting variables (number of past concussions or length of time between concussions) that were not
377 included in the analysis presented in this paper. However, the results presented in this paper provide an
378 exploratory investigation into the effect a history of concussion (one or multiple) may have on balance
379 performance, and how this may confound and/or interact with risk of future concussion. Further
380 research should be conducted to investigate the relationship between a history of single or multiple
381 concussions, length of time between multiple past-concussions, balance performance and the
382 association this may have with risk of future concussion.

383 **Conclusions**

384 This is the first study to investigate the association between dynamic balance performance and
385 concussion in elite Rugby Union. The results demonstrate that poor balance performance is significantly
386 associated with subsequent concussion injury, even when controlling for concussion history. Thus,
387 individuals with sub-threshold dynamic balance control, as measured by a wearable internal sensor, are
388 three-times more likely to sustain a concussive head injury. The findings of this exploratory study are
389 significant as dynamic balance is a modifiable risk factor, with balance and motor control training
390 interventions frequently demonstrating their efficacy in improving balance and reducing
391 musculoskeletal injury risk^{2, 18, 29, 41}. As such, early identification of such modifiable risk factors may

392 allow medical teams to introduce appropriate targeted interventions to reduce player's risk of sustaining
393 a concussion in Rugby Union. Further research is required, leveraging a larger cohort, representing
394 males and females across a range of sports.

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