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Research Article

Impacts to The Head in A Premier One Domestic Netball Team Measured With A Wireless Head Impact Sensor Over A Domestic Competition Season: An Exploratory Analysis

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Abstract

Aim: To determine the exposure to subconcussive and concussive head injuries during amateur women's netball.

Method: Eleven female amateur netball players were monitored during a netball season with X2 accelerometers for impact exposures above 10 *g* and the King-Devick test for neuropsychological outcomes. The clinical concussion rate was recorded.

Results: A mean of 3 ±2 impacts >10 *g* were recorded per-player per-match. Players in centre positions recorded more impacts to the head than attack (RR: 1.8 [95% CI: 1.4 to 2.2]; p<0.0001) and defence (RR: 1.6 [95% CI: 1.3 to 1.9]; p=0.0002) positions, but a lower median resultant peak linear acceleration (13 [11-18]*g*) when compared with attack ($\chi^2_{(1)}$=90.0; p<0.0001; z=-8.9; p<0.0001) and defence ($\chi^2_{(1)}$=105.0; p<0.0001; z=-8.4; p<0.0001) positions. There were four concussions identified over the study resulting in a concussion incidence of 33.6 per 1,000 match hours. For players without any signs of a concussive injury, a median difference of 0.8 [0.4 to 2.8] seconds between baseline and post-match K-D assessments was noted (z=-2.0; p=0.04217).

Conclusion: Netball players experience significant head impacts capable of causing clinical concussion. Furthermore, they experience repetitive head impacts in excess of subconcussive thresholds. Impact frequency and magnitude are player position dependent.

Key Points:

- Amateur netball players recorded an average of 3 impacts to the head per-player per-match.
- Use of the head impact biomechanics RWE_{CP} >0.75 was able to identify player at risk of a concussive injury
- Although the median linear accelerations were lower than the median of other sporting activities, the median rotational accelerations recorded were similar to those reported for women's soccer, youth rugby union and rugby league.
- Centre players had higher player loads (player load per-minute, forward per-minute, sideward per-minute, and vertical per-minute) than any other position

Introduction:

First invented in the late nineteenth century,[1] netball was designed as a version of basketball, but with rules to "de-power" the game making it "more suitable" for women [2]. Predominately a female team court sport,[3] netball is typically played by two teams with seven players each over 4 x 15 minute quarters. The netball court is 15.25 m x 30.5 m divided into equal thirds defining where particular player positions are able to move. The aim of the game is to score a goal through an elevated ring, at the top of a 3.05 m high pole [3]. The rules require the game to be played without any contact, with players unable to run with the ball, being allowed only one step with the

ball, which must be passed within three seconds [3].
American soldiers in World War II was 35.8% after repair and
Despite these rules, the speed at which the game is played and the permission of player movement in flight, inevitably results in player collision. Whilst most collisions appear innocuous, significant injuries are sustained requiring player removal and medical attention. In addition, the repetitive sudden deceleration and landing from jumping has raised the hypothesis that netball players are exposed to repetitive subconcussive injuries.

This study, therefore undertook to record the frequency, duration, magnitude and location of head impacts that occur to players participating in a premier one domestic amateur netball competition over a single season of matches. As a result of this monitoring, the study also undertook to record the incidence of diagnosed concussions that occurred from match participation.

Methods

A prospective cohort design was used to study the head impact frequency, magnitude and duration during women's netball matches. Eleven female amateur netball players were enrolled into the study with a mean (±SD) age of 23.5 ±6.2 yr. The players competed in 17 competition matches resulting in match exposure of 119.0 hours. Players were placed into three positional groups: (1) Defence (n=3: Goal Keep; Goal Defence; Wing Defence); (2) Attack (n=3: Goal Shoot; Goal Attack; Wing Attack); and (3) Centre (n=1). The player positions were categorised according to the primary playing position at the start of the match and some players were interchanged into other positions during the matches. All matches were played indoors on a sprung wooden floor at the same venue throughout the study. The lead researchers' university ethics committee (AUTEC 16/35) approved all procedures in the study and all players gave informed consent prior to participating in the study.

Head impact biomechanics

Head impact exposure was measured with the XPatch (X2Biosystems, Seattle, USA). The XPatches were synchronised the morning of every match. The XPatch is a 1 cm x 2 cm device that measures acceleration and is mounted with a single-use adhesive behind the right ear. Containing a triaxial accelerometer and a triaxial angular rate gyroscope to capture six degrees of freedom for linear acceleration and rotational velocity, the XPatch has a 4.2 v battery and a small memory chip measuring continuously at 1 kHz for impacts greater than a pre-set level of 10 *g*. This threshold was chosen based on a review of previously published studies[4, 5] and given that running and jumping elicit ~9.5*g* of linear head acceleration [6]. Prior to the players commencing their warm-up, the lead researcher applied the XPatch behind each player's right ear ensuring it was fitted over the mastoid process and that loose hair was not in the adhesive. The patches were allocated to individual players' and the players' positions were recorded. Data collection was delimited to matches only - not team training sessions.

When an impact above the threshold (10 *g*) occurred, the device saved 10-ms prior to the impact and 90-ms after the impact providing X, Y and Z coordinates of acceleration at 1-ms intervals. Peak linear acceleration (PLA) was measured and peak rotational acceleration (PRA) was then calculated. The time stamp of the match was synchronised with the XPatch prior to every game. The frequency, location, PLA, PRA and duration of all head impacts ≥ 10 *g* threshold of linear acceleration were recorded by the XPatch for each match and stored on the device until uploaded.

Prior to statistical analysis, the raw data were reduced in the following manner. Data captured on the XPatch were uploaded to the Impact Management System (IMS) provided by X2Biosystems. The data were then downloaded and filtered through the IMS to remove any spurious linear acceleration that did not meet the proprietary algorithm for a head impact [7]. The data underwent a second filtering waveform parameter proprietary algorithm during data exporting to remove spurious linear acceleration data with additional layers of analysis [7]. This included the area under the curve, the number of points above threshold and filtered versus unfiltered peaks [7]. The remaining data were exported onto an Excel spreadsheet (version 2016; Microsoft Corporation, Redmond, WA) for visual examination. The data were then reviewed by impact time stamps (hr:min:s) to identify identical and sequential patterns for each player. Time stamps with multiple (≥2) linear accelerations having the same impact time stamp in quick succession, milliseconds after the preceding impact were removed. Once the review was completed, the data estimates were adjusted to estimates of the Hybrid III headform criterion standard[8] and all impacts <10 *g* were removed (n=38) from the database.

The impact variables were non-normally distributed with skewness of 3.37 (*SE*=0.13) and kurtosis of 17.23 (*SE*=0.25), therefore data were expressed as median [IQR] and 95th percentile. Three measures of impact frequency were computed for each player: (1) *player position impacts*, the total and median number of head impacts recorded for the playing position for all matches; (2) *player group impacts*, the total and median number of recorded head impacts for the playing group (defence, attack and centres) for all matches and (3) *impacts per match*, the total and median number of impacts per match for all matches.

The head impact location variables were computed as previously explained[4, 9, 10] and were categorised as front, side, back and top [11]. Head impacts were also assessed for injury tolerance level,[12-14] for impact severity,[15-17] and Risk Weighted Exposure Combined (linear and rotational) Probability (RWE_{CP}) [18]. The RWE_{CP} is a logistic regression equation and regression coefficient of injury risk prediction of an injury occurring[19-22] and combines the linear and rotational accelerations to elucidate individual player and team-based exposure to head impacts. The RWE_{CP} were evaluated by values of 25% risk (<0.2500) 25% to 75% risk (0.2500-0.7500) and >75% risk (>0.7500).

King-Devick test in association with Mayo Clinic

The K-D test is a neuropsychological test that measures the speed a participant performs rapid number naming in a timed manner [23]. The test takes less than two minutes to administer [24, 25]. The K-D test involved the player's reading aloud a series of random single-digit numbers from left to right. The K-D test included one practice (demonstration) card and three test cards varied in format as an application on an IPad Air2 platform. Players were asked to read the numbers from left to right across the card as quickly as they could without making any errors using standardised instructions. The time was kept for each test card, and the K-D summary score for the entire test was based on the cumulative time taken to read all three test cards. The number of errors made in reading the test cards was recorded.

Baseline K-D times for all participants were established prior to the study as part of their pre-competition assessment. The best time (fastest) of two trials 10 minutes apart, without errors, errors recorded then compared to the subject's baseline. Worsening of time and/or errors identified on the sideline or post-match K-D test have been associated with concussive injury [24-30]. All participants with worsening of time and/or errors on their K-D were referred for a full medical assessment by a health practitioner. Only those participants with a medical diagnosis of concussion were recorded as such in the study.

The K-D test performance is unaffected by various noise levels and testing environments [31]. The K-D test has been reported to have significant correlations (p<0.0001) with the visual motor speed (VMS), reaction time (RT), verbal memory (VEM) and visual memory (VIS) of the Immediate Post-concussion Assessment Cognitive Test (ImPACT®) [32] computerised concussion evaluation system. The K-D test has a reported inter-class correlation for test-retest reliability of 0.96 [33] and 0.97 [24]. The K-D test utilised was v3.0 (http://www.kingdevicktest.com) on an IPad Air2. The IPad Air2 version enables the use of the K-D test with three different number sets and these were varied over the study. Test set 1 was used for all baseline assessments. The other 2 test sets were varied each week to ensure the same set was not used twice in a row.

Statistical Analysis

The data were exported onto an Excel spreadsheet and analysed with SPSS (V.25.0.0). Total frequency impact burden per-match was analysed using a Kruskal-Wallis one-way ANOVA with a Dunn's post-hoc test for all pairwise comparisons with player positions. Although to date there is no standardised method to quantify total frequency impact burden, [13] the sum of linear and rotational accelerations associated with each individual head impact per-match over the study was calculated for these parameters. Head impact exposure including impact duration, frequency, magnitude and location of impacts were quantified using established methods [34, 35].

Median peak linear and rotational accelerations and impact became the established baseline K-D test time [24]. When head trauma was suspected, or the participant had a RWE$_{CP}$ of 0.75 or greater, the K-D test was used as a screening tool. The test was administered once using the same instructions and the time and locations between player positions were assessed using a Friedman repeated measures ANOVA on ranks with a Wilcoxon signed-rank test for post hoc analysis with a Bonferroni correction applied. Impact locations were analysed by front, back, side and top impacts using a Friedman repeated measures ANOVA on ranks by comparing impacts sustained in each location. A one sample chi-squared (χ^2) test and risk ratio (RR), with 95% confidence intervals (CI), were used to determine whether the observed impact frequency was significantly different from the expected impact frequency. Statistical significance was set at p<0.05.

Results

During competition there were 366 impacts (range 10 g to 118 g) recorded over 10 g (see Table 1) with a mean of 22 ±11 impacts per-match resulting in a mean of 3 ±2 impacts per-player per-match. Players recorded a median [IQR] and 95th percentile of 13 [11 to 20] g, and 43 g respectively for resultant peak linear, and 2,395 [1,402 to 4,556] rad/s^2 and 11,427 rad/s^2 respectively for resultant peak rotational accelerations. As a result, players recorded a median [IQR] and 95th percentile RWE$_{CP}$ of 0.0005 [0.0002 to 0.0039] and 0.7507 respectively. Centre players recorded more impacts to the head than attack (RR: 1.8 [95% CI: 1.4 to 2.2]; p<0.0001) and defence (RR: 1.6 [95% CI: 1.3 to 1.9]; p=0.0002) players during the study. Centre players recorded a lower median resultant peak linear acceleration (13 [11-18] g) when compared with attack ($\chi^2_{(1)}$=90.0; p<0.0001; z=-8.9; p<0.0001) and defence ($\chi^2_{(1)}$=105.0; p<0.0001; z=-8.4; p<0.0001) players. Attack players recorded a higher mean impact duration (17.9 ±14.3 ms) when compared with defence ($\chi^2_{(1)}$=12.0; p=0.0005; z=-5.0; p<0.0001) and centre ($\chi^2_{(1)}$=11.9; p=0.0006; z=-5.1; p<0.0001) players.

	Impact to the head				PLA (g)			PRA (rad/s^2)			RWE$_{CP}$	
	Total n=	Per-match Mean ±SD	Per-player per-match Mean ±SD	Impact duration (ms) Mean ±SD	Median [IQR]	95th	Total Frequency Impact burden[i]	Median [IQR]	95th	Total Frequency Impact burden[i]	Median [IQR]	95th
Total	366	22 ±11	3 ±2	12.1 ±10.5	13 [11 - 20]	43	6,614	2,395 [1,402 - 4,556]	11,427	1,307,842	0.0005 [0.0002 - 0.0039]	0.7507
Defence[$]	105[c]	6 ±3	3 ±2	8.8 ±6.8[b]	14 [12 - 22][bc]	43	1,959	2,918 [1,768 - 5,348][c]	11,560	442,360	0.0008 [0.0003 - 0.0109][c]	0.7873
Attack	94[c]	6 ±5	3 ±2	17.9 ±14.3[ac]	12 [11 - 19][ac]	47	1,702	2,283 [746 - 4,703]	12,061	320,152	0.0005 [0.0001 - 0.0056]	0.8126
Centre[$]	167[ab]	10 ±5	6 ±4	11 ±8.5[b]	13 [11 - 18][ab]	42	2,953	2,329 [1,410 - 3,876][a]	10,661	545,329	0.0005 [0.0002 - 0.0021][a]	0.6462
Goal Keep	25[fgi]	2 ±1	2 ±1	10.0 ±6.0[efi]	17 [13 - 23][efghi]	40	460	3,234 [2,053 - 7,897][efghij]	14,040	122,532	0.0012 [0.0004 -0.1138][efghi]	0.9333
Goal Defence	28[fgi]	2 ±2	3 ±2	7.5 ±6.7[dhij]	12 [1 1-19][dfghij]	46	483	2,114 [1,184 - 4,106][dghij]	11,540	98,655	0.0004 [0.0002 - 0.0028][dghij]	0.7974
Wing Defence[$]	52[deghj]	4 ±2	3 ±2	9.0 ±7.2[dhij]	15 [12 - 24][deghij]	45	1,016	3,024 [1,783 -	11,456	221,173	0.0009 [0.0003 - 0.0109][dghij]	0.5407

								5,264]^{dghij}				
Centre$^{\$}$	167^{defhij}	10 ±5	6 ±4	11.0 ±8.5^{i}	13 [11 - 18]^{defhij}	42	2,953	2,329 [1,410 - 3,876]^{defhj}	10,661	545,329	0.0005 [0.0002 - 0.0021]^{defhj}	0.6462
Wing Attack	18^{fgi}	2 ±1	2 ±1	10.6 ±7.8^{efi}	17 [11 - 36]^{defgij}	*	404	3,813 [2,096 - 6,653]^{defgij}	*	88,822	0.0019 [0.0004 - 0.0319]^{defgij}	*
Goal Attack	55^{deghj}	4 ±3	4 ±3	23.7 ±15.3^{defghj}	12 [10 - 1 6]^{defghj}	54	948	1,120[31 - 4,666]^{defhj}	12,465	153,820	0.0002[0.0001 - 0.0045]^{defhj}	0.8137
Goal Shoot	21^{gi}	2 ±1	2 ±1	9.0 ±5.9^{efi}	16 [12 - 20]^{defghi}	35	350	2,514 [2,078 - 4,111]^{defghi}	13,948	77,510	0.0007 [0.0004 - 0.0027]^{efghi}	0.9164

ms = milliseconds; PLA = Peak Linear Acceleration; PRA (rad/s^2) = Peak Rotational Acceleration in radians per second per second; RWE_{CP} = Risk Weighted Exposure (Combined Probability) $^{\$}$ = concussion recorded; (i) = The total impact frequency is the sum of all of the impacts by linear and rotational accelerations; Significant difference (p<0.05) then (a) = Defence; (b) = Attack; (c) = Centre; (d) = Goal Keep; (e) = Goal Defence; (f) = Wing Defence; (g) = Centre; (h) = Wing Attack; (i) = Goal Attack; (j) = Goal Shoot

Table 1: Impacts to the head greater than 10 *g* in amateur women's premier netball over a domestic competition season by total impacts recorded and player position group for total impacts, impacts per match, impacts per-player per-match, impact duration, resultant peak linear and rotational accelerations. Data are presented as mean (± standard deviation), median [25th to 75th interquartile range], 95th percentile and total frequency impact burden.

The total number of head impacts, resultant peak linear and rotational accelerations and the total frequency impact burden by individual player positions were captured (see Table 2). There were observable differences in the impact duration ($\chi^2_{(6)}$=31.2; p<0.0001), resultant peak linear ($\chi^2_{(6)}$=87.8; p<0.0001) and rotational ($\chi^2_{(6)}$=56.8; p<0.0001) accelerations and the RWE_{CP} ($\chi^2_{(6)}$=59.7; p<0.0001) score by player positions over the study. The centre recorded a mean of 6 ±4 impacts per-match, the wing attack recorded the highest median resultant peak linear acceleration of 17 [11-36] *g* and the highest median resultant peak rotational acceleration of 3,813 [2,096 to 6,653] rad/s^2. Centre players recorded the highest total frequency impact burden for resultant peak linear (2,953 *g*) and rotational (545,239 rad/s^2) accelerations. The wing attack recorded the highest median RWE_{CP} of 0.0019 [0.004 to 0.0319] over the study.

	Impacts			**Duration (msec) Mean ±SD**	**PLA (*g*)**		**PRA (rad/s^2)**		**RWE_{CP}**	
	Location	**No.**	**%**		**Median [IQR]**	**95th**	**Median [IQR]**	**95th**	**Median [IQR]**	**95th**
Total (n=11)										
	Front	54^{cd}	14.8	12.9 ±11.0^{b}	16 [13-36]^{bcd}	69	3,960 [2,511-8,842]^{bc}	14,376	0.0019 [0.0006-0.2808]	0.9855
	Back	71^{cd}	19.4	9.1 ±7.1^{a}	14 [12-22]^{acd}	39	2,877 [1,576-5,342]^{acd}	10,816	0.0008 [0.0002-0.0106]	0.5709
	Side	232^{abd}	63.4	12.9 ±11.2	13 [11-16]^{abd}	37	2,048 [1,281-3,628]^{abd}	9,822	0.0004 [0.0002-0.0015]	0.3129
	Top	9^{abc}	2.5	10.8 ±8.9	20 [11-27]^{abc}	*	3,791 [2,267-6,802]^{bc}	*	0.0022 [0.0004-0.0763]	*
Defence (n=5)										
	Front	18	17.1	5.7 ±3.3^{fg}	13 [11-16]^{bcfg}	*	2,608 [1,979-3,106]^{bfg}	*	0.0006 [0.0003-0.0012]^{bfg}	*
	Back	33	31.4	8.7 ±5.6^{cg}	13 [11-24]^{acdfg}	37	2,286 [1,186-5,534]^{afg}	9,062	0.0004 [0.0002-0.0128]^{afg}	0.2451
	Side	49	46.7	9.8 ±7.9^{bdfg}	16 [12-24]^{abfg}	46	3,190 [1,872-6,828]^{fg}	15,483	0.0014 [0.0003-0.0370]^{fg}	0.9878
	Top	5	4.8	11.4 ±9.9^{c}	20 [11-36]^{b}	*	3,791 [2,125-8,382]	*	0.0022 [0.0006-0.4114]	*
Attack (n=4)										
	Front	16	17.0	11.8 ±7.7^{bce}	17 [14-40]^{bce}	*	4,741 [2,439-8,635]^{e}	*	0.0056 [0.0006-0.2529]^{bce}	*
	Back	23	24.5	9.4 ±9.0^{aceg}	14 [11-21]^{aceg}	60	2,972 [1,641-5,182]^{eg}	15,057	0.0008 [0.0003-0.0052]^{acg}	0.9884
	Side	53	56.4	23.6 ±15.2^{abeg}	11 [11-16]^{abeg}	44	1,517 [28-2,929]^{e}	11,018	0.0002 [0.0001-0.0009]^{abe}	0.6790
	Top	2	2.1	13.5 ±13.4	20 *	*	5,286 *	*	0.0723 *	*
Centre (n=2)										
	Front	20	12.0	20.4 ±13.1^{bce}	28 [15-43]^{bce}	117	7,036 [3,616-11,297]^{bce}	21,589	0.0478 [0.0015-0.7293]^{bce}	0.9995
	Back	15	9.0	9.5 ±7.1^{af}	18 [12-22]^{acef}	*	3,449 [1,726-4,756]^{acef}	*	0.0017 [0.0003-0.0044]^{ace}	*
	Side	130	77.8	9.8 ±6.7^{aef}	13 [11-15]^{abef}	30	1,941 [1,368-2,816]^{abe}	5,764	0.0003 [0.0002-0.0008]^{abe}	0.0172
	Top	2	1.2	6.5 ±0.7	18 *	*	3,720 *	*	0.0040 *	*

second; RWE_{CP} = Risk Weighted Exposure (Combined Probability); (i) = The total impact frequency is the sum of all of the impacts by linear and rotational accelerations; * = Unable to calculate; Significant difference ($p<0.05$) than (a) = Front; (b) = Backs; (c) = Side; (d) = Top; (e) = Defence; (f) = Attack; (g) = Centre

Table 2: Impacts to the head greater than 10 *g* in amateur women's premier one netball team over a single domestic competition season of matches by total impacts and player-position group for impact location, total impacts, impact duration, resultant peak linear, peak rotational accelerations and risk weighted exposure (combined probability). Data are presented as median [25-75th interquartile range], 95th percentile and total frequency impact burden.

The side of the head (n=232) recorded more impacts than the back ($\chi^2_{(1)}$=85.5; $p<0.0001$), front ($\chi^2_{(1)}$=110.8; $p<0.0001$) and top ($\chi^2_{(1)}$=206.3; $p<0.0001$) of the head (see Table 3). Attack players recorded a longer mean impact duration (23.6 ±15.2 ms) to the front of the head than centre ($\chi^2_{(1)}$=19.6; $p<0.0001$; z=-5.2; $p<0.0001$) and defence ($\chi^2_{(1)}$=8.3; p=0.0039; z=-2.0; $p<0.0001$) player positions. Defence players recorded a higher median peak resultant linear acceleration impact to the side of the head (16 [12 to 24] *g*) than centres ($\chi^2_{(1)}$=49.0; $p<0.0001$; z=-3.7; p=0.0002) and attack ($\chi^2_{(1)}$=49.0; $p<0.0001$; z=-3.4; p=0.0005) player positions. Centres recorded a higher median peak resultant rotational acceleration (7,036 [3,616 to 11,297] rad/s^2) to the front of the head than attack ($\chi^2_{(1)}$=4.0; p=0.0455; z=-1.8; p=0.0703) and defence ($\chi^2_{(1)}$=18.0; $p<0.0001$; z=-3.7; p=0.0002) player positions. As a result, centres recorded a higher median RWE_{CP} (0.0478 [0.0015 to 0.7293]) to the front of the head than attack ($\chi^2_{(1)}$=4.0; p=0.0455; z=-1.5; p=0.0796) and defence ($\chi^2_{(1)}$=18.0; $p<0.0001$; z=-3.7; p=0.0002) player positions. There were 68 impacts (19%) recorded above the rotational injury risk limit (see Table 4). Centres recorded more impacts in the moderate rotational acceleration (4,600 to 7,900 rad/s^2) than defence (p=0.4233) and attack (p=0.0863) player positions. The majority of impacts were in the mild impacts severity limit for linear (99%), rotational (75%) and RWE_{CP} (91%) data acquisition limits.

			Total	Defence	Attack	Centre
			n= (%)	**n= (%)**	**n= (%)**	**n= (%)**
Injury Tolerance						
	Linear	>95*g*	1 (0.3)	0 -	0 -	1 (0.6)
	Rotational	>5,500 rad/s^2	68 (18.6)	25 (23.8)	19 (20.2)	24 (14.4)
Injury Severity (Linear)						
	Mild	<66*g*	363 (99.2)	104 (99.0)	94 (100.0)	165 (98.8)
	Moderate	66-106*g*	2 (0.5)	1 (1.0)	0 -	1 (0.6)
	Severe	>106*g*	1 (0.3)	0 -	0 -	1 (0.6)
Injury Severity (Rotational)						
	Mild	<4,600 rad/s^2	275 (75.1)	70 (66.7)	70 (74.5)	133 (79.6)
	Moderate	4,600-7,900 rad/s^2	49 (13.4)	17 (16.2)	12 (12.8)	22 (13.2)
	Severe	>7,900 rad/s^2	42 (11.5)	18 (17.1)	12 (12.8)	12 (7.2)
Risk Weighted Exposure combined probability (RWE_{CP})						
	Mild	<0.2500	334 (91.3)	94 (89.5)	84 (89.4)	156 (93.4)
	Moderate	0.2500-0.7500	17 (4.6)	5 (4.8)	3 (3.2)	5 (3.0)
	Severe	>0.7500	15 (4.1)	6 (5.7)	7 (7.4)	6 (3.6)

Table 3: Impacts to the head greater than 10 *g* amateur women's premier netball over a single domestic competition season of matches for total impacts recorded and impacts per player positional group for injury tolerance level,[12-14] and impact severity limits,[15-17] and risk weighted cumulative exposure (combined probability)[18] by total impacts recorded and percentage of impacts recorded (%).

Eight players recorded impacts above the RWE_{CP} of 0.75 over the (see Table 5). Four concussions were identified over the duration of the study resulting in a concussion incidence of 33.6 per 1,000 match hours. All eight players were tested on the King-Devick test and three players recorded changes in their post-match assessment when compared with their baseline K-D test. One Centre player recorded two concussions over the competition and did not compete after the second concussion. There was a median (worsening) difference of -5.5s [-6.5 to -3.6 s] between the baseline and post-match K-D assessments (z=-1.8; p=0.0679) for players with a confirmed concussion. Players without any signs of a concussive injury recorded a median (increase) difference of 0.8 [0.4 to 2.8] s between baseline and post-match K-D assessments (z=-2.0; p=0.0427). There were observable differences between concussed and non-concussed players for median resultant peak linear ($\chi^2_{(1)}$=4.5; p=0.0039; z=-2.2; p=0.0251), rotational accelerations ($\chi^2_{(1)}$=8.0; p=0.0047; z=-2.5; p=0.0117) and RWE_{CP} ($\chi^2_{(1)}$=8.0; p=0.0047; z=-2.5; p=0.0.0117) values.

	Impacts	PLA (*g*)	PRA (rad/s^2)	RWE_{CP}	King-Devick Test		
	n=	**Median [IQR]**	**Median [IQR]**	**Median [IQR]**	**B 1 (s)**	**P-M 1 (s)**	**Diff (s)**

Wing Defence$	2	57 -	16,240 -	0.9962 -	46.4	51.5	*-4.6*
Goal Shoot	1	36 -	14,336 -	0.9681 -	44.7	43.9	0.8
Centre$*	1	44 -	14,896	0.9839 -	36.0	42.5	*-6.5*
Centre	2	42 -	11,853 -	0.8188 -	49.4	44.8	4.6
Goal Defence	2	64 -	14,720 -	0.9884 -	37.2	36.8	0.4
Goal Attack	1	48 -	11,599 -	0.8144 -	36.3	35.3	1.0
Goal Defence$	1	56 -	11,992 -	0.8885 -	42.3	45.6	*-3.3*
Goal Keep	2	38 -	13,331 -	0.8861 -	44.3	43.9	0.4
Centre$*	3	91 [57-118]	13,843 [12,016-21,941]	0.9906 [0.8926-0.9999]	35.8	42.2	*-6.4*
Total	**15**	**48 [38-65]**	**14,023 [11,933-15,152]**	**0.9743 [0.8186-0.9928]**	**42.3 [36.5-45.6]**	**43.9 [39.5-45.2]**	**0.4 [-5.5-0.9]**
Total non-concussed	5	40 [37-47][a]	11,953 [11,568-13,789][a]	0.8228 [0.7955-0.9482][a]	44.3 [36.8-47.1]	43.9 [36.1-44.4]	0.8 [0.4-2.8][a]
Total concussed	7	64 [50-85]	15,067 [13,933-16,252]	0.9920 [0.9834-0.9967]	39.2 [35.9-45.4]	44.1 [42.3-49.7]	-5.5 [-6.5--3.9]

$ = concussion identified; * = 3 impacts >0.7500 recorded in 1 match; PLA(g) = Peak Linear Accelerations; PRA(rad/s^2) = Peak Rotational Accelerations recorded in radians per second per second; RWE_{CP} = Risk Weighted Exposure (Combined Probability); s = seconds; B = Baseline; P-M = Post-Match; Diff = Difference; Significant difference (p<0.05) than (a) = concussed players

Table 4: Players with Risk Weighted Exposure (Combined Probability) greater than 0.75 by number of impacts, resultant peak linear and rotational accelerations, risk weighted exposure (combined probability) and King-Devick test results for amateur premier one netball players over a domestic competition season. Data are reported as median [25th to 75th interquartile range] and seconds.

Discussion

This study reports for the first time, the frequency, duration, magnitude and location of head impacts that occur on players participating in a premier one domestic amateur netball competition over a single season of matches. Despite netball being a 'non-contact' sporting activity, high magnitude impacts (>80 g) were experienced by this cohort during match participation. This level of severity was similar to impacts reported in other studies [10, 12, 34-38] reporting on contact sporting activities such as rugby, however the current cohort of players were female participating in a non-contact sporting activity. As there are no other studies reporting on head impact biomechanics in women's netball, the comparisons were limited to contact sporting activities such as women's soccer, [39] American football [12, 36, 37, 40-43] and New Zealand youth (U9) rugby union [10] and U11 rugby league [38].

Netball is classically thought of as a non-contact sport, designed to depower basketball and make it "more suitable" for women [2]. However, the speed at which the game is now played, particularly with players travelling in flight, questions how "depowered" the sport actually is. Furthermore, because of the limitation that players are only allowed to take one step with the ball in hand, it is clear, whilst watching a game that players are exposed to rapid acceleration and deceleration movements often caused by bodies coming into contact when stopping once they have the ball. This stochastic nature of netball has been attributed to the high number of orthopaedic injuries sustained during participation in this sport [44, 45]. It therefore seems intuitive that, during the course of the game, players are exposed to linear impact forces, in excess of 10 g, which may result in sub-concussive type injuries [4, 5].

However, to date, no data exists on the head impact exposure that netball players incur. Additionally, the rate of concussive injuries has also not been determined.

This study, of amateur netball players, playing a competitive season indoors on a sprung wooden floor, revealed a concussive rate of 33.6 per 1,000 match hours and a mean of 3 ±2 impacts >10 g per-player per-match. Thus, netball, while described as a non-contact, depowered sport, does in fact expose players to repetitive impacts resulting in subconcussive and concussive injuries. In assessing for the effects of sub-concussive and concussive type injuries, the K-D test was utilised. This sideline rapid-number naming test can test for changes in visual processing as 7/12 cranial nerves, along with approximately 30% of the brain [46, 47] are involved in this process such as saccadic eye movements. Saccadic eye movements can be utilised to assess cognitive domains such as attention, spatial and temporal orientation and working memory [27, 48]. These saccadic eye movements need to be both accurate, and fast, to effectively acquire image information in real time and are particularly demanding on the brain [27, 49]. Injuries resulting in the disruption of areas involved in the production and regulation of saccades can result in changes in these cognitive domains.[27] Undertaking the K-D test enables the analysis of numerous circuits throughout the brain involved in motivation, visual-spatial integration, attention, motor planning, and spatial organisation [50] as well as seven of the cranial nerves [46, 47]. The K-D test requires the utilisation of saccades to enable completion of the test, and may also reflect concentration and language function [27]. Injuries to any of the areas involved in saccade production and regulation may explain the eye movement and memory related problems that can occur following a concussive injury [27].

All players were observed for any impacts, or being knocked to the ground and, if this occurred, the players were assessed on the side of the court with the K-D test in line with previous guidelines [51]. Only one player over the study was observed to have suffered an impact to the head and was assessed courtside with a resulting delay (worsening) of the K-D test when compared with her baseline. The player's head impact biomechanics were also reviewed post-match and she recorded the maximum result peak linear (118 *g*) and rotational (21,941 rad/s^2) accelerations over the study. Post-match all the head impact biomechanics data were downloaded and screened for the RWE_{CP}. Any individual impact with a RWE_{CP} >0.75 were recorded and the coach of the team was notified. Individual players were assessed the following day with the K-D test and if they had a delay or worsening of the time from their baseline they were referred for a further evaluation by a health professional. Although not all players with a RWE_{CP} >0.75 recorded changes from their baseline K-D score, players with an RWE_{CP} >0.98 did record a worsening of the post-match times on the K-D when compared with their baseline score. As a result, there were three concussions that were identified through the combined use of the XPatch and the K-D test. Future studies recording head impact biomechanics may consider the use of the RWE_{CP} to assist with the identification of concussive injuries in a non-contact sport such as netball.

The average number of impacts to the head recorded per-player per-match was less than youth American football players (5.8 [40] to 12 [41]), women's soccer (7.2) [39] and youth rugby union (10) [10] and rugby league (13) [38]. When compared by player positional groups, impacts for the centre (6 ±4) were similar to the 6 to 9 yr old American football players (5.8) [40] and women's soccer (7.2) [39]. The median linear acceleration (13*g*) recorded per-player per-match for the netball players was higher than the median reported for 9 to12 year old American football players (18*g*) [42] but lower than the median reported for youth American football players (16*g*,[43] 18*g* [42] and 22*g*[41]), youth rugby union (15*g*) [10] and rugby league (16*g*) [38] players. The median rotational acceleration (2,395 rad/s^2) recorded per-player per-match for the netball players was higher than the median reported for 7 to 8 year olds (686 rad/s^2), [43] 9 to 12 year olds(829 rad/s^2), [42] 12 to 14 year olds (987 rad/s^2), [41] high school [36, 37] (903 rad/s^2) and collegiate (904-981 rad/s^2) [21, 35] American football players. When compared with women's soccer (2,094 rad/s^2), [39] youth rugby union (2,296 rad/s^2) [10] and rugby league (2,773 rad/s^2) [38] players, the results were similar for the netball players. Head impact exposure varies with player position with centre players recording more impacts than attack and defence players. However, the magnitude of the impact was lower when compared with the attack and defence playing positions. Whilst it is unknown what frequency, or magnitude, of head impact constitutes a long-term risk to the player, it is of interest to note that these parameters are position specific, which may allow for position specific preventative therapy and training. The finding that the resultant peak rotational accelerations were similar to other non-helmeted sports was unexpected, especially when considering that netball is considered a non-contact game. Although women's soccer [39] is non-contact they do allow head contact with the ball, are able to run while in control of the ball and can physically attempt to retain possession. Netball requires the players to stop once they receive the ball, not to make physical contact and to release the ball within a limited time period.

Inter-study comparisons can be difficult given different thresholds utilised to count an impact and standardization of this has been called for [5]. For example, the data acquisition limit of 30*g* was utilised for the recording of impacts to the head for Pop Warner youth football [52]. Other studies have utilised a 10*g* [40] 14.4*g* [41-43] and 15*g* [12, 13, 36] impact threshold limit. By utilising a 30*g* data acquisition threshold, approximately 80 to 85% of the impacts may have been excluded from the data set [52]. Daniel [40] reported on 6 to 9 yr. old American football players, approximately 85% of the impacts recorded had a linear acceleration <30 *g*. Cobb [42] reporting on 9 to 11 yr. old American football players recorded 80% of impacts at 30*g*. Although some of these published studies were included as comparisons with the current study, the comparisons should be undertaken with caution as the reported data acquisition limit utilised in the current study was set at 10*g*. The variation of impact thresholds limits inter-study comparisons and a standardised reporting format for impacts needs to be established [5] identifying which parameters should be included (and at what linear data acquisition limit the data should be reported from. The identification of thresholds for head impacts that are sub-concussive versus non-sub-concussive is also needed.

The centre position recorded six impacts >10*g* per-match, accounting for this position experiencing the highest total frequency impact burden for resultant peak linear (2,953*g)* and rotational (545,239 rad/s^2) accelerations. In contrast, the wing attack recorded the highest median resultant peak linear acceleration of 17*g* and the highest median resultant peak rotational acceleration of 3,813 rad/s^2. Furthermore, the wing attack recorded the highest median RWE_{CP} of 0.0019 over the study. These findings likely result from the centre having the highest workload of ball handling and freedom of movement on the court. Chandler [53] utilised accelerometers to measure player load during training and games amongst eight collegiate level players. The centre players had higher player loads (player load per-minute, forward per-minute, sideward per-minute, and vertical per-minute) than any other position. Fox [54] confirmed this, reporting that the centre player had the highest proportion of match time for being active. In contrast, another study [55] involving elite level players using triaxial accelerometers reported that the centre, wing defence, wing attack and goal attack could be characterised as having the highest playing intensity and the lowest proportion of match time spent in the low intensity zone. The goal shoot, goal keep and goal defence positions tended to have the opposite characteristics [55]. The highest proportion of match time in the high playing intensity zone were the wing defence (4.7%) and the wing attack (4.6%) respectively, whilst the centre spent 3.9% of match time in the high playing intensity zone [55]. These results indicate that the wing positions may complete a high number of these types of movements in a match and the wing attack and wing defence positions complete sprints more frequently than any other position, during international level netball matches [54].

In addition, impacts overall were more commonly recorded on the side of the head. This may be reflective of how the game of netball has evolved with players running in one direction whilst facing perpendicular to this in order to receive the ball. As recorded in this study, centres experienced the highest median peak resultant rotational acceleration that likely represents the rapid changing direction for this position in the game.

Limitations

This study is limited by the low numbers of players thus the extrapolation of these individual players' exposures to player position in general needs to be viewed as indicative only. In addition, this study only assessed amateur adult female netball players playing indoors on a sprung wooden floor. Future studies should seek to determine the effects of player age, experience, fitness level and gender, as well as court flooring type, including the more common outdoor sealed court which most amateur players frequent.

Conclusion

Although the game of netball is considered a non-contact sport it is evident from data presented in this study, that players can experience significant head impacts capable of causing clinical concussion. Furthermore, they experience repetitive head impacts in excess of sub-concussive thresholds. Head impact frequency and magnitude are player position dependent. The players in the centre position are more exposed to impacts because of the pivotal role and freedom of movement in all thirds of the court. However, these impacts may not be as severe compared to players in attack and defence positions who travel at greater speed in their role to distribute the ball across and down the court often resulting in unintentional contact. Players in the goal positions tend to mark their opposites quite closely because of their restricted movements in their half of the court resulting in multiple but less severe contacts.

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Compliance with Ethical Standards

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