Gender Differences and Influence of Impact Mechanism and Location on Head Impact Kinematics in High School Soccer

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ABSTRACT

An estimated 1.6-3.8 million sports- and recreation-related mild traumatic brain injuries occur in the U.S. annually. Adolescents are particularly vulnerable due to slower recovery times, higher injury rates, and under-reporting. In equivalent sports, females have a higher incidence of concussion possibly attributed to differences in head impact kinematics due to cervical strength, head mass, and impact rate. The objective of this study was to characterize gender differences and the effect of impact location and mechanism on head impact kinematics in high school soccer and analyze data acquired in the real-world in the context of sensor validation data collected in a controlled laboratory setting. Male and female high school soccer players were instrumented with the SIM-G (Triax Technologies Inc.), a headband-based head impact sensor comprised of a tri-axial accelerometer and gyroscope. Based on laboratory tests, SIM-G sensors had high inter-sensor reliability (R^2>0.99) and correlated strongly with the reference (R^2>0.99) but consistently underestimated peak angular velocity (3.5±1.2 rad/s underestimation (16%); p=0.005), suggesting that the on-field measures may be less than what participants actually experienced. On-field head impact data were collected for 889 player-games (509 male). After detailed video analysis to remove false positives, 1305 (1034 male) impacts were identified; 79% were head-to-ball, 10% were falls, 11% were player contact. Female player-to-player impacts (6.2±3.8 rad/s^2) resulted in significantly higher peak angular accelerations than males (4.3±3.0 rad/s^2; p=0.026). Male (17.6±6.6 rad/s) and female (16.6±7.1 rad/s) frontal head-to-ball impacts resulted in significantly lower mean peak angular velocity than side (M=21.6±7.2 rad/s, p<0.001; F=22.4±9.1 rad/s, p=0.041), rear (M=23.6±8.2 rad/s, p<0.001), or crown (M=20.3±6.8 rad/s, p=0.001; F=20.8±8.2 rad/s, p=0.003) head-to-ball impacts. Proper heading technique using the front of the head should be emphasized to reduce higher kinematic loading in repetitive heading. These on-field data further our understanding of gender differences in impact characteristics that may ultimately help explain injury rate disparities.

INTRODUCTION

An estimated 1.1 million people in the U.S. are treated in the emergency department (ED) for traumatic brain injury (TBI) each year, and 1.6-3.8 million sports- and recreation-related TBIs, occur each year (CDC 2007; DePadilla 2018). Concussions, a subset of mild TBIs, are of particular concern because sporting activity is a common exposure for injury risk and up to 50% of concussions go unreported and untreated (Llewellyn 2014; McCrea 2004). Concussion occurs from rotational loading of the head giving rise to diffuse stresses and strains in the brain tissue, which leads to axonal and synaptic damage (Meaney 2011; Stemper 2014). Injured patients exhibit symptoms of headache, dizziness, light sensitivity, and nausea, and they develop physiological deficits in multiple brain functions measurable by vestibular balance and oculomotor tracking clinical exams (Kontos 2017). Adolescents are particularly vulnerable to concussion as evidenced by slower recovery times, higher injury rates, and under-reporting (Llewellyn 2014). Head impact sensors use accelerometers and gyroscopes to measure linear acceleration and angular velocity for a biomechanical measure of impact severity. As such, head impact sensors provide a unique opportunity to study repetitive head impacts in contact sports. Several recent research studies have emphasized the need for video confirmation to eliminate false positives from sensor recordings (Lamond 2018; Cortes 2017). Systematic validation studies from sensor manufacturers and independent researchers show high variability of sensor accuracy even in controlled laboratory settings, so it is necessary to interpret on-field data in the context of validation work (Sandmo 2019; Allison 2015).

In equivalent sports such as soccer, females have a higher incidence of concussion possibly attributed to differences in head impact kinematics due to cervical strength, head mass, and impact rate (Frommer, 2011; Maher, 2014). Controlled heading experiments found a correlation between smaller neck girth and higher linear and angular acceleration, and females had higher head kinematics in equivalent heading drills (Bretzin 2016; Caccese 2018A). Repetitive heading can cause short-term balance deficits, but the long-term effects are not understood (Caccese 2018B). Proper heading technique with the forehead reduces head kinematics and can reduce loading from repetitive heading in practice and games (Caccese 2016; Harriss 2019). Despite intentional heading being the leading head impact mechanism in soccer, player-to-player contact is the most frequent cause of injury for both males and females (Chandran 2017). On-field soccer impact kinematics has shown mixed findings for gender differences, likely due to differences in speed of play and player mass between males and females that may influence impact loading characteristics. Reynolds (2017) and Nevins (2018) found higher average peak linear acceleration and angular accelerations for collegiate and high school males than females, while Chrisman (2017) found higher linear acceleration for youth females compared to males. The objective of the current study was to characterize gender differences and the effect of impact location and mechanism on head impact kinematics in high school soccer and analyze data acquired in the real-world in the context of sensor validation data collected in a controlled laboratory setting.

METHODS

Triax Technologies Smart Impact Monitor (SIM-G) Head Impact Sensor

Triax Technologies' Smart Impact Monitor (SIM-G) is a head impact sensor comprised of a triaxial accelerometer and gyroscope that measure linear acceleration and angular velocity, respectively (Figure 1). The sensor provides continuous monitoring of head impact loading during sporting activity, while secured to the back of an athlete's head in a neoprene tightly fitted headband to maximize coupling. Linear acceleration data were transformed from the device location to the center of gravity of the head, and resultant data were calculated from axis-specific data. Angular velocity was directly recorded by the three-axis gyroscope, and angular acceleration was calculated by differentiating the angular velocity measurements. SIM-G sensors measure linear acceleration from 3-150g, but they only trigger a recording when a linear acceleration threshold is surpassed (>16g). The sensor records 62 ms of data at 1000 Hz, 10 ms before and 52 ms after linear acceleration exceeds the threshold (Triax Technologies 2014).

Figure 1: Triax SIM-G sensor (left) fitted just above the greater occipital protuberance in a neoprene headband (right). Figure adapted from Triax (2018).

Laboratory Angular Velocity Accuracy Evaluation

To evaluate sensor accuracy, SIM-G sensors, without the headband, were attached to an adapted HYGE pneumatic linear actuator device that converts linear actuation to pure angular motion (Figure 2; Raghupathi and Margulies 2002). Two magnetohydrodynamic (MHD) angular velocity sensors (custom-built ARS-06 from Applied Technology Associates, Albuquerque, NM) were attached to the sidearm linkage as the reference angular velocity for comparison to each of the SIM-G sensors (Cullen 2016). Data were collected at 10 kHz. Two SIM-G sensors were attached to the HYGE device with a custom press-fit aluminum casing and screw-tightened cover to maximize coupling. The SIM-G rotation arm distance was set based on anthropometric data for the average pediatric participant. Specifically, the sensor was secured 92.5 mm from the center of rotation as the average distance from the geometric center of the head to the greater occipital protuberance at age 10 for females is 91.4 mm and 94.6 mm for males at age 14 (Farkas 1992; Arboleda 2011).

Figure 2: Experimental setup for testing SIM-G accuracy in pure rotation. (Left) The center of rotation and moment arm attachment bolts are indicated by arrows (A and B). SIM-G sensors were secured 92.5 mm from the center of rotation as indicated by the arrow C. Magnetohydrodynamic sensors (D1 and D2) provide the reference angular velocity of the HYGE. (Right) A custom aluminum casing created a press fit in two axes (XY plane) for two SIM-G sensors, allowing inter-sensor reproducibility to be tested. The last degree of freedom (Z axis) is secured by a screw tightened top.

Two sets of SIM-G sensor pairs were tested for at least four trials at each of five peak angular velocities driven by air pressure input (Table 1). A target peak velocity range of 10-30 rad/s covered the typical head impacts observed in this study high school soccer. Since the HYGE device is a pneumatically driven system with analog input pressures, the resulting angular kinematics had some variation in peak velocity within an impact magnitude group. The HYGE produces a consistent rotation angle (38.8±1.8 degrees) across all angular velocities, resulting in a range of event durations (35-87 ms). This range is similar to angular velocity impact pulse durations observed in video-confirmed head impacts in adolescent soccer and longer than a typical linear acceleration head impact in football (8–12 ms) (Cobb 2013; Broglio 2009).

Table 1: Test matrix

Sensor Group	Angular Velocity Magnitude: Provided as Input Pressure Ratio (PSI)				
	25/5	40/8	50/10	75/15	100/20
1 & 2	6	4	8	4	8
3 & 4	4	4	9	4	4

High School Soccer Head Impact Analysis

Adolescent male varsity and female varsity soccer teams from a suburban US high school (grades 9-12) were instrumented with headband-mounted impact sensors (SIM-G, Triax Technologies) during competitive games for two seasons. Video footage from games was captured from a single-camera view (Sony HD Camcorder CX405) located close to the mid-point of the pitch from as high a vantage point as possible. Approximately one-third of the soccer pitch was filmed in the field-of-view, and the videographer panned the camera to follow the action of the ball. Prior to the start and end of each half, a few seconds of a world clock website was filmed, which provided a timestamp for the video footage. All sensor data outside of the start and end of the game were excluded. Sensor-recorded events associated with players who were not on the pitch or out of frame at the sensor-recorded time were excluded. Remaining sensor-recorded events associated with a player who was in-frame at the time were analyzed to categorize each event as either an impact event (e.g. player heading the ball), trivial event (e.g. player adjusting headband), or non-event (e.g. player stationary and not touching headband). The mechanism of identified impact events was coded as ball-to-head (e.g. ball impacting face of unsuspecting player), head-to-ball (e.g. purposeful heading of the ball), fall (e.g. player makes contact with ground after losing balance) or player contact (e.g. elbow of opposing player impacting the head during aerial contest). The impact location of identified impact events was coded as front (e.g. face, forehead), side, crown (top center of the head), and rear. Data were summarized overall and by gender.

Data Analysis and Statistics

Key outcome measures include peak resultant linear acceleration, angular velocity, and angular acceleration in which peak is the maximum value during the impact event. For the laboratory evaluation, reproducibility was assessed by correlation analysis (Pearson correlation coefficient) and paired t-test ($\alpha = 0.05$) of peak angular velocity comparing the two SIM-G sensors from the same trial. SIM-G accuracy was assessed by correlation analysis and paired t-test (α=0.05) of peak angular velocity comparing SIM-G to HYGE reference values. For the on-field soccer head impact analyses, ANOVA determined differences between mean peak linear accelerations, angular velocities, and angular accelerations for the four impact mechanisms and four impact locations separately for each gender. A Tukey's post-hoc determined specific group differences. Significant differences ($p<0.05$) in kinematic outcomes between female and male varsity players were assessed using Student's two-sample t-test.

RESULTS

SIM-G Has High Reproducibility and Consistently Underestimates Angular Velocity

From the laboratory tests, peak angular velocities between the two SIM-G sensors paired for each test strongly correlated with one another (Figure 3; R^2>0.99, y=1.0046x, p<0.001), and magnitudes significantly but not substantially differed as sensor two consistently recorded a slightly higher peak angular velocity (mean difference of 0.09±0.09 rad/s, p<0.001). SIM-G sensors showed high inter-sensor reproducibility by consistently recording similar peak angular velocity with an average 0.43% difference. SIM-G peak angular velocity strongly correlated with the reference measures from the HYGE (Figure 4; R^2>0.99, y=0.8428x, p<0.001). On average, the peak angular velocity of the SIM-G was 85.0(±1.6) % of the reference HYGE measure.

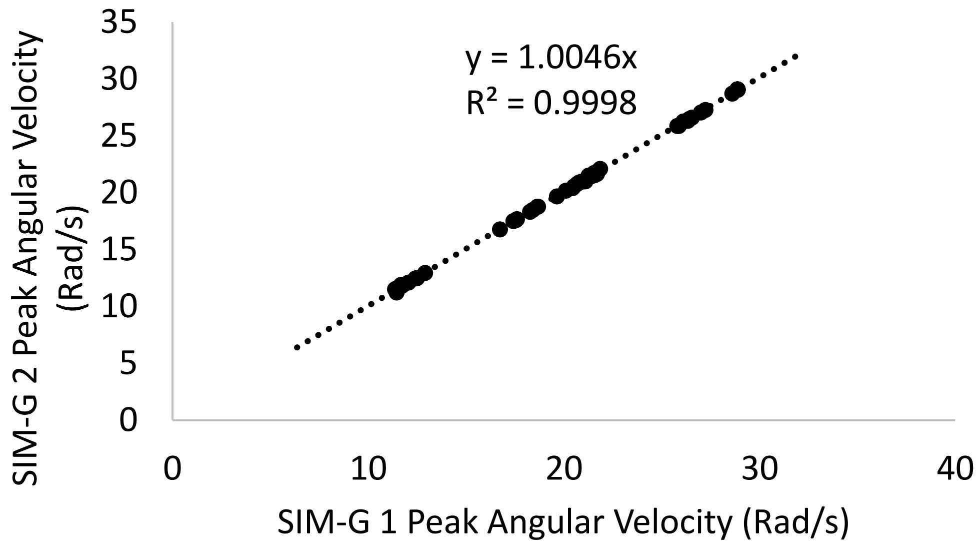

Figure 3: Measurement of peak angular velocity shows strong reproducibility between the pairs of SIM-G sensors subjected to the same angular event (n = 2 pairs of sensors; $p < 0.001$, $y = 1.0046x$, $R^2 > 0.99$). The intercept was set to zero for linear regression.

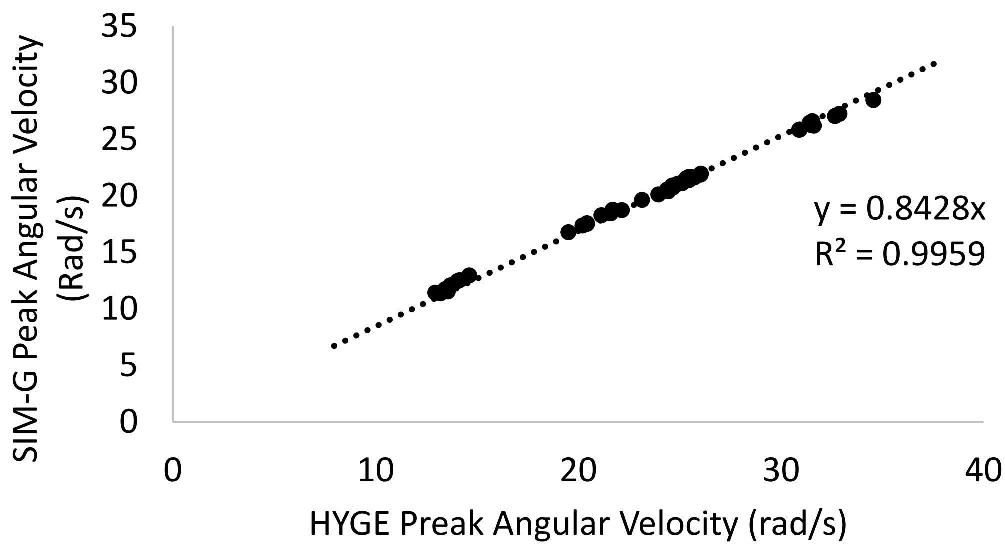

Figure 4. SIM-G peak angular velocity strongly correlates with peak HYGE reference measurements ($p < 0.001$, $y = 0.8428x$, $R^2 > 0.99$).

Gender Differences in Impact Kinematics

Data were collected for 88 player-seasons (45 male) totaling 889 player-games (509 male). For varsity game days, 40352 sensor events were recorded. A total of 6796 sensor events were recorded during verified game times (Table 2). The number of sensor-recorded events was further reduced to 2775 after excluding data from players who were not on the pitch and to 1893 after excluding data from players not in the frame of the video footage at the time the sensor recorded the event.

Table 2: Sensor-recorded events.

	All (41 games)		Female varsity (18 games)		Male varsity (23 games)	
	n	**Proportion**	**n**	**Proportion**	**n**	**Proportion**
During verified game times	6796		1758		5038	
With on-field players	2775	29%	1191	51%	1584	22%
With players in field-of-view	1893	20%	565	24%	1328	19%
Non-events*	181	10%	83	15%	98	7%
Trivial events*	396	21%	207	37%	189	14%
Impact events*	1316	70%	275	49%	1041	78%
Ball-to-head+	11	1%	2	<1%	9	1%
Fall+	129	10%	18	7%	111	11%
Player contact+	144	13%	24	13%	120	12%
Head-to-ball+	1032	77%	231	80%	801	77%
Rear#	68	7%	6	3%	62	8%
Side#	199	20%	22	10%	177	22%
Crown#	248	24%	67	29%	181	23%
Front#	505	50%	133	58%	372	47%

*expressed as a proportion of impacts for on-field players within the field of view
+ expressed as a proportion of impacts events
# expressed as proportion of head-to-ball impacts

After detailed video analysis, 1316 (1041 male) impacts were identified; 77% were head-to-ball, 10% were falls, 13% were player contact, 1% were ball-to-head. Ball-to-head were not included in analysis due to the small number of impacts. Impact mechanism had a significant effect on peak linear acceleration in females ($p<0.001$) and males ($p<0.001$; Figure 5). Head-to-ball linear accelerations (43.6±14.0 g) were significantly higher than falls (33.0±8.8 g; $p=0.011$) in females. For males, head-to-ball impacts (45.9±18.1 g) were significantly higher than falls (29.7±13.2 g; $p<0.001$) and player contacts (38.4±18.1 g; $p<0.001$), and player contacts were significantly higher than falls ($p<0.001$). Male head-to-ball linear accelerations were significantly higher than females ($p=0.041$), but there were no differences amongst player contacts ($p=0.294$) and falls ($p=0.199$). For peak angular velocity, male head-to-ball impacts (19.6±7.2 rad/s) were significantly higher than male falls (15.1±7.7 rad/s; $p<0.001$; Figure 6). Male peak angular velocities for head-to-ball impacts were significantly higher than females (18.5±7.9 rad/s; $p=0.048$), and female player contacts (21.7±8.6 rad/s) had higher peak angular velocities than males (17.3±8.8 rad/s; $p=0.002$). For peak angular acceleration, male head-to-ball impacts (5.6±3.0 rad/s^2) were significantly higher than male falls (3.3±2.4 rad/s^2; $p<0.001$) and player contacts (4.3±2.9 rad/s^2; $p<0.001$; Figure 7). Female player contacts (6.2±3.8 rad/s^2) resulted in significantly higher peak angular accelerations than falls (3.3±1.9 rad/s^2; $p=0.036$). Female player contacts resulted in significantly higher peak angular accelerations than male player contacts ($p=0.024$), and male head-to-ball impacts were significantly higher than female head-to-ball impacts (5.1±2.8 rad/s^2; $p=0.036$).

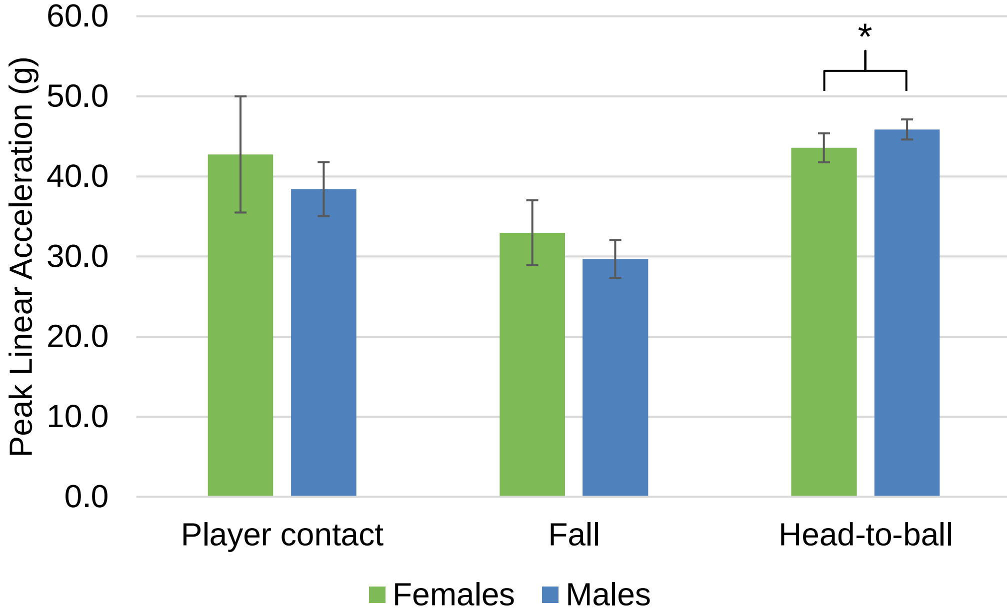

Figure 5: Impact mechanism had a significant effect on mean peak linear head accelerations. Data are presented mean ± 95% confidence interval (CI). *Significant difference ($p<0.05$) between genders. Significant differences between impact mechanism described in text.

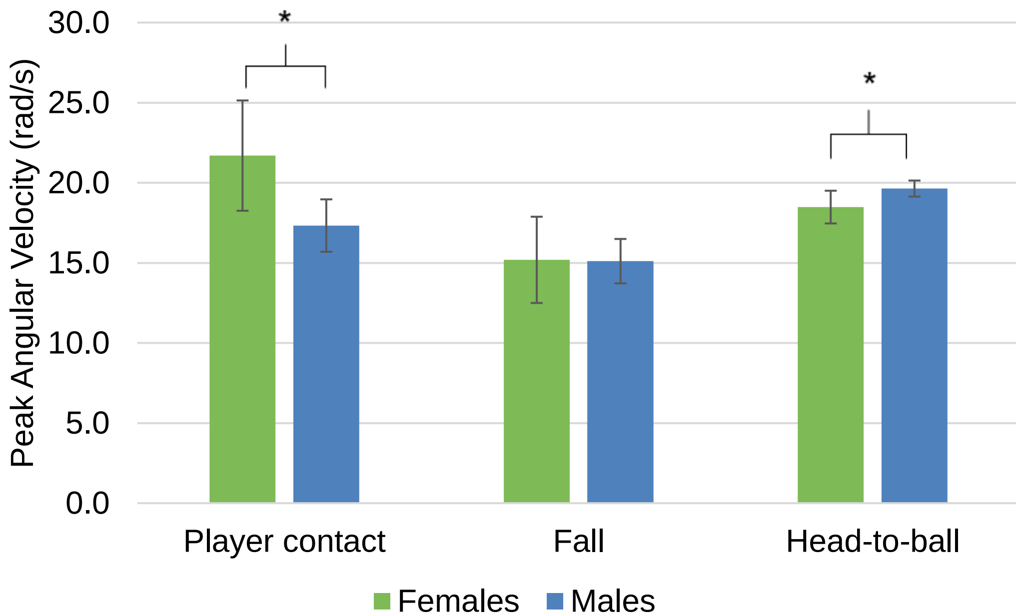

Figure 6: Impact mechanism had a significant effect on mean peak angular head velocity. Data are presented mean ± 95% CI. *Significant difference ($p<0.05$) between genders. Significant differences between impact mechanism described in text.

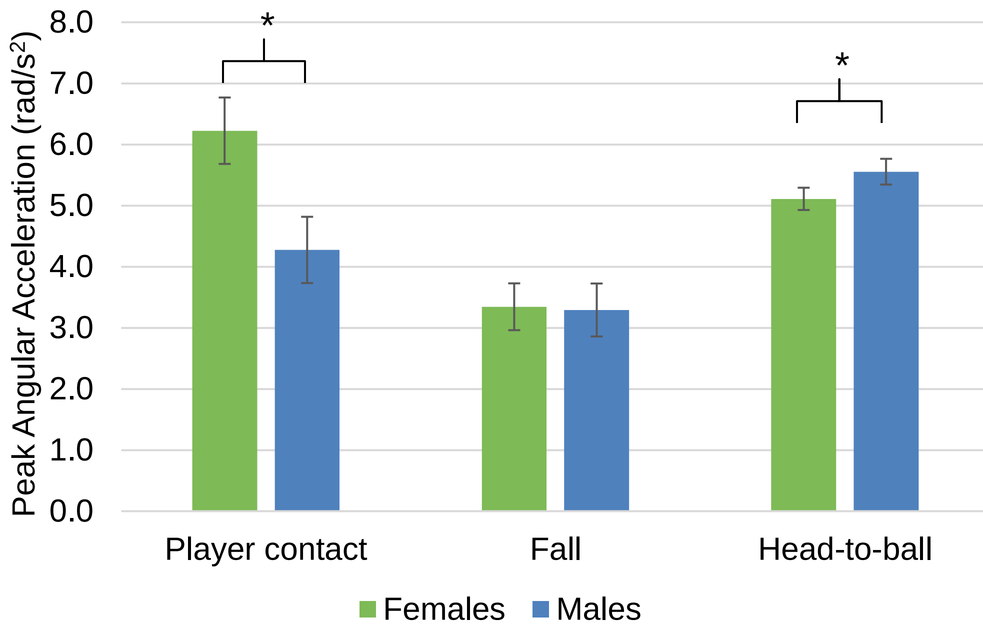

Figure 7: Impact mechanism had a significant effect on mean peak angular head accelerations. Data are presented mean ± 95% CI. *Significant difference ($p<0.05$) between genders. Significant differences between impact mechanism described in text.

To analyze the effect of impact location on impact severity, head-to-ball impacts were used for clarity of impact location on video and higher number of events captured. Of the head-to-ball impacts, the distribution of impact location was: 50% front, 20% side, 7% rear, 24% crown. For males, frontal head-to-ball impacts (39.1±12.4 g) had significantly lower peak linear acceleration than side (49.6±18.0 g; $p<0.001$), rear (67.3±25.4 g; $p<0.001$), and crown (48.4±17.3 g; $p<0.001$; Figure 8) impacts. Male rear impacts were significantly higher than side ($p<0.001$) and crown ($p<0.001$) impacts. Female mean peak linear acceleration for rear impacts (65.9±31.4 g) was significantly higher than for frontal impacts (40.9±11.4 g; $p=0.005$). There were no significant differences between genders on frontal, side, rear, and crown impacts for peak linear acceleration.

For peak angular velocity, male frontal impacts (17.6±6.6 rad/s) had significantly lower peak angular velocities than side (21.6±7.2 rad/s; $p<0.001$), rear (23.8 ± 8.2 rad/s; $p<0.001$), and crown impacts (20.3±6.8 rad/s; $p=0.001$; Figure 9). Female frontal impacts (16.6±7.1 rad/s) were significantly lower than side (21.9±8.9 rad/s; $p=0.041$) and crown impacts (20.8±8.2 rad/s; $p=0.003$). Male frontal impacts (4.5±2.3 rad/s^2) had significantly lower peak angular acceleration than side (6.2±3.1 rad/s^2; $p<0.001$), rear (9.1±4.4 rad/s^2; $p<0.001$), and crown impacts (5.9±2.7 rad/s^2; $p<0.001$; Figure 10), and rear impacts were significantly higher than side ($p<0.001$) and crown impacts ($p<0.001$). Female angular acceleration had no significant differences based on impact location. Again, there were no significant differences between genders on frontal, side, rear, and crown impacts for peak angular velocities or accelerations.

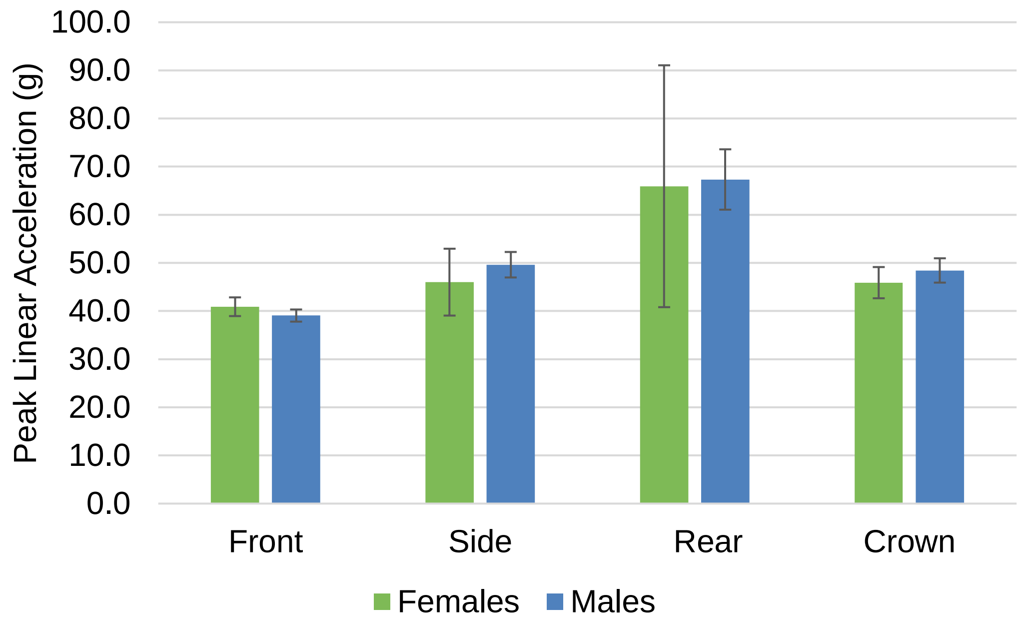

Figure 8: Impact location for head-to-ball impacts had a significant effect on mean peak linear head acceleration. Data are presented mean ± 95% CI. Significant differences between impact mechanism described in text.

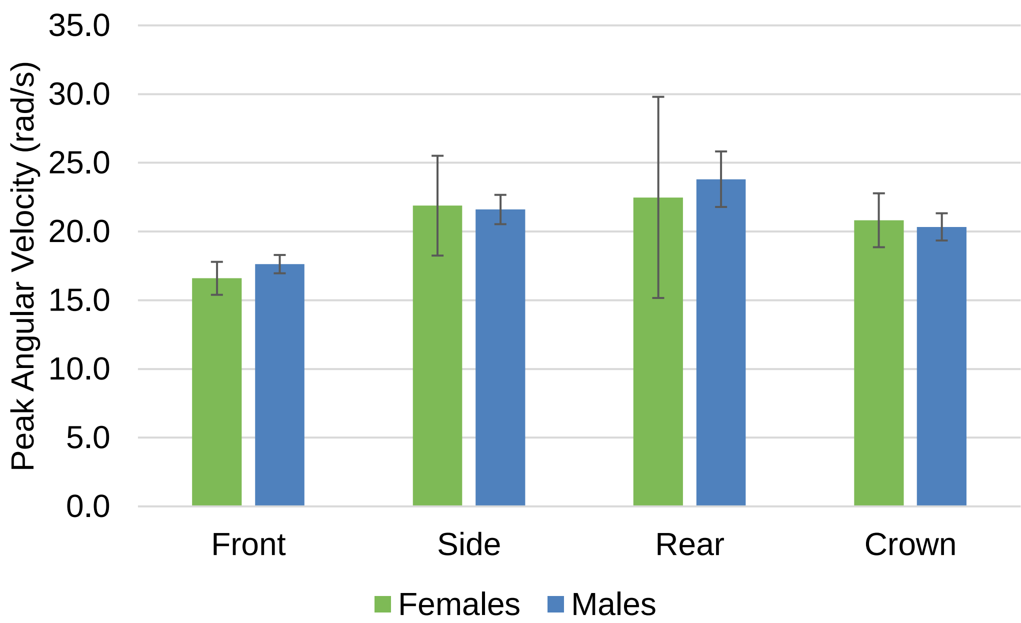

Figure 9: Impact location for head-to-ball impacts had a significant effect on mean peak angular head velocity. Data are presented mean ± 95% CI. Significant differences between impact mechanism described in text.

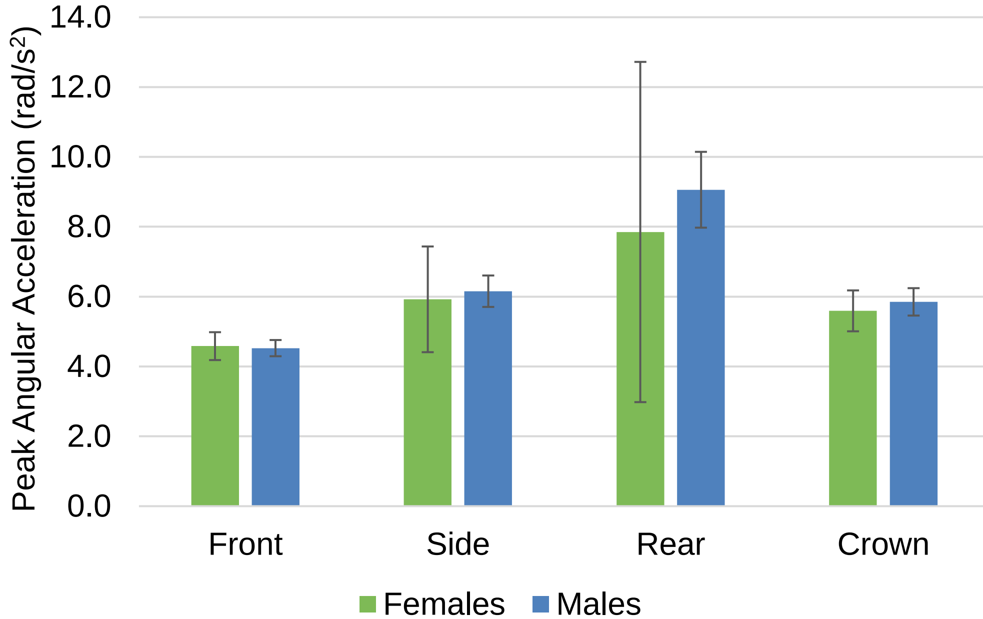

Figure 10: Impact location for head-to-ball impacts had a significant effect on mean peak angular head acceleration. Data are presented mean ± 95% CI. Significant differences between impact mechanism described in text.

DISCUSSION

Studying the effect of repetitive head impacts on long-term physiological outcomes in athletes requires reliable sensor measurement of head kinematics. In addition to capturing all impacts in live sport and eliminating false positives with video analysis (Lamond 2018; Cortes 2017), sensor reproducibility and accuracy is critical for comparisons between individual players, teams, and genders. In this study, we evaluated these metrics for the Triax SIM-G for angular velocity; reproducibility was evaluated by comparing results from two SIM-G sensors in the same test and accuracy was evaluated by comparing to a known reference.

The SIM-G sensor was highly reproducible; independent SIM-G sensors had an average peak angular velocity difference of only 0.5% when simultaneously subjected to the same rotational impulse event. Although statistically significant, the difference between the two sensors (mean difference: 0.09 ± 0.09 rad/s) was insubstantial and not meaningful compared to mean head impact angular velocities of approximately 20 rad/s observed in high school soccer. Consistent differences between sensors may have been due to slight calibration differences in manufacturing, or axis orientation differences (positive y-axis vs. negative y-axis rotation) may have had a slight effect.

The SIM-G sensor was also highly accurate; peak angular velocity strongly correlated with reference measures but consistently underestimated the reference by approximately 16%. In Triax Technologies testing (2014) of the SIM-G device on a human head surrogate (NOCSAE headform), peak angular velocity correlated highly with the reference (R^2=0.98; slope~1). This may be an indication that the inherent underestimation of the sensor was counteracted by an overestimation error introduced by coupling of the sensor to the headband and the headband to the surrogate. Further investigation is required to assess head coupling and system error utilizing a human head surrogate and work towards describing on-field sensor accuracy. Overall, the SIM-G provides consistent measurement of angular velocity in a rigidly attached system with a predictable underestimation of peak angular velocity, suggesting that on-field measures may be less than what participants actually experienced.

Impact mechanism in high school soccer had a significant effect on average head kinematics and these relationships differed by gender. Male head-to-ball impacts resulted in higher peak linear acceleration, angular velocity, and angular acceleration than females, possibly due to differences in speed of play that may influence intention head impact kinematics. Player contacts are the most common cause of concussion in soccer (Frommer, 2011; Maher, 2014), and angular acceleration has shown better predictive ability of diffuse brain injuries such as concussion than linear acceleration (Cullen 2016; Meaney 2011). Player contacts in females resulted in significantly higher angular velocities and accelerations than male player contacts and female falls. Female players have lower head-neck segment mass, cervical strength, and neck girth which may lead to higher head kinematics, especially angular acceleration and velocity as the head rotates about the neck (Bretzin 2016; Caccese 2018A). Gender differences in falls were probably not evident because of the heterogeneous nature of the fall category that spans intentional slide tackles to directly hitting the ground after jumping. These gender differences in head impact kinematics may provide crucial information to understand injury rate disparities, but further research is needed to connect repeated player impacts to potential deficits in vestibular and ocular function and actual diagnosed concussive injury.

Head-to-ball impacts, or intentional headers, resulted in higher average peak linear acceleration, angular velocity, and angular acceleration than falls for males and higher linear acceleration than falls for females. Intentional headers represent approximately 80% of head impacts in soccer, so they were further analyzed for the effect on impact location on severity. Proper heading technique uses the forehead (frontal impact) with a tensed neck to limit head motion and increase power to the ball, and Harriss (2019) found frontal headers resulted in lower peak angular velocities than crown (top of the head) impacts. In our study, male frontal impacts resulted in lower peak linear acceleration, angular velocity, and angular acceleration than side, crown, and rear impacts. In addition, females had lower peak angular velocity from frontal headers than side, crown, and rear impacts. Therefore, emphasis on proper heading technique should be made to reduce repetitive head loading. Rear impacts may have resulted in higher kinematics due to high neck flexion needed for intentional heading with the back of the head (flick headers); however, some high-magnitude rear impacts may be due to ball-to-sensor contact resulting in erroneously high values.

The current study has a few limitations pertaining to scope and sensor event capturing. The laboratory validation study only investigated angular velocity. Angular acceleration is derived from angular velocity, and the lower sampling rate of the SIM-G would have introduced increased error compared to the reference HYGE during the integration process. The HYGE produces a purely rotational event and does not have built in calibrated linear acceleration measurement devices; therefore, linear acceleration was not analyzed. For on-field data collection, a single camera was used to follow the play, so potential off-the-ball impacts may have occurred. Additionally, only games were studied which does not provide a holistic view of head loading in high school season including activities such as heading drills in practice. Lastly, only a single high school was studied; these results may not be generalizable to other schools, level of soccer play (e.g. middle school or collegiate) or other sports.

CONCLUSIONS

Quantifying SIM-G sensor reproducibility and accuracy provides crucial information for interpreting data collected from the sensor quantifying the biomechanics attributable to impacts recorded in live sporting activity. The SIM-G was highly reproducible and strongly correlated with reference measures for peak angular velocity. It did, however, consistently underestimate velocity magnitude, but this systematic error can be analytically accounted for when interpreting on-field data from this sensor. Female players had higher angular acceleration in player contacts, which have been reported to be the most frequent mechanism of head injury in soccer. Frontal headers resulted in lower kinematics than side, crown, or rear head-to-ball impacts suggesting proper heading technique can minimize kinematics. Understanding gender differences and impact specific differences in head impact kinematics may provide crucial information to understand injury rate disparities between males and females and causes of head injury in high school soccer.

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