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Concussion recovery evaluation using the inertial sensor instrumented Y Balance Test

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Running Title: Concussion recovery assessment

Abstract

The current sports concussion assessment paradigm lacks reliability, has learning effects and is not sufficiently challenging for athletes. As a result, subtle deficits in sensorimotor function may be unidentified, increasing the risk of future injury. This study examined if the inertial-sensor instrumented Y Balance test could capture concussion induced alterations in dynamic movement control. A cohort of 226 elite Rugby Union, American Football and Ice Hockey athletes were evaluated using the inertial-sensor instrumented Y balance test. Dynamic balance performance was quantified using normalised reach distance, jerk magnitude root-mean-squared (Jerk Mag RMS) and gyroscope magnitude sample entropy (Gyro Mag SEn). Concussed athletes who consented to follow-up were evaluated 24 to 48-hours post-injury, and at the point of return to full contact training (RTP). Seventeen athletes sustained a concussion and consented to both the 24 to 48-hour and RTP follow-up testing. Twenty uninjured control athletes were re-tested 6-months following initial screening. Concussed athletes had reductions in normalised reach distance (Cohens D = 0.66-1.16) and Jerk Mag (Cohens D = 0.57-1.14) 24 to 48-hours post-injury, which returned to pre-injury levels by the point of RTP. There was no significant difference in performance between the baseline and 6-month follow-up in the 20 un-injured athletes (Cohens D=0.06-0.51). There was a statistically significant linear association between Jerk Mag RMS 24 to 48-hours post-injury and the natural log of RTP duration (R^2 = 0.27 to 0.33). These results indicate that concussed athletes possessed alterations in dynamic movement control 24 to 48-hours post-concussion, which typically returns to pre-injury levels by the point of RTP. Furthermore, evaluation of dynamic movement control 24 to 48 hours post injury may aid in the evaluation of recovery prognosis.

Abbreviations

SRC: Sports related concussion

SCAT: Sports Concussion Assessment Tool

mBESS: Modified balance error scoring system

YBT: Y Balance Test

RTP: Return to full contact training

NCAA D1: National Collegiate Athletics Association Division 1

Gyro Mag: Gyroscope magnitude

Jerk Mag: Jerk Magnitude

SEn: Sample entropy

RMS: Root-mean-square

ICC: Intra-class correlation coefficient

MDC: Minimal detectable change

MD: Mean difference

IR: inter-quartile range

Key Terms: Mild traumatic brain injury, postural control, sports medicine, digital Health, rehabilitation

Introduction

Sports related concussion (SRC) is one of the most common injuries reported across a myriad of different sports, such as American Football, Ice Hockey and Rugby Union.[1, 2] Acute concussion results in a series of symptoms, with the most common presentation including headaches, dizziness and balance deficits.[3] While athletes have been shown to typically clinically recover within 12 days,[4] emerging evidence has demonstrated that young athletes across numerous sports have an increased risk of sustaining subsequent concussive or musculoskeletal injuries for up to two years following return to sport after a concussion.[5] In addition, research has suggested that some athletes may present with sensorimotor and neurocognitive changes which extend beyond the resolution of these clinical symptoms.[6] These persistent sub-clinical deficits have been hypothesised to help explain the increased risk of sustaining subsequent concussion and/or musculoskeletal injuries following return to sport.[7]

The current consensus on the management of SRC centres around the use of an assessment battery called the Sports Concussion Assessment Tool (SCAT).[8] The SCAT attempts to address the multifactorial nature of concussion through a series of clinical assessments: the symptom scale, standardised assessment of concussion and modified balance error scoring system (mBESS). However, these assessments have many limitations, lacking reliability[9], are subject to learning effects[10] and are often not sufficiently challenging for concussed athletes.[11]

One potential solution which has been proposed centres around leveraging laboratory and mobile sensing technology to capture objective data pertaining to sensorimotor performance during a range of challenging balance and gait tasks. For example, Howell et al demonstrated that laboratory based measures of gait stability are correlated with recovery duration post-concussion, highlighted that the timing of return to activity post-concussion was significantly associated with dual-task gait stability.[12] Additionally, early examples of the potential role of mobile sensing technology have highlighted the capacity of inertial sensor obtained measures of gait and balance to differentiate concussed and healthy individuals.[13-15] For example, recent research has demonstrated that the instrumentation of the Y Balance Test (YBT) using a single lumbar mounted inertial sensor can provide a reliable measure of movement control, that is more sensitive to changes in performance than the

traditional scoring method (reach distance).[16, 17] Furthermore, there is emerging evidence that movement control measured using the inertial sensor quantified YBT may be a modifiable risk factor for SRC in rugby union athletes[16] and play a role in post-concussion evaluation[18]. As such, concomitant longitudinal collection of objective data pertaining to movement control (using an inertial sensor) outside of the laboratory setting, during the acute stages post-injury and at the point of full recovery, may allow for the thorough evaluation of the impact of SRC on sensorimotor performance.

The primary aim of this study was to investigate if the inertial sensor instrumented YBT can discriminate pre and post-concussion performance, 24 to 48 hours post-injury, and at the point of returning to full contact training (RTP). A secondary aim was to investigate if SCAT symptom scores, mBESS and YBT performance 24 to 48 hours post-injury were significantly associated with RTP duration. It was hypothesised that the inertial sensor instrumented YBT would capture alterations in movement control during the dynamic balance test 24 to 48 hours post-injury, and this performance would be significantly associated with RTP duration.

Methods

Study Population

A convenience sample of male Elite Rugby Union players and National Collegiate Athletics Association Division 1 (NCAA D1) male American Football players and male/female Ice Hockey players were recruited for this study. The Rugby Union athletes were recruited from a senior Irish provincial Rugby Union team and the Irish National Under-20 squad during 2016/2017 pre-season screening. The NCAA D1 athletes were all recruited from the University of Wisconsin-Madison during the 2018/2019 pre-season screening. Athletes who were aged ≥18 years, registered with the relevant squad and provided written informed consent were eligible to participate. Exclusion criteria were as follows: self-reported vestibular, visual, or balance impairment or any neurological disease which may affect their balance. Ethical approval was sought and obtained from the University College Dublin and University of Wisconsin-Madison Health Sciences research ethics boards for the Rugby Union players and NCAA D1 athletes, respectively. All participants were advised that they had the right to withdraw from the study at any point.

Study Protocol

Baseline Testing Protocol

Recruited participants underwent baseline testing during the relevant 2016/2017 (Rugby Union) and 2018/2019 (NCAA) pre-seasons screening periods. Prior to competing the balance protocol, age, height, weight and leg length data were obtained. As part of the screening protocol, dynamic balance performance was evaluated using the YBT instrumented with a single inertial sensor (Shimmer3, Shimmer, Ireland). The inertial sensor was placed at the level of the 4th lumbar vertebrae, using a custom-made elastic strap secured at the level of the iliac crests in order to closely match the accelerations of the centre of mass during the YBT (Figure 1). The inertial sensor was connected via Bluetooth to an Android tablet (Galaxy Tab 2; Samsung), operating a custom developed mobile application (Supplemental Figure 1) that was designed to facilitate data capture and annotation. The inertial sensor was calibrated and configured to stream tri-axial accelerometer (±2g), gyroscope (±500 deg/sec) and magnetometer (1.9 gauss) data at a frequency of 51.2Hz. The testing protocol and data acquisition parameters were determined based on pilot testing and previous work leveraging inertial sensor data in the quantification of YBT performance.[16, 17] Participants completed four practice to eliminate the training effect and three recorded trials in the three defined directions of the YBT: anterior (ANT), posteromedial (PM) and posterolateral (PL). During the practice trials, the participant was provided with guidance to ensure maximal reach excursions. The YBT testing protocol was designed and completed in compliance with the guidelines laid out by Gribble and colleagues.[19] The YBT scores were obtained by recording the maximal reach distance, while inertial sensor data was recorded for the duration of time the individual was in unilateral stance during the reach excursion. Inertial sensor data was stored locally on the Android tablet, prior to being processed offline using Matlab (2018b, MathWorks).

Figure 1 Here

Follow-up Testing

Throughout the 2016/17 Rugby Union and 2018/19 American Football and Ice Hockey seasons, the incidence of match and training SRC were recorded by the respective teams medical staff, and reported to the lead study investigator (WJ). A clinical diagnosis of the SRC was made by the team physician in compliance with the definition outlined by the International Consensus conference on concussion in sport.[20] In line with this, concussed athletes were evaluated using the multifactorial SCAT3 as part of the assessment process. The symptom score (scored out of 22), symptom severity (scored out of 132) and mBESS (scored out of 30) results were aggregated for the concussed athletes 24 to 48 hours post-injury. Concussed athletes who underwent baseline testing were followed longitudinally and provided with the opportunity to undergo repeat YBT testing at two defined time points: 24 to 48 hours post injury and at the point of RTP. The 24 to 48 hour testing time point was selected to align with the World Rugby[21] and Care Consortium[22] timelines for post-concussion evaluation, allowing for a direct comparison with the components of the SCAT. A convenience sample of healthy rugby union athletes who did not sustain a SRC or lower limb injury during a 6-month follow-up period were re-tested using the YBT protocol during a mid-season screening session. The follow-up YBT testing procedures were identical to the baseline screening protocol, involving four practice trials and three recorded trials.

Signal Processing & Data Analysis

Dynamic balance performance was quantified using the following variables: normalised reach distance, gyroscope magnitude (Gyro Mag) sample entropy (SEn) and jerk magnitude (Jerk Mag) root-mean-squared (RMS). Normalised reach distance was calculated using the following formula:

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

Normalised reach distance quantifies dynamic balance performance by measuring the distance an individual can reach outside of their base of support, while maintaining balance equilibrium. Gyro Mag SEn was computed by first deriving the magnitude of the angular velocity, calculated using the vector magnitude of the gyroscope x, y and z axes. The SEn of the Gyro Mag signal, of length $\boldsymbol{N} = \{\boldsymbol{x_1}, \boldsymbol{x_2}, \boldsymbol{x_3}, \dots, \boldsymbol{x_N}\}$, was then calculated using the following formula:

$$Sample\ Entropy = -\log\left(\frac{A}{B}\right) \quad [2]$$

$\boldsymbol{A}$ was the number of template vector pairs having a Chebyshev distance $\boldsymbol{d}[\boldsymbol{X_{m+1}(i)}, \boldsymbol{X_{m+1}(j)}] < \boldsymbol{r}$ of length $\boldsymbol{m+1}$ and $\boldsymbol{B}$ was the number of template vectors pairs having $\boldsymbol{d}[\boldsymbol{X_m(i)}, \boldsymbol{X_m(j)}] < \boldsymbol{r}$ 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 $\boldsymbol{X_m(i)} = \{\boldsymbol{x_i}, \boldsymbol{x_{i+1}}, \boldsymbol{x_{i+2}}, \dots\dots, \boldsymbol{x_{i+m-1}}\}$. Gyro Mag SEn allows for the quantification of the regularity/irregularity of the angular rotations about the lumbar spine, providing a measure of movement control during the YBT excursions. Entropy based measures are unitless non-linear measures of the complexity of a time-series, frequently used in the analysis of balance data.[16, 23-25] Jerk Mag RMS, was computed by first finding the time-derivative of the three axes of acceleration. The Jerk Mag was then calculated using the vector magnitude of the Jerk x, y and z signals. The RMS of the Jerk Mag signal of length $\boldsymbol{N} = \{\boldsymbol{x_1}, \boldsymbol{x_2}, \boldsymbol{x_3}, \dots, \boldsymbol{x_N}\}$, was computed using the following formula:

$$\text{RMS} = \sqrt{\frac{\mathbf{1}}{\boldsymbol{N}}(\boldsymbol{x_1^2} + \boldsymbol{x_2^2} + \cdots . + \boldsymbol{x_N^2})} \quad [3]$$

Jerk Mag RMS provides a measure of the amplitude of the rate of change in acceleration, affording the capacity to quantify the smoothness of the movement during the YBT reach excursions.[26, 27] The mean of the three recorded trials completed in each reach direction were obtained for each variable (normalised reach distance; Gyro Mag SEn; Jerk Mag RMS), to ensure measurement reliability. The inter-session test-retest reliability of these variables collected using this protocol has previously been investigated, with the normalised reach distance possessing moderate to excellent reliability (ICC = 0.72 to 0.92; standard error of measurement = 1.52% to 3.94%; minimal detectable change = 4.21% to 10.92%), Gyro Mag SEn possessing moderate reliability (ICC = 0.66 to 0.69; standard error of measurement = 0.12 to 0.17; minimal detectable change = 0.32 to 0.48) and Jerk Mag RMS demonstrating moderate to excellent reliability (ICC = 0.70 to 0.85; standard error of measurement = 0.02 m/s^3 to 0.03 m/s^3; minimal detectable change = 0.06 m/s^3 to 0.08 m/s^3).[28]

Statistical Analysis

Demographic data were summarised using means and standard deviations (SD) for scale variables and frequencies and percentages for nominal variables. The effect of player group (pre-season

baselined, concussed and healthy control) on demographic data (age, height, weight and leg length) was investigated using one-way analysis of variance (ANOVA) to determine how representative the concussion and control group are of the wider cohort. Repeated measures ANOVA and partial eta squared effect sizes (η^2) were used to investigate the effect of testing time-point on dynamic balance performance in the concussed athletes for the independent variables of normalised reach distance, Jerk Mag RMS and Gyro Mag SEn. Where a significant effect was present, post-hoc Bonferroni comparisons were used to investigate the effect of concussion on balance performance. Cohens D effect sizes were calculated to quantify the magnitude of the effect of concussion on dynamic balance performance. As only two time points were available for analysis in the uninjured control group, paired t-tests were used to determine if there was a statistically significant difference in balance performance between the pre-season baseline and six-month follow-up assessments. The *a-priori* level of significance was set to $P < 0.017$, to reduce the potential for the occurrence of type I errors. Spearman's Rank order correlations were used to investigate the correlation between the number of days to RTP and the SCAT symptoms score, symptom severity, mBESS errors and the dynamic balance variables collected at the 24 to 48 hours testing point. Variables which were statistically significantly correlated with RTP duration were included in linear regression models as independent variables to investigate the association between them and RTP duration (dependent variable). Statistical analysis was conducted using SPSS (v24, IBM).

Results

Two-hundred and twenty-six athletes participated, including male Rugby Union players (n = 80), National Collegiate Athletics Association Division 1 (NCAA D1) male American Football players (n = 97) and Ice Hockey players (n = 25 male; n = 24 female). Of the 226 athletes, 21 went on to sustain a concussion during the season. Of these, seventeen concussed athletes consented to YBT testing at both the 24 to 48-hours post-concussion and RTP testing points; thus, having a full data set available for analysis. Twenty rugby union athletes who did not sustain any injury during the follow-up period were re-tested six-months following the baseline testing, to form a convenience sample of uninjured

athletes. Figure 2 presents a flow diagram of the cohort demographic breakdown and the follow-up testing.

Figure 2 Here

One-way ANOVA analysis comparing the demographic and anthropometric data of the three groups is presented in table 1. Post-hoc comparisons demonstrated that the control group were significantly older (mean difference [MD] = 6.02 years; $P < 0.001$) than the concussed group and the athletes tested in the pre-season baseline (MD = 5.7 years; $P < 0.001$); however, there was no significant difference between the concussion group and the athletes tested during the pre-season (MD = 0.35 years; $P = 0.42$).

Table 1 Here

Of the 17 athletes, eight were tested 24 hours post-injury, while nine were tested 48 hours post-injury. The median (interquartile range [IR]) of the 24 to 48-hour SCAT3 components were as follows: number of symptom: median 8 (IR 6 to 15.5), symptom severity: median 18 (IR 6 to 36) and mBESS errors: median 4 errors (IR 1 to 7.75). The median (IR) RTP duration of the 17 athletes was 15 days (IR 11 to 21).

Repeated measures ANOVA demonstrated a statistically significant main effect of testing time point on YBT normalised reach distance for the ANT ($F = 6.44$; $P = 0.004$; $\eta^2 = 0.29$), PM ($F = 14.65$; $P < 0.001$; $\eta^2 = 0.48$) and PL ANT ($F = 11.80$; $P < 0.001$; $\eta^2 = 0.42$) directions. There was a statistically significant main effect of testing time point on YBT Jerk Mag RMS for the ANT ($F = 7.93$; $P = 0.002$; $\eta^2 = 0.33$) and PM ($F = 11.88$; $P < 0.001$; $\eta^2 = 0.43$) reach directions, but not the PL ANT ($F = 3.59$; $P < 0.039$; $\eta^2 = 0.18$) direction. There was no statistically significant main effect of time on Gyro Mag SEn for the ANT ($F = 1.47$; $P = 0.244$; $\eta^2 = 0.08$), PM ($F = 0.25$; $P = 0.778$; $\eta^2 = 0.02$) and PL ($F = 1.56$; $P = 0.227$; $\eta^2 = 0.09$) directions. Post-hoc comparisons highlighted that on average, athletes demonstrated a reduction in normalised reach distance 24 to 48-hours post-concussion, which reached the *a priori* ($P < 0.017$) level of significance for the ANT (MD = -3.36%; 95% CI = -5.99 to -0.73; $P = 0.015$), PM (MD = -7.75%; 95% CI = -11.20 to -4.30; $P < 0.001$) and PL (MD = -7.56%; 95% CI = -11.54 to -3.58; $P < 0.001$) reach directions. The concussed athletes demonstrated a reduction in Jerk Mag RMS 24 to 48-hours post-concussion, which reached the *a priori* ($P < 0.017$) level of significance

for the ANT (MD = -0.08m/s^3; 95% CI = -0.11 to -0.04; $P < 0.001$), PM (MD = -0.06 m/s^3; 95% CI = -0.10 to -0.04; $P = 0.015$) reach directions, but not the PL reach direction (MD = -0.03 m/s^3; 95% CI = -0.06 to -0.01; $P = 0.021$). There was no statistically significant difference between the baseline and RTP testing points for the normalised reach distance, Jerk Mag RMS and Gyro Mag SEn variables, across all three reach directions. Paired t-test analysis demonstrated that there was no statistically significant change in Jerk Mag RMS or normalised reach distance between the baseline and six month follow-up testing for the un-injured control group. The post-hoc (concussed group) and paired t-test (uninjured control group) analyses comparing performance across the different time points are presented in table 2. Figure 3 illustrates the changes in dynamic balance performance for both the concussed and un-injured cohorts.

Figure 3 Here

Table 2 Here

There was a statistically significant moderate negative correlation between the 24 to 48-hour Jerk Mag RMS and RTP duration across all three reach directions (ρ = -0.55 to -0.72; P < 0.017). There was no significant correlation between the RTP duration and normalised reach distance (ρ = -0.02 to 0.22; P > 0.017) or Gyro Mag SEn (ρ = -0.06 to 0.12; P > 0.017). There was no significant correlation between RTP duration and number of SCAT symptoms (ρ = 0.05: ; P > 0.017), SCAT symptom severity (ρ = 0.08; P > 0.017) or total mBESS errors (ρ = -0.40; P > 0.017) 24 to 48-hours post injury (supplemental table 1).

Linear regression models were used to investigating the association between RTP duration and the variables that were significantly correlated with RTP duration. Due to the non-normal distribution of the RTP duration data, the natural log of the RTP duration (LN RTP Duration) was used within these models. There was a statistically significant linear association between Jerk Mag RMS and LN RTP Duration for the ANT and PM, but not the PL reach direction (Table 3).

Table 3 Here

Discussion

The findings presented in this paper suggest that the concussed athletes were not able to reach as far outside of their base of support and completed this reach with a more constrained movement pattern (lower Jerk Mag RMS), 24 to 48-hours post-injury, when compared to their previous healthy pre-season baseline measurement. On average, these changes in performance had returned to baseline levels at the point of RTP. Importantly, the scores for Jerk Mag RMS in the ANT and PM directions 24 to 48 hours post-concussion exceeded previously published minimal detectable change (MDC) values. Conversely, the PL Jerk Mag RMS and all three directions for the normalised reach distance did not exceed the MDC 24 to 48 hours post-concussion. There was no statistically significant difference in dynamic balance performance between the baseline and 6-month follow-up in the 20 uninjured control athletes (Table 2). Furthermore, the mean differences for the control group did not exceed the MDC thresholds, signifying that the change in the healthy individuals performance was not greater than the margin of error. It is possible that the uninjured control athletes 6-month follow-up performance may have been influenced by the long-term effects of routine training and/or sub-concussive impacts. However, it was seen that the uninjured controls performance did not significantly change over the course of the season, suggesting no significant impact of the demands of the sporting season. To further strengthen these findings, future research should compare longitudinal changes in performance across sports (contact and non-contact), to investigate the potential effect of aspects such as routine training and sub-concussive impacts on sensorimotor performance. Figure 3 illustrates the changes in performance over time, across the two cohorts.

The theories of movement variability previously outlined by Stergiou and Decker[29] help to explain these findings. Based on this theory, it may be hypothesised that the concussive injury resulted in the acute adoption of a smoother or more ‘constrained’ movement strategy (lower Jerk Mag RMS) during the YBT reach excursions, resulting in a reduction in an athletes capacity to freely reach outside of their base of support during the challenging dynamic task. However, these changes in performance had returned to baseline levels at the point of RTP. Conversely, the present study demonstrated that the non-linear Gyro Mag SEn variable captured during the YBT was not significantly influenced by

concussion. This is in contrast to the findings presented by Cavanaugh et al[25], who reported that the non-linear force platform measures obtained during the sensory organisation test demonstrate that concussed athletes have more regular movement control 24 to 48-hours post-concussion, when compared to their baseline. When viewed in conjunction with the presented study, it is clear that while the entropy based measure of performance was more sensitive to the effects of concussion during the sensory organisation test[25], the Jerk Mag RMS variable was capable of capturing changes in YBT performance that were not reflected by the non-linear Gyro Mag SEn variable.

A secondary aim of the study was to explore the relationship between the measures of dynamic balance performance and the length of time required for individuals to RTP. The correlation analysis presented in supplemental table 1 demonstrated that there was a statistically significant moderate inverse correlation between the 24 to 48-hour Jerk Mag RMS variable and the number of days taken to RTP. Conversely, neither GM SEn, normalised reach distance, mBESS errors or symptoms were significantly correlated with the length of time to RTP. Further linear regression modelling demonstrated that Jerk Mag RMS accounts for 33% (ANT), 27% (PM) and 22% (PL) of the variance in the RTP duration (Table 3). These findings highlight that while the traditional clinical outcomes of interest (normalised reach distance, mBESS errors, SCAT3 symptoms) demonstrated a trivial relationship with RTP duration, the inertial-sensor derived measure of movement control (Jerk Mag RMS) was significantly associated with an increased time to RTP. This suggests that those athletes with a more constrained movement control (lower Jerk Mag RMS) 24 to 48-hours post-injury were more likely to have a longer time until RTP than those with a less constrained movement strategy (higher Jerk Mag RMS). These results indicate that while the traditional normalised reach distance and inertial sensor derived Jerk Mag RMS both demonstrated acute changes 24 to 48-hours post-concussion, the inertial sensor-based measure of movement control may have additional prognostic value.

The findings of this analysis are consistent with those of previously published research carried out by Howell and colleagues[12] who demonstrated that measures of gait stability obtained at the point of RTP were correlated with RTP duration. While Howell et al[12] investigated the relationship between RTP and gait stability retrospectively, the findings reflect the results presented in this prospective study, highlighting that movement control during a dynamic task is sensitive to the timing of RTP. While the

mechanism underlying this relationship is unknown, it is possible that the individuals who present with more severe dynamic balance deficits may in turn require a longer period to progress through the RTP process. Previous research investigating predictors for symptom resolution in sports related concussion (N = 568 participants) reported that female sex, a higher positive symptom total and cervicogenic and/or vestibulo-ocular predominant symptom cluster increased the odds of an individual having prolonged symptom resolution (> 14 days)[30]. Interestingly, McGeown et al highlighted that athletes who presented with a vestibulo-ocular predominant symptom cluster may have an increased likelihood of having a prolonged recovery[30]. This may in part help explain these observations, highlighting that poorer balance performance was associated with an increased time to RTP. It is important to note that the results presented within this paper do not suggest that the instrumented YBT should replace assessments such as the mBESS. Further, it is likely that accurate prediction of clinical outcome will not be possible using a single measure alone. Rather, they should be incorporated as part of wider objective multi-factorial and multi-time-point assessment batteries, designed to more thoroughly monitor athletes as they move from diagnosis to recovery, and beyond. To achieve this, further large scale high quality research focusing on modelling the predictors of concussion recovery using multi-factorial batteries of objective measures, specifically tailored to the relevant time-points in the recovery process, is required.

While this study is exploratory in nature, the results have implications for sports medicine and rehabilitation clinical practice. The findings suggest that alterations in dynamic balance performance manifest as a more constrained movement strategy, limiting one's capacity to reach outside of their base of support, when compared to pre-injury. Furthermore, these acute alterations in movement control captured using the inertial-sensor are linearly associated with an increased time to RTP. The importance of these findings are highlighted by the recent emerging evidence which suggests that history of concussion is associated with an increased risk of sustaining musculoskeletal injuries[5] and/or further concussion[31] in young athletes. Furthermore, there is a growing body of evidence which demonstrates that poor sensorimotor control is associated with a higher relative risk of anterior cruciate ligament injuries,[32] as well as SRC.[16] As such, the quantification of an athlete's movement control during the YBT, using a single cheap and accessible wearable sensor, coupled with current multifactorial clinical assessment batteries and other mobile computing solutions, may facilitate improved injury assessment,

prognostication and recovery tracking, beyond what is capable using traditional analogue clinical tests. Such tools may be incorporated into a wider technology supported paradigm of assessments, designed to objectively evaluate aspects of sensorimotor and neurocognitive function using cheap and ubiquitous mobile and wearable sensing technology.[33] This approach may help clinicians and researchers identify those who might benefit from additional targeted interventions, with the view to improving the concussion recovery process.

Despite the strengths of this prospective observational cohort study, there are several limitations which should be acknowledged. Firstly, the cohort of concussed athletes recruited within this study is relatively small. However, a notable strength of this research is the prospective longitudinal design and the recruitment of an uninjured control group facilitating a paired pre and post-injury analysis in healthy and injured athletes. Additionally, the median RTP time for the concussed athletes was 15 days, similar to that observed in previously published NCAA data (12 days).[4] As such, despite the small sample, it is likely that the concussed athletes recovery is representative of those typically seen within the sporting context. Furthermore, aside from age, there was no difference in the demographic or anthropometric characteristics of the concussion group when compared to the wider cohort tested at baseline or the control Rugby Union athletes. Secondly, the control group, consisting of Irish Rugby Union players, was selected as a sample of convenience and not matched to the injured cohort. Further research should leverage a study design which uses a prospective matched case-control design. Thirdly, the presented study only captured YBT performance at three time points: baseline, 24 to 48 hours post injury and the point of RTP. Further research should investigate the role the inertial sensor instrumented YBT may play in evaluating balance performance at multiple time-points throughout the RTP process, comparing it to standard clinical assessments such as the mBESS. However, researchers should acknowledge the increased burden this may place on research participants and medical staff. Fourthly, the cohort consisted primarily of male athletes, with only one concussed female athlete, limiting the generalisability of the findings. Therefore, further research investigating the utility of approach within the concussion context should include a more representative sample of both male and female athletes, across a range of sports.

Conclusion

This prospective cohort study demonstrates that athletes possess alterations in both traditional measures of dynamic balance and inertial sensor-based measures of movement control, 24 to 48-hours post-concussion. However, these alterations in performance typically return to pre-injury levels by the point of return to full contact training. Furthermore, the inertial sensor-based measures of dynamic movement control captured 24 to 48-hours post injury were significantly associated with the length of time to RTP. This suggests that athletes with a lower Jerk Mag RMS (smoother or more constrained movement control strategy) during the YBT reach excursions were more likely to have a longer time until RTP. As such, the exploratory research presented within this paper suggests that inertial sensor technology may have value in the longitudinal evaluation of athletes post-concussion, potentially aiding in injury prognostication and targeted intervention delivery.

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Author disclosure statement

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Table 1: One-way ANOVA comparing the demographic and anthropometric data across the group.

The Pre-season Baseline cohort consists of all athletes tested at baseline, excluding the healthy control (n = 20)

Variable	Cohort	Mean	SD	F	P Value
Left Leg Length (cm)	**Control Group**	98.3	5.2		
	Concussed Group	98.1	5.1	0.12	0.89
	Pre-season Baseline	98.7	6.1		
Right Leg Length (cm)	**Control Group**	98.3	5.3		
	Concussed Group	98.3	5.0	0.11	0.90
	Pre-season Baseline	98.8	6.1		
Height (cm)	**Control Group**	185.7	6.2		
	Concussed Group	184.6	7.2	0.58	0.56
	Pre-season Baseline	183.7	8.4		
Weight (kg)	**Control Group**	102.6	12.4		
	Concussed Group	97.6	18.9	0.84	0.43
	Pre-season Baseline	96.5	20.7		
Age (years)	**Control Group**	25.7	3.9		
	Concussed Group	19.6	1.2	97.92	**<0.001**
	Pre-season Baseline	20.0	1.4		

and injured concussion (n = 17) groups. A priori level of significance set to $P < 0.017$ and is denoted in **bold with an *.**

Table 2: Pairwise comparisons of the testing time points for the concussed (n = 17) and un-injured control groups (n = 20).

Cohort	Variable	Direction	Baseline Vs…	Mean Difference	95% Confidence Interval for the Difference		P value	Cohen's D
					Lower Bound	Upper Bound		
(A) Concussed Group (n = 17)	**Normalised Reach (%)**	**Anterior**	**24-48 hours**	-3.36	-5.99	-0.73	**0.015***	0.66
			RTP	0.06	-2.26	2.38	0.956	0.01
		Posteromedial	**24-48 hours**	-7.75	-11.20	-4.30	**<0.001***	1.16
			RTP	-1.05	-4.33	2.23	0.507	0.17
		Posterolateral	**24-48 hours**	-7.56	-11.54	-3.58	**<0.001***	0.98
			RTP	-0.92	-4.01	2.17	0.536	0.16
	Jerk Mag RMS (m/s^3)	**Anterior**	**24-48 hours**	-0.08	-0.11	-0.04	**<0.001***	1.14
			RTP	-0.01	-0.06	0.04	0.654	0.12
		Posteromedial	**24-48 hours**	-0.06	-0.10	-0.03	**0.001***	1.02
			RTP	-0.01	-0.04	0.02	0.465	0.19
		Posterolateral	**24-48 hours**	-0.03	-0.06	-0.01	0.021	0.57
			RTP	-0.01	-0.04	0.02	0.534	0.18
(B) Uninjured Group (n = 20)	**Normalised Reach (%)**	**Anterior**	**6-month**	-0.10	-0.95	0.75	0.81	0.06
		Posteromedial	**6-month**	0.69	-1.18	2.58	0.45	0.18
		Posterolateral	**6-month**	-0.33	-2.35	1.68	0.73	0.08
	Jerk Mag RMS (m/s^3)	**Anterior**	**6-month**	0.01	-0.01	0.03	0.46	0.17
		Posteromedial	**6-month**	0.02	0.001	0.04	0.04	0.49
		Posterolateral	**6-month**	0.02	0.002	0.04	0.03	0.51

(A) Post-hoc comparison investigating the effect of concussion on YBT performance (Baseline vs 24 to 48-hours and return to contact training [RTP]). (B) Paired t-test analysis comparing performance at the two testing points for the healthy control group (baseline vs 6-months). The a-priori significance was set to $p < 0.017$ and is denoted in **bold with an *.**

Table 3: Linear regression models investigating the association between Return to play duration and Jerk Mag RMS. Statistically significant associations are marked in **bold with an ***.

Dependent variable is the natural log of the return to play duration.

Direction	Model	Independent Variable	Unstandardized Coefficients	95% Confidence Interval		Standardized Coefficients	R^2	P Value
			B	Lower Bound	Upper Bound	Beta		
Anterior	**1**	**Constant**	3.68	2.99	4.37		0.33	<0.001
		Jerk Mag RMS	-4.21	-7.22	-1.20	-0.61		**0.009***
Posteromedial	**2**	**Constant**	3.62	2.80	4.44		0.27	<0.001
		Jerk Mag RMS	-4.44	-8.50	-0.37	-0.52		**0.035***
Posterolateral	**3**	**Constant**	3.32	2.71	3.94		0.23	<0.001
		Jerk Mag RMS	-2.70	-5.42	0.02	-0.48		0.051

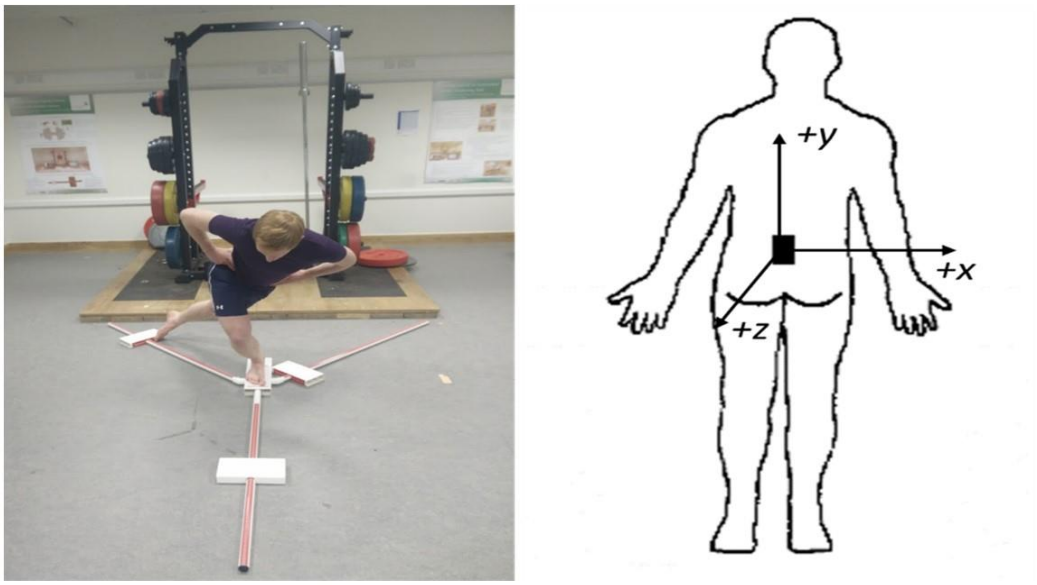


Figure 1: Presents an individual reaching in the posterolateral direction of the y balance test, and the inertial sensor mounting location and associated sensor axes orientation.

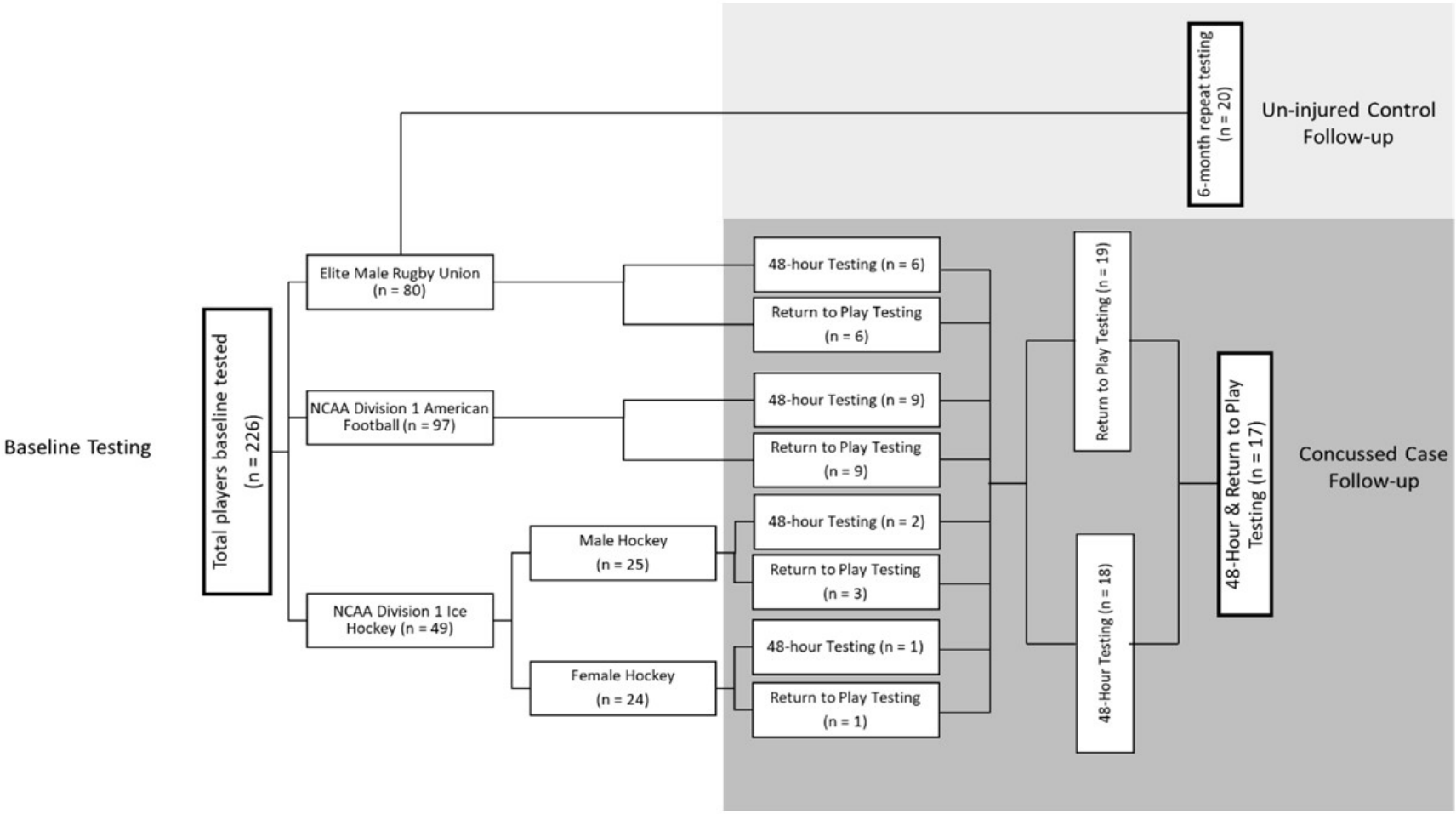


Figure 2: Flow diagram of the follow-up of the concussed athletes.

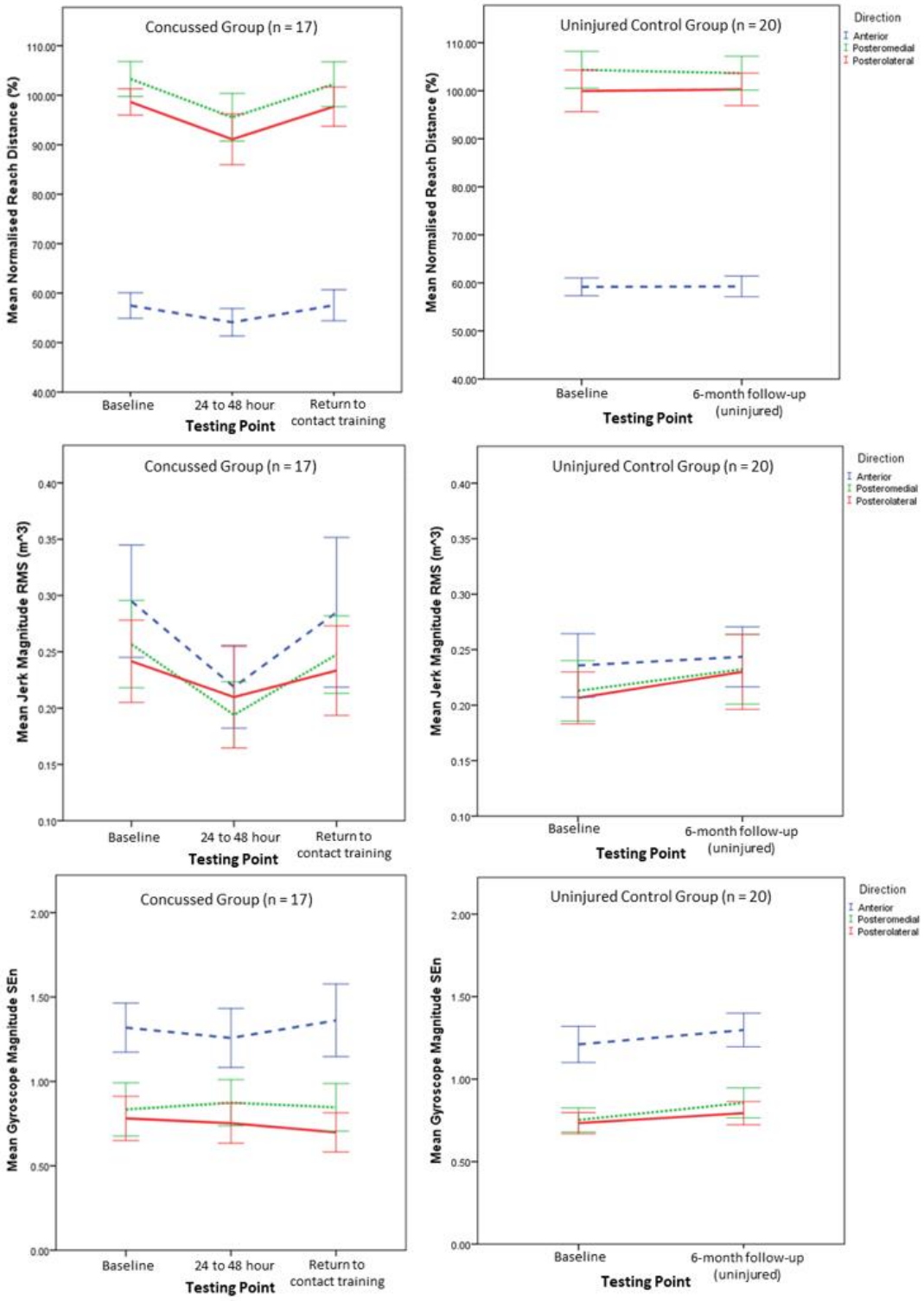
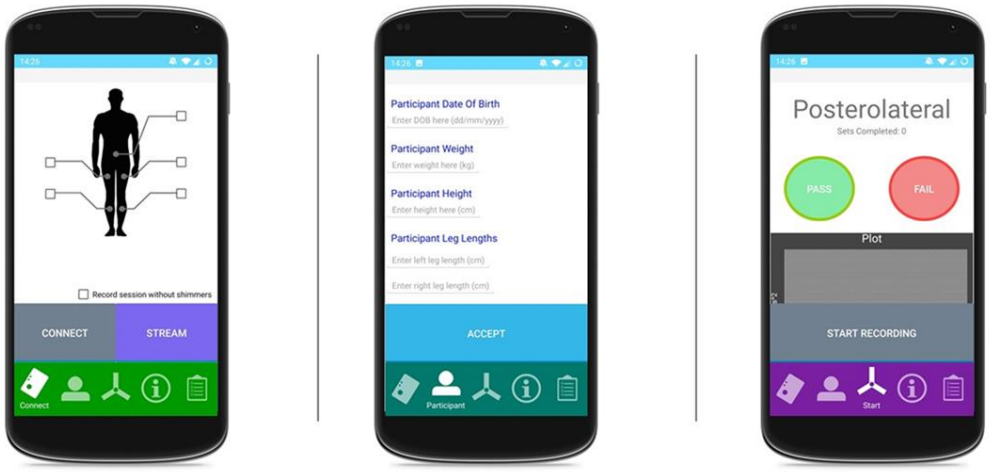


Figure 3: Dynamic balance performance across the different testing time points and balance variables across the concussed cohort (n = 17) and un-injured control group (n = 20). Error bars represent the 95% confidence intervals.

Supplemental Digital Data



A) Sensor connection

B) Participant demographic information

C) Y Balance Test protocol page

Supplemental Figure 1: The mobile application used within this study. (A) connection and streaming of inertial sensor data; (B) aggregation of participant demographic information; (C) implementation of the inertial sensor instrumented Y Balance Test protocol.

Supplemental Digital Data

Supplemental Table 1: Spearman rank order correlation between the outcomes of interest 24 to 48-hours post injury, and the length of time to return to full contact training.

	Outcome Measure	Spearman Rank Order Correlation	P Value
Anterior	**Normalised Reach**	0.22	0.408
	Gyro Mag SEn	0.12	0.650
	Jerk Mag RMS	-0.72	**0.001***
Posteromedial	**Normalised Reach**	-0.02	0.928
	Gyro Mag SEn	0.01	0.973
	Jerk Mag RMS	-0.55	**0.022***
Posterolateral	**Normalised Reach**	-0.06	0.812
	Gyro Mag SEn	-0.06	0.834
	Jerk Mag RMS	-0.61*	**0.009***
SCAT3 Components	**mBESS ¥**	-0.40	0.136
	Number of Symptom	0.05	0.844
	Symptom Severity	0.08	0.753

¥ One participant did not complete the mBESS <48-hours post-injury. Therefore n = 16 were used in the analysis.

Statistically significant correlations are marked in **bold with an *.**