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Athletes with a concussion history in the last two years have impairments in dynamic balance performance

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Running Header: Concussion related balance impairments.

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ABSTRACT

The purpose of this study was to determine if National Collegiate Athletics Association Division 1 American Football and Ice Hockey athletes with a history of concussion have impaired dynamic balance control when compared to healthy control athletes. This cross-sectional observational study recruited 146 athletes; 90 control athletes and 56 athletes with a history of concussion. Athletes were tested during a pre-season evaluation using the inertial-sensor instrumented Y Balance Test. Independent variables were normalised reach distance, gyroscope magnitude sample entropy and jerk magnitude root-mean-square. Kruskal-Wallis H test and Dunn-Bonferroni analysis demonstrated that individuals with a concussion history within the last two years have statistically significantly lower jerk magnitude root-mean-square in the posteromedial ($Z = 23.22$, $P = 0.015$) and posterolateral ($Z = 24.64$, $P = 0.010$) reach directions, when compared to the control group. There was no significant difference between those who sustained a concussion longer than two years ago and the control group for the posteromedial ($Z = -1.25$; $P = 0.889$) and posterolateral ($Z = 6.44$; $P = 0.469$) directions. These findings show that athletes with a concussion history within the last two years possess dynamic balance deficits, when compared to healthy control athletes. Conversely, athletes whose injury occurred greater than two years ago possessed comparable performance to the healthy controls. This suggests that sensorimotor control deficits may persist beyond clinical recovery, for up to two years. Therefore, clinicians should integrate balance training interventions into the return-to-play process to accelerate sensorimotor recovery and mitigate the risk of future injury.

KEYWORDS

Mild traumatic brain injury, physiotherapy, rehabilitation, digital health, wearable sensor, balance, postural control.

INTRODUCTION

The current consensus on sports related concussion assessment focuses on the use of a multifactorial assessment battery called the Sports Concussion Assessment Tool (SCAT).[1] The SCAT includes the evaluation of symptomatology, neurocognitive function and static balance, with these markers typically demonstrating 'recovery' within seven days of injury in over 85% of concussed collegiate athletes.[2]

Despite this symptom resolution trajectory, there is a growing body of evidence suggesting that the consequences of concussion may extend beyond this 'clinical recovery'. Specifically, athletes with a history of a concussive injury have an increased risk of sustaining future concussive[3] and/or lower-limb musculoskeletal injuries.[4] While the underlying mechanism behind this relationship has yet to be fully uncovered, it has been suggested that the association may be related to the presence of subtle sub-clinical sensorimotor and neurocognitive deficits which persist beyond the resolution of the traditional signs and symptoms of concussion.[5] These concerns are beginning to be substantiated, with research demonstrating that sensorimotor control deficits post clinical recovery from concussion may be more pronounced during dynamic balance[6] and dual-task situations.[7] Furthermore, research has demonstrated that laboratory based kinetic and kinematic evaluation during gait and balance tasks can detect deficits in those with a history of concussion, when compared to healthy controls.[8,9] As such, the objective and quantifiable evaluation of movement control during dynamic tasks may provide a means to sufficiently challenge the sensorimotor system in individuals who have sustained a concussion, uncovering persistent sub-clinical performance deficits which may increase an individual's risk of injury.

The Y Balance Test (YBT) is a valid and reliable means to evaluate dynamic balance capacity in athletes, by measuring the distance which they can reach outside of their base of support.[10] While it provides a measure of dynamic balance performance, the current scoring approach fails to objectively quantify an individuals' control of movement during the dynamic task; restricting its capabilities of capturing subtle alterations in sensorimotor function. As such, clinicians must rely on subjective visual observations of movement control which have reduced validity and reliability.[11] One pragmatic solution to this problem involves leveraging cheap and accessible inertial sensor technology (typically less than €250) in the quantification of movement control during balance tasks.[12] This approach can address many of the limitations of expensive and inaccessible laboratory based methods, improving the efficacy of assessments within the clinical environment.[5] For example, recent research has shown that a single lumbar-worn inertial sensor can provide a valid and reliable measure of dynamic movement control during the YBT.[13,14] Early investigations of this approach within the clinical context have shown that it may have value in identifying athletes at a three-times higher relative risk of sustaining a concussion,[15] as well as identifying post-concussion deficits.[6] Therefore, the inertial sensor instrumentation of the YBT may allow for the accessible and objective quantification of sensorimotor performance outside of the laboratory environment, helping to identify individuals who may be at an increased risk of future injury.

The primary aim of this study was to investigate if a single inertial sensor, similar to those embedded within smart phones, can capture differences in dynamic balance performance in National Collegiate Athletics Association division 1 (NCAA D1) athletes with and without a history of concussion. As sports related concussion has previously been shown to result in the adoption of a more constrained and predictable movement control strategy,[6,16,17] in the present study, it is hypothesised that the concussive injury would result in the adoption of a more constrained and predictable movement strategy during the YBT reach excursions. Additionally, while research has demonstrated that athletes may be at risk of sustaining future musculoskeletal injury for up to two years following a sports related concussion[4], little attention has been paid to the effect of time since injury on these persistent sub-clinical deficits. As such, the secondary aim was to investigate if athletes with no history of concussion, those who sustained an injury within the last two years, and those who sustained an injury greater than two years ago possess differences in dynamic balance performance. It was hypothesised that athletes with a history of concussion within the last two years would demonstrate poorer dynamic balance performance than healthy control athletes and those who sustained an injury greater than two years ago.

METHODS

Participants

A convenience sample of NCAA D1 male American Football and male and female Ice Hockey athletes were recruited for this study. The athletes were recruited from the University of Wisconsin-Madison during the 2018/2019 pre-season screening period. Athletes were eligible to take part in this study if they were aged ≥18 years, registered with the relevant squad and provided informed consent. Athletes who self-reported any vestibular, visual, or balance impairment or any neurological disease which may affect their balance were excluded from participation in this study. Ethical approval was sought and obtained from the University of Wisconsin-Madison's Health Sciences research ethics board. All participants rights were protected and were advised that they had the right to withdraw from the study at any point.

Study Protocol

Dynamic Balance Testing

Athletes who were eligible for participation in this study underwent baseline evaluation during the 2018/2019 pre-season screening period. Participants sex, age, height, weight and leg length were obtained. Dynamic balance performance was evaluated using the YBT, instrumented using a single lumbar worn inertial sensor. The inertial sensor was mounted at the level of the fourth lumbar vertebra, in line with the top of the iliac crests, to allow for repeatable placement of the sensor, and to closely match estimates of the body's centre of mass, reported to lie in the region of L3-L5.[18,19] The inertial sensor was calibrated and configured to stream tri-axial accelerometery (±2 g), gyroscope (±500 deg/sec) and magnetometer (1.9 gauss) data at a frequency of 51.2 Hz. The intra-session reliability and inter-session reliability of the data acquisition parameters and sensor mounting location have been previously published.[14,15] Furthermore, recent research has demonstrated the discriminant validity of the inertial sensor based approach,[13,20] as well as highlighted the capacity of the assessment to capture balance deficits with are associated with an increased risk of concussion in rugby union players.[15] It has previously been reported that investigating the discriminant capabilities of inertial sensor based variables may be the most appropriate method for validation of these tools.[21] In line with the YBT guidelines, individuals completed four practice trials followed by three recorded trials in the three defined directions: anterior (ANT), posteromedial (PM) and posterolateral (PL) to eliminate the training effect associated with YBT completion.[22] During the three recorded YBT trials, performance was scored by recording the maximal distance an individual could reach outside of their base of support, while the inertial sensor data was recorded for the duration the individuals were in unilateral stance.

Injury History Data

A record review of athletes who underwent baseline testing was conducted to extract information pertaining to concussion injury history. Concussion was defined in line with International Consensus Conference on Concussion in Sport.[23] The date of each previous concussion was obtained and the length of time (days) since the last concussive injury and the baseline evaluation was computed. Concussions which occurred prior to the athletes entering collegiate medical care (i.e. high school injuries) were self-reported, while injuries which occurred since entering collegiate medical care could be confirmed with clinical data. The YBT evaluators were blinded to previous concussion injury history status during the baseline evaluation.

Signal Processing and Data Analysis

Dynamic balance performance was quantified during the YBT using normalised reach distance, gyroscope magnitude sample entropy (Gyro SEn) and jerk magnitude root mean squared (Jerk RMS). Normalised reach distance was computed by representing the maximal reach distance as a percentage of the individuals leg length. Normalised reach distance allows for the quantification of dynamic balance performance by measuring the distance an individual can reach outside of their base of support, without losing their balance. Gyro SEn was computed by calculating the vector magnitude of the three gyroscope axes. The SEn of the gyroscope magnitude signal, of length $\boldsymbol{N} = \{\boldsymbol{x_1}, \boldsymbol{x_2}, \boldsymbol{x_3}, \ldots, \boldsymbol{x_N}\}$, was then calculated using the following formula:

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

A was the number of template vector pairs having a Chebyshev distance $\boldsymbol{d}[\boldsymbol{X}_{\boldsymbol{m}+\boldsymbol{1}}(\boldsymbol{i}), \boldsymbol{X}_{\boldsymbol{m}+\boldsymbol{1}}(\boldsymbol{j})] < \boldsymbol{r}$ of length ***m+1*** and ***B*** was the number of template vectors pairs having $\boldsymbol{d}[\boldsymbol{X}_{\boldsymbol{m}}(\boldsymbol{i}), \boldsymbol{X}_{\boldsymbol{m}}(\boldsymbol{j})] < \boldsymbol{r}$ of length ***m***, where the embedding dimension, ***m***, was equal to 2 and the tolerance, ***r,*** was equal to 0.1. The template vectors were defined such that $\boldsymbol{X}_{\boldsymbol{m}}(\boldsymbol{i}) = \{\boldsymbol{x}_{\boldsymbol{i}}, \boldsymbol{x}_{\boldsymbol{i}+\boldsymbol{1}}, \boldsymbol{x}_{\boldsymbol{i}+\boldsymbol{2}}, \ldots\ldots, \boldsymbol{x}_{\boldsymbol{i}+\boldsymbol{m}-\boldsymbol{1}}\}$. Gyro SEn provides a means to quantify the regularity/irregularity of the rotational velocity about the lumbar spine during the YBT excursions, allowing for the measurement of complexity of the dynamic movement control. Entropy measures are unitless non-linear measures of the regularity or complexity of a time-series, commonly used in the analysis of movement data.[15-17,24] Jerk, the rate of change of acceleration, was computed by finding the time-derivative of the three axes of acceleration. The jerk magnitude was then calculated using the vector magnitude of the jerk x, y and z signals. The RMS of the jerk magnitude signal of length $\boldsymbol{N} = \{\boldsymbol{x}_{\boldsymbol{1}}, \boldsymbol{x}_{\boldsymbol{2}}, \boldsymbol{x}_{\boldsymbol{3}}, \ldots, \boldsymbol{x}_{\boldsymbol{N}}\}$ was computed using the following formula:

$$\text{RMS} = \sqrt{\frac{\boldsymbol{1}}{\boldsymbol{N}}(\boldsymbol{x}_{\boldsymbol{1}}^{\boldsymbol{2}} + \boldsymbol{x}_{\boldsymbol{2}}^{\boldsymbol{2}} + \ldots. + \boldsymbol{x}_{\boldsymbol{N}}^{\boldsymbol{2}})}$$

Jerk RMS is a measure of the amplitude of the rate of change in acceleration, allowing for the measurement of the 'constraint' of movement during the YBT reach excursions by quantifying the smoothness of the movement. [25,26] The mean of the three maximal reach attempts in each reach direction were obtained for each variable (normalised reach distance; Gyro SEn; Jerk RMS), to ensure measurement reliability. The signal processing and data analysis was conducted using MATLAB (2018b, MathWorks, Natwick).

Statistical Methods

Demographic data was summarised using means and standard deviations (SD) for scale variables, and frequencies and percentages for nominal variables. Shapiro-Wilk tests and histograms demonstrated the non-normal distribution of the data. The difference between individuals with and without a history of concussion were evaluated using inferential statistics Mann-Whitney U Tests and eta^2 effect sizes. The *a-priori* level of statistical significance for the hypothesis testing was set to $P < 0.05$. The cohort was then stratified into three groups: (1) no history of concussion; (2) history of concussion within the last two years; (3) history of concussion greater than two years ago. The difference between the three groups was investigated using Kruskal-Wallis H tests and associated Dunn-Bonferroni post-hoc comparisons. The *a-priori* level of significance was set to $P < 0.017$ for the post-hoc analysis to account for multiple comparisons, using a Bonferroni adjustment. Statistical analysis was conducted using SPSS (IBM, Version 24). Violin plots were generated using the *seaborn.violinplot* function in Python (v3.8).

RESULTS

One hundred and forty-six NCAA D1 athletes, consisting of 97 male American Football and 49 Ice hockey players (n = 25 male; n = 24 female) were recruited as part of this study. One Ice Hockey athlete had missing data related to the date of the last concussion. Of the 145 athletes with full datasets, 38% (55/145) had a history of a previous concussion, with a median time since the last injury of 900 days (range 81 to 3,853 days). Seventeen percent (25/145) of the athletes sustained their most recent concussion within the last two years (median 294 days; range 81 to 717), while 21% (30/145) of athletes sustained their last concussion longer than two years ago (median 1,306 days; range 820 to 3,853). Of the 25 athletes who sustained a concussion within the last two years, 19 had a history of one concussion, while six athletes had a history of > 2 concussions. Additionally, of the thirty athletes who sustained a concussion greater than two years ago, 26 had a history of one concussion, while four athletes had a history of > 2 concussions. Descriptive statistics for age, height and weight are presented in table 1. Thirty-eight percent (37/97) of the American football and 38% (18/48) of Ice Hockey players had a history of a previous concussive injury. The median time since injury for American Football and Ice Hockey athletes was 702 days (range 81 to 3,853 days) and 983 days (range 270 to 2,157 days), respectively (Z = -1.247; P = 0.21). Nine male and ten female ice hockey athletes had a history of concussion (χ^2 = 0.166; P = 0.684). There was no significant difference in the number of days since concussion between the male (median 1,093 days; range 279 to 1,763) and female (median 968 days; range 270 to 2,157) ice hockey athletes (Z = -0.444; P = 0.657).

TABLE 1 HERE

There was no significant difference in normalised reach distance between athletes with and without a history of concussion. Jerk RMS and GM SEn was lower in the athletes with a history of concussion when compared to the healthy controls across all three reach directions; however, this did not reach the *a priori* level of statistical significance (Table 2). Figure 1 presents a violin plot, illustrating the population density of the two groups of athletes.

TABLE 2 HERE

FIGURE 1 HERE

There was no significant effect of player group (no concussion history [n = 90]; concussion history < 2 years ago [n = 25]; concussion history > 2 years ago [n = 30]) on reach distance or GM SEN. There was a statistically significant effect of group on Jerk RMS for the PM and PL reach directions, but not the ANT reach direction (Table 3). Post-hoc Dunn-Bonferroni analysis demonstrated that individuals with a history of concussion within the last two years have statistically significantly lower Jerk RMS (more constrained/conservative movement control strategy) for the PM (Z = 23.22, P = 0.015) and PL (Z = 24.64, P = 0.010) reach directions, when compared to the healthy control group. There was no significant difference between the group with a history of concussion longer than two years ago and the healthy control group for the PM (Z = -1.25; P = 0.889) and PL (Z = 6.44; P = 0.469) reach directions. Similarly, there was no significant difference in Jerk RMS between the individuals with a history of concussion in the last two years and those whose concussion took place greater than 2 years ago for the PM (Z = 2.43; P = 0.033) and PL (Z = -1.59; P = 0.112) reach directions. Figure 2 presents a violin plot illustrating the population density of the three groups of athletes.

TABLE 3 HERE

FIGURE 2 HERE

DISCUSSION

The focus of this study was to investigate if a single inertial sensor, similar to those embedded within smart phones, can capture differences in dynamic balance performance in individuals with and without a history of concussion. When crudely comparing athletes with (median 900 days; range 81 to 3,853) and without a history of concussion, it was seen that there was no significant difference in balance performance between the two groups. However, when stratifying the athletes with prior concussion into two groups based on time since last concussion (i.e. within the last two years and greater than two years ago), our findings indicate that athletes who sustained a concussion within the last two years (median 294 days; range 81 to 717) possessed statistically significantly lower Jerk RMS in the PM and PL directions than those athletes with no history of concussion. The performance of athletes who sustained a concussion greater than two years ago (median 1,306 days; range 820 to 3,853) were not different to the healthy control group.

These findings demonstrate that athletes with a history of concussion within the last two years have a more constrained movement control (lower Jerk RMS) during the dynamic PM and PL reaching tasks than those with no history of concussion – suggesting incomplete sensorimotor recovery. Importantly, these differences in performance were detected by the inertial sensor based Jerk RMS variable, despite comparable reach distance performance. Furthermore, those who sustained their last concussion greater than two years previously appear to possess comparable dynamic balance performance to the athletes who have never sustained a concussive injury – suggesting full sensorimotor recovery. While it is not overtly clear why there were significant differences between the concussed (< 2 years ago) and healthy athletes in the PM and PL, but not the ANT reach directions, previous research has established key differences between the YBT reach direction strategies.[28] Specifically, the ANT direction requires an individual to complete a predominantly sagittal plane movement, while maintaining visual contact with the reach distance. Conversely, the PM and PL directions involve the individual completing a complex multiplanar movement, not facilitating visual observation of the reach distance [28]. As a result, the PM and PL directions may provide a greater challenge to the sensorimotor sub-systems of the individuals, highlighting deficits in performance which are not detected by the ANT direction.

To date, a series of studies have reported conflicting findings related to the impact of concussion history on balance. For example, Merritt et al[29] reported that there was no difference in dynamic balance performance, as measured by the traditional analogue YBT reach distances, between collegiate athletes with and without a history of concussion. Conversely, Sosnoff and colleagues[9] reported differences in force-plate measured postural-sway dynamics during the sensory organisation test between athletes with and without a history of concussion. Similarly, Lynall et al[8] reported differences in centre of pressure speed during a dual-task eyes closed tandem gait task. One of the key differentiating factors between these studies is the use of an analogue measurement tool (YBT reach distances) by Merritt et al,[29] while Sosnoff et al[9] and Lynall et al[8] both used laboratory based biomechanical measures during balance and gait tasks. As such, Merritt et al[9] hypothesised that the YBT reach distances may not be sensitive enough to detect the subtle sensorimotor deficits that persist beyond clinical recovery. The findings of our study support Merritt et al's[29] hypothesis, demonstrating that despite the control and concussion history groups demonstrating comparable YBT reach distance performance, individuals who had a history of concussion (< 2 years ago) had a more constrained movement control strategy (lower Jerk RMS) than those with no history of concussion. Furthermore, this study contributes to a growing body of evidence highlighting that the inertial sensor based measures of balance performance are more sensitive to concussion related deficits than traditional clinical measures in both athletic [30,31] and general populations.[32,33] For example, King and colleagues have reported that the inertial sensor instrumented mBESS (AUC = 0.81; 95% CI 0.64 to 0.99) can discriminate chronic concussion (average time since concussion 5 months ± 3.3) and healthy adults with greater accuracy than the clinical mBESS error scoring method (AUC = 0.64; 95% CI 0.42 to 0.85).

This study is among the first to demonstrate that balance performance is impaired in athletes with a history of concussion.[8,9,34] Importantly, the results of our study are the first to highlight that these balance deficits are only present in athletes with a history of concussion within the last two years and that inertial sensor technology can capture these subtle alterations. This inertial sensor technology is low cost in nature and embedded in modern smartphones and wearable activity trackers. As such this approach may provide a means to examine chronic concussion neurological deficits in a cheap and objective manner. The presence of these sensorimotor deficits in individuals whose injury occurred < 2 years ago (despite 'clinical recovery') may help explain the growing body of evidence demonstrating that athletes with a recent history of concussion are at a greater risk of sustaining further concussive[3] and lower-limb musculoskeletal injuries.[4] Furthermore, the use of inertial sensor technology may help address some of the limitations of the traditional clinical assessments which have shown no utility in identifying those at an increased risk of musculoskeletal injury post-concussion.[35] For example, recent prospective research by Johnston et al[15] reported that Rugby Union players with poorer dynamic balance performance measured using inertial sensor technology during the YBT were at a three times greater relative-risk of concussion than individuals with optimal performance. Additionally, individuals with impaired dynamic balance performance have been shown to possess an increased risk of sustaining lower limb injuries such as lateral ankle sprains[36] and anterior cruciate ligament ruptures[37]. As such, it is possible that the deficits possessed by individuals whose injury occurred < 2 years ago may be a mediating factor in the observed increased injury-risk following sports related concussion. Conversely, the longer time-since-injury in those whose injury occurred > 2 years ago may have resulted in improved sensorimotor recovery. This assertion is supported further by prospective research which has highlighted the association between recent history of concussion and an increased risk of musculoskeletal injury.[38,39] Therefore, clinicians and rehabilitation specialists should look to introduce targeted dynamic balance and motor control training interventions into the return to play process following sports-related concussion. Such an approach may accelerate the athletes sensorimotor recovery, addressing the potential underlying mechanism for the increased injury-risk post-concussion.

The findings of this study should be interpreted within the context of its limitations. This study was cross-sectional and therefore it was not possible to investigate the causative effect of the previous concussive injuries on the balance performance impairments. While this study highlighted differences in performance between groups with and without a history of concussion, it is possible that these differences existed prior to the original injury. An important consideration is that this study focused on the impact of concussion on balance and did not investigate a comprehensive battery of demographic, cognitive, sensory and clinical characteristics (i.e. mBESS). As such, future research should investigate the impact of concussion on a wide multifactorial assessment battery to better understand the long term impact of sports related concussion and the relationship between these measures. An important factor to consider was that concussion history which occurred prior to the athletes entering collegiate medical care (i.e. high school injuries) were self-reported and could not be confirmed with clinical data. However, an internationally recognised definition of concussion[23] was used within this study which has been used extensively in similar investigations,[9,34] limiting the risk of error. Furthermore, the majority of injuries which occurred within the cohort of athletes with a history of concussion in the last two years would have occurred while under collegiate medical care. It is worth considering that despite a well-established concussion diagnosis definition being employed within this study, it is possible that there may be an under estimation of the actual quantity of true concussions. In particular, as the control cohort are contact sports athletes, it is possible that some concussion may have gone undiagnosed, while sub-concussive impacts may have affected the balance performance. Finally, while this cross-sectional study presented a relatively large cohort of collegiate American Football and Ice Hockey athletes (n = 146), the generalisability of our findings across other populations may be limited. Thus, further research is required to investigate this relationship across a more heterogeneous population of athletes from a range of sports.

PERSPECITVE

This study highlighted that athletes with a history of concussion within the last two years have poorer dynamic balance performance, when compared to healthy control athletes. Conversely, athletes whose injury occurred greater than two years ago possessed comparable dynamic balance performance to the healthy control group. Importantly, these impairments were not highlighted by traditional clinical assessments, but were captured using inertial sensor technology. These findings are part of a growing body of evidence demonstrating that deficits in sensorimotor function may exist beyond clinical recovery post-concussion,[6,7,40] contributing to an increased risk of future injury[4]. As such, clinicians and rehabilitation specialists should introduce targeted balance training interventions into the return to play process to accelerate sensorimotor control recovery and mitigate the risk of future injury. Future prospective longitudinal research is required to thoroughly evaluate the role this technology and additional targeted rehabilitation may play in improving the recovery process following sports related concussion.

AUTHOR CONTRIBUTION

The authors alone are responsible for the writing of this paper. W.J, B.H, M.A.B and BC contributed to the study conception, design and methodology. W.J and J.S coordinated the study and managed the data collection. W.J and B.C conducted the data analysis and wrote the initial manuscript draft. All authors contributed to the writing and drafting of the final manuscript.

CONFLICTS OF INTEREST

This study was supported by the Science Foundation of Ireland (12/RC/2289_P2). W.J and B.C are employees of University College Dublin. J.S is an employee of University of Wisconsin-Madison Athletics, A.B is a team physician and B.H is a Physical Therapist at University of Wisconsin-Madison Athletics.

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Table 1: Descriptive statistics for the recruited athletes

Variable	No Concussion History (n = 90)		Concussion History (< 2 years ago) (n = 25)		Concussion History (> 2 years ago) (n = 30)	
	Mean	SD	Mean	SD	Mean	SD
Age (yr)	20.2	1.5	20.5	0.9	20.3	1.7
Height (cm)	183.6	9.2	186.6	7.2	180.5	9.5
Weight (kg)	96.8	23.4	104.5	23.0	92.3	23.0

Table 2: Mann-whiney U test investigating the difference between the two cohorts.

Direction	Variable	No History of Concussion (n = 90)		History of Concussion (n = 56)		P Value	Eta^2
		Mean	SD	Mean	SD		
Anterior	Reach Distance (%)	59.04	6.16	59.32	6.49	0.84	<0.001
	Jerk RMS (m/s^3)	0.27	0.08	0.25	0.07	0.14	0.013
	GM Sen	1.26	0.27	1.20	0.25	0.23	0.013
Posteromedial	Reach Distance (%)	104.50	6.10	105.34	7.55	0.17	0.004
	Jerk RMS (m/s^3)	0.25	0.07	0.24	0.06	0.24	0.008
	GM Sen	0.86	0.24	0.81	0.26	0.14	0.010
Posterolateral	Reach Distance (%)	99.63	7.00	100.16	7.44	0.41	0.001
	Jerk RMS (m/s^3)	0.23	0.06	0.22	0.06	0.09	0.018
	GM Sen	0.70	0.19	0.67	0.24	0.17	0.005

A statistically significant ($P < 0.05$) main effect is represented in **bold** with an *.

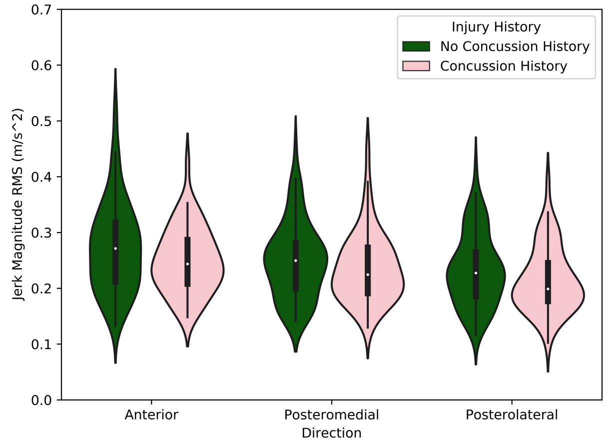
Table 3: Means, standard deviations (SD) and Kruskal-Wallis H-test results comparing the three groups; No concussion history, concussion history < 2 years ago and concussion history > 2 years ago.

Reach Direction	Variable	No History of Concussion (n = 90)		Concussion <2 years (n = 25)		Concussion >2 years (n = 30)		Kruskal-Wallis Test	
		Mean	SD	Mean	SD	Mean	SD	$\chi^2(2)$	P value
Anterior	Reach Distance (%)	59.04	6.16	59.25	6.04	58.82	6.59	0.03	0.987
	Jerk RMS (m/s^3)	0.27	0.08	0.24	0.06	0.28	0.12	2.72	0.257
	GM Sen	1.26	0.27	1.22	0.26	1.24	0.34	1.01	0.604
Posteromedial	Reach Distance (%)	104.50	6.10	104.30	5.76	105.95	8.81	3.32	0.190
	Jerk RMS (m/s^3)	0.25	0.07	0.21	0.05	0.25	0.07	**6.43**	**0.040***
	GM Sen	0.86	0.24	0.80	0.29	0.80	0.24	2.94	0.227
Posterolateral	Reach Distance (%)	99.63	7.00	98.60	7.08	101.05	7.61	2.22	0.328
	Jerk RMS (m/s^3)	0.23	0.06	0.20	0.05	0.22	0.06	**6.68**	**0.035***
	GM Sen	0.70	0.19	0.66	0.26	0.66	0.21	3.13	0.209

n = 1 Ice hockey athlete had missing data for the date of their last concussion, thus was excluded from the analysis. A statistically significant (P < 0.05) main effect is represented in **bold** with an *.

Figure 1: Violin plots illustrating the population density of jerk magnitude variable for the healthy control athletes (green) and the athletes with a history of concussion (pink).

Figure 2: Violin plots illustrating the population density of jerk magnitude for the healthy control athletes (green), those with a history of concussion in the least two years (red) and those whose injury occurred greater than two years ago (blue). There was a statistically significant difference between the healthy control group and those who sustained a concussion within the last two years for the posteromedial and posterolateral reach directions.



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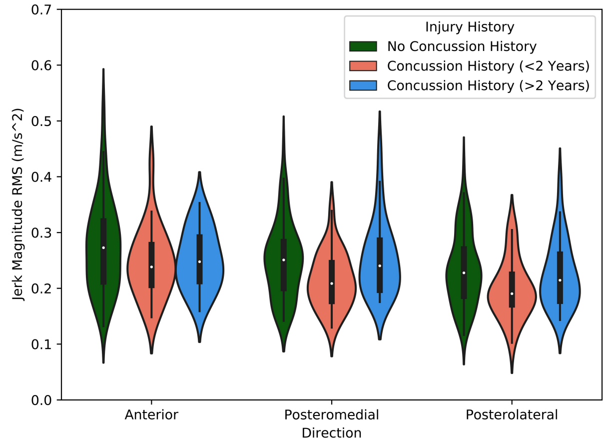

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