Comparison of Head Impact Biomechanics Across Multiple Sports

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ABSTRACT

Athletes may sustain numerous head impacts during sport, leading to potential neurological consequences. Wearable sensors enable real-world head impact data collection, offering insight into sport-specific brain injury mechanisms. Most instrumented mouthguard studies focus on a single sport, lacking quantitative comparison of head impact biomechanics across sports. Additionally, direct comparison of prior studies can be challenging due to variabilities in methodology and data processing. Therefore, we gathered head impact data across multiple sports and processed all data using a uniform processing pipeline to enable direct comparisons of impact biomechanics. Our aim was to compare peak kinematics, impulse durations, and head impact directionality across ice hockey, American football, rugby, and soccer. We found American football had the highest magnitude head impact kinematics and observed directionality differences in linear and angular kinematics between sports. On the other hand, there were no significant differences in impulse durations, which was unexpected given different impacting objects and protective equipment across sports. In future work, we aim to expand our dataset to better match sports for understanding the influence of sex, equipment, and playstyle on head impact biomechanics.

INTRODUCTION

Concussion, or mild traumatic brain injury (mTBI) continues to be a major health concern for many contact sport athletes (Yue et al., 2020) and a leading cause of disability, especially in youth and adolescents (Halstead et al., 2018). More recently, there is a growing body of literature suggesting repeated subconcussive events can give rise to similar neurophysiological changes as concussion (Rawlings et al., 2020). To further understand how head impacts during sport are influencing brain health, researchers have applied wearable sensors to collect on-field head impact biomechanics data. In particular, the instrumented mouthguard (iMG) is now a standard validated wearable device for measuring head impact kinematics in more real-world settings (Kuo et al., 2022). Commonly, iMGs contain an accelerometer for measuring linear accelerations, and a gyroscope for measuring angular velocities, thus capturing the skull's motion in 6 degrees-of-freedom during an impact. Researchers are leveraging data from iMGs to quantify potential brain injury risk through peak kinematics measures such as peak linear and rotational accelerations (Camarillo et al., 2013) as well as simulated brain strains (Ji et al., 2014). Various studies have deployed iMGs to gather head impact data in sports such as American football, ice hockey, rugby,

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and soccer (Gabler et al., 2020 & King et al., 2015). Despite increasing application of wearable sensors to measure sports head impact exposure, most studies focus on investigating single sports, and there has been little quantitative comparison of impact biomechanics across sports using field data.

Some studies highlight potential sport-specific impact characteristics. For example, American football, involves high impact magnitude player-to-player collisions, with the highest kinematics found from forces to the top of the helmet (Broglio et al., 2009). Interestingly, rugby displays similar magnitude impact kinematics to American football, however, most of the impacts observed were direct, bare head contacts, primarily from the shoulder to the tempero-parietal region (McIntosh et al., 2000). In contrast, soccer often displays lower magnitude heading impacts with soccer headers representing approximately 90% of all head impacts experienced, and the remaining impacts coming from player-to-player or player-to-ground impacts (Ahmed et al., 2022 & Press et al., 2017). Interestingly, jumping headers from a long kick resulted in higher impact kinematics as compared to standing headers or headers from a throw-in (Kenny et al., 2022). Further, ice hockey literature has highlighted most head impacts to occur near the boards, with the side of the helmet being contacted the most from player-to-player collisions resulting in player-to-board impacts (Patton et al., 2017). Patton et al. found ice hockey players are most likely to be impacted on the head by the shoulder (31%) than followed by another helmet (12%). Other studies in ice hockey demonstrate significant relationships between initial speeds and head kinematics while finding directional differences in frontal collisions resulting in greatest magnitude kinematics (Swenson et al., 2022).

Numerous factors may contribute to the biomechanical variability in head impacts across sports, including playing style and position (Mihalik et al., 2008). Studies find play style and position to influence head impact exposure, for example, soccer defenders are more likely to head long balls thus having larger magnitude impacts (Basinas et al., 2020), and hockey forwards are more likely to receive higher head impact frequencies, particularly at lower magnitudes (Butterfield et al., 2023). Game speed can also contribute to the biomechanical variability in mechanisms observed (Bailes et al., 2001) as initial player velocity before an impact has been associated with increased concussion risk (Withnall et al., 2005 & Oeur et al., 2019). Further, sex-differences are often highlighted when comparing sports as men are likely experiencing more frequent and higher-magnitude impacts than women (Saunders et al., 2020 & Eckner et al., 2018). Additionally, in soccer, men are more likely to experience higher head impact magnitudes likely due to higher head-to-head contacts (Saunders et al., 2020), however, in hockey, females experience higher-magnitude impacts compared to males (Eckner et al., 2018). Finally, the presence of protective equipment, such as helmets, can differentiate head impact mechanisms between sports (Lewis et al., 2001). Mixed results in the literature highlight helmets to reduce linear accelerations but not significantly reduce angular accelerations in football players (Lloyd et al., 2016). Although researchers have expanded impact studies across a wide range of sports, direct comparison between sports is challenging due to distinct methodology between studies (i.e., sensor type, sensor specifications, processing techniques) along with the inherent biomechanical variability between sports.

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Uniquely, we have gathered raw iMG impact data across multiple sports and processed all data with a uniform technique to enable fair comparison of head impact biomechanics across ice hockey, American football, soccer, and rugby. With this dataset, we aim to compare peak kinematics, directionality, and impulse durations across sports. Since these head impact biomechanics parameters have been associated with brain injury risk, further investigation would enable insight into sport-specific injury mechanisms.

METHODS

Dataset Descriptions

A head impact database was curated from previously collected iMG data from collegiate level men's American football (MF) (Hernandez et al., 2014 & Wu et al., 2017), women's soccer (WS) (Kenny et al., 2022), men's ice hockey (MH) and women's rugby (WR) (Luke et al., 2024) teams. Both MH and WR teams wore Prevent Biometrics (Bartsch et al., 2019) iMG's during practices and games. The WS team wore instrumented mouthpieces from Wake Forest Center for Injury Biomechanics (Rich et al., 2019) and MF wore Stanford University iMG's (Wu et al., 2014). All iMG impacts were video-verified and only direct head contacts were included in the analysis. All impacts were visually inspected to keep only recordings where clearly observable linear and rotational acceleration impulses could be identified around the time of trigger. The Prevent iMG, Wake Forest Mouthpiece, and Stanford University iMG had all varying initial recording settings such as sampling frequency, trigger thresholds, and impact durations. Table 1 includes the varying settings of all iMGs which were then harmonized to follow one uniform processing pipeline. All subjects were consented, and each dataset had research ethics board approval as detailed in the original publications.

Table 1: Initial sensor specifications and uniform processing settings.

	Sensor Specifications	**Prevent iMG**	**Wake Forest Mouthpiece**	**Stanford iMG**
Initial	Sampling Frequency	3200 Hz	1000 Hz	1000 Hz
	Linear Acceleration Threshold (any axis)	8 g	5 g	5 g
	Impact Duration (Pre-Trigger/Post Trigger)	50 ms (10 ms/40 ms)	150 ms (30 ms/120 ms)	100 ms (10 ms/90 ms)
Changes Made	Sampling Frequency	Down sampled to 1000 Hz	-	-
	Linear Acceleration Threshold (Resultant)	Increase to 10 g	Increase to 10 g	Increase to 10 g
	Impact Duration	-	Decrease to 50 ms	Decrease to 50 ms
Uniform	Sampling Frequency	1000 Hz		
	Linear Acceleration Threshold (Resultant)	10 g		
	Impact Duration	50 ms		

Processing Methodology

To account for iMG differences, we applied a uniform pre-processing and processing script to the raw data to minimize potential sampling and processing differences (Table 1). We down-sampled the Prevent iMG to 1000 Hz and truncated the impact duration window for the Wake Forest mouthpiece and Stanford iMG to match the Prevent iMG (10 ms pre-impact, 40 ms post-impact). We aligned and centered all the impacts to ensure a trigger at 10 ms in the 50 ms impact window. To account for trigger threshold differences, we thresholded all data 10g resultant linear acceleration.

Data were rotated and anatomical axes were aligned for all data using a rotation matrix specific to each athlete and iMG, with the final frame definition of x – anterior/coronal, y – left/sagittal, and z – superior/horizontal. Following rotation and alignment, data were filtered using a low-pass 4^{th} order Butterworth filter at 300Hz for linear accelerations and 180Hz for angular velocity. Following filtering, a fourth-order differentiation was applied to angular velocities to determine angular accelerations, followed by a transformation to the head center of gravity.

Data and Statistical Analysis

Processed signals were used to compute metrics of interest such as per-axis and resultant peak linear acceleration (PLA), peak angular velocity (PAV), and peak angular acceleration (PAA). Head motion was characterized by determining dominant directions of acceleration and dominant planes of rotation. Dominant directions of linear accelerations were determined by examining if peak PLA in any direction exceeded 85% of the resultant PLA for each impact. Similarly, dominant planes of rotation were characterized by examining if peak PAA in any direction exceeded 85% of the resultant PAA for each impact. We also extracted linear and angular acceleration impulse durations from the maximum linear and angular acceleration directions for each impact, respectively. Impulse durations were extracted by calculating the width of the impulse at half of the peak acceleration value. All features were then compared across sports using pairwise Mann-Whitney U tests with $\alpha = 0.05$ and Bonferroni correction for multiple comparisons.

RESULTS

Our database consisted of 1228 video-verified direct total head impacts, where 331 were from MH, 54 from WR, 583 from WS, and 260 from MF. Comparing across sports, we observed MF to have the highest resultant median peak linear acceleration (23.3 g), peak angular velocity (10.9 rad/s), and angular acceleration (1945 rad/s^2) compared to MH, WR, WS (Figure 1). We also observed WS to have the lowest median peak kinematics compared to the other sports (14.5 g, 5.5 rad/s, 792 rad/s^2) (Figure 1). Pairwise comparisons resultant PLA, PAV, and PAA showed statistically significant differences between sports for all combinations, except between MH and WR for PLA and PAV.

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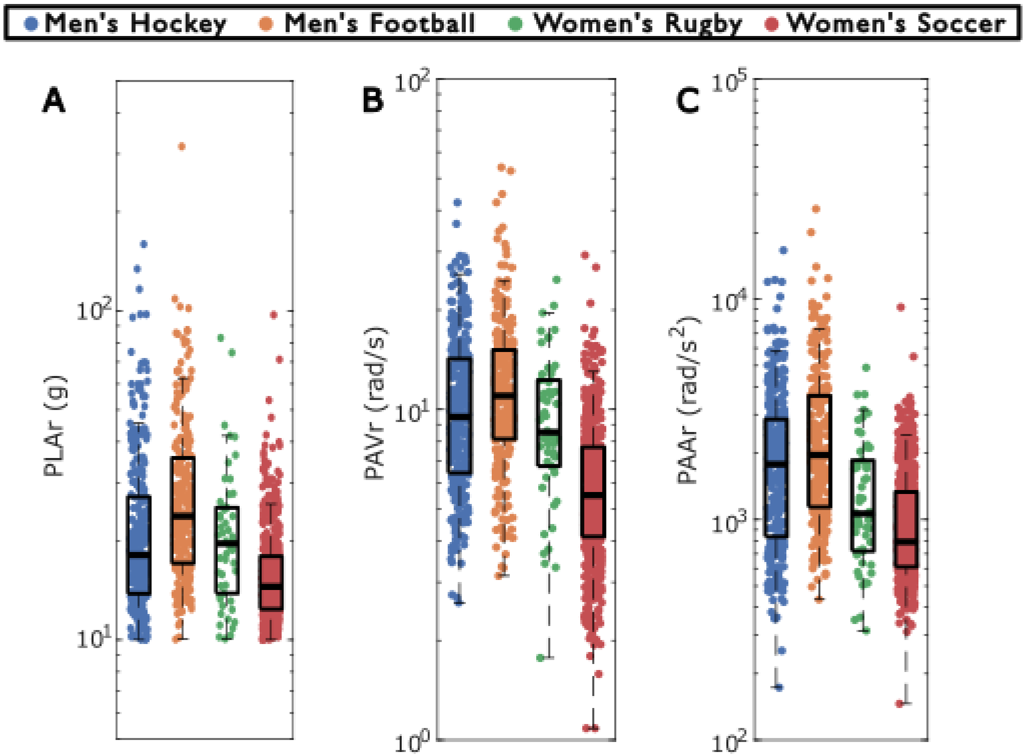

Figure 1: (A) Resultant peak linear acceleration, (B) peak angular velocity, and (C) peak angular acceleration for all sports.

Analysis of kinematics directions highlighted MH, MF, and WR impacts to have more impacts with linear accelerations dominant in the left-right direction (21.1%, 33.0%, 37.0%, respectively), while WS involved 57.8% of impacts with dominant anterior-posterior acceleration. Additionally, MH and WS impacts involved more dominant sagittal plane rotation (33.8% and 26.4%, respectively), while MF and WR involved 49.6% and 27.8% dominance in the coronal plane, respectively (Figure 2). Table 2 summarizes percentages across each sport and direction.

Table 2: Dominant directions of accelerations and planes of rotation for each sport.

		Men's Hockey	**Men's Football**	**Women's Rugby**	**Women's Soccer**
Linear Acceleration	*Anterior-Posterior*	18.7 %	18.8 %	27.8 %	57.8 %
	Left-Right	21.1 %	33.0 %	37.0 %	2.3 %
	Inferior-Superior	5.4 %	2.7 %	3.7 %	4.3 %
Angular Acceleration	*Coronal*	16.3 %	49.6 %	27.8 %	20.2 %
	Sagittal	33.8 %	11.5 %	27.8 %	26.4 %
	Horizontal	4.2 %	5.4 %	12.9 %	0.7 %

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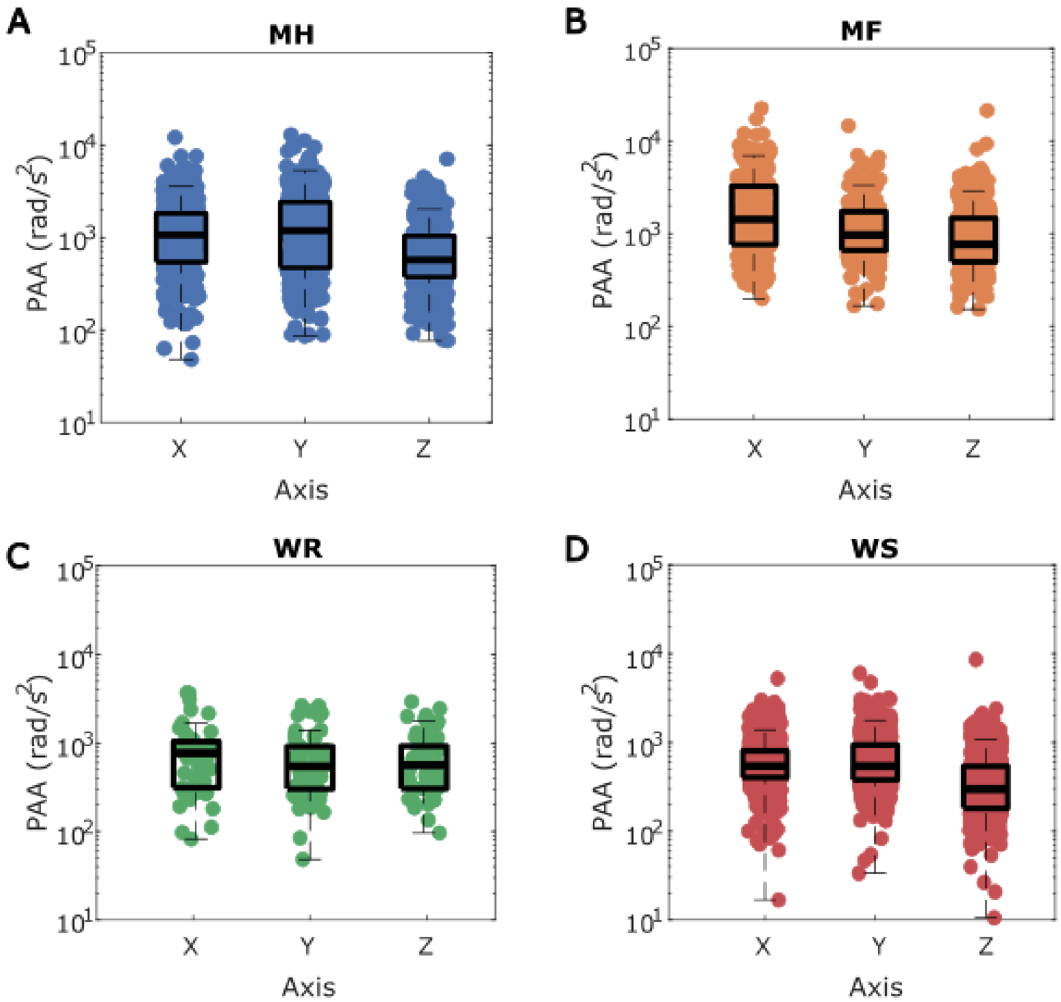

Figure 2: Peak angular acceleration across directions for each sport.

Comparing linear acceleration impulse durations, WS and MF displayed the longest median impulse duration with 8 ms, while WR and MH had slightly shorter median durations of 7 ms and 6.5 ms, respectively. Although the medians were similar, MH and MF displayed higher variability in durations, with absolute ranges of 3-38 ms and 3-30 ms, respectively. For angular acceleration, WS displayed the longest median impulse duration with 8 ms, while MH displayed the shortest duration of 7 ms (Figure 3). Similarly, the MH and MF displayed higher variability with ranges of 4-23 ms and 4-26 ms, respectively. No significant differences were found between sports for impulse durations.

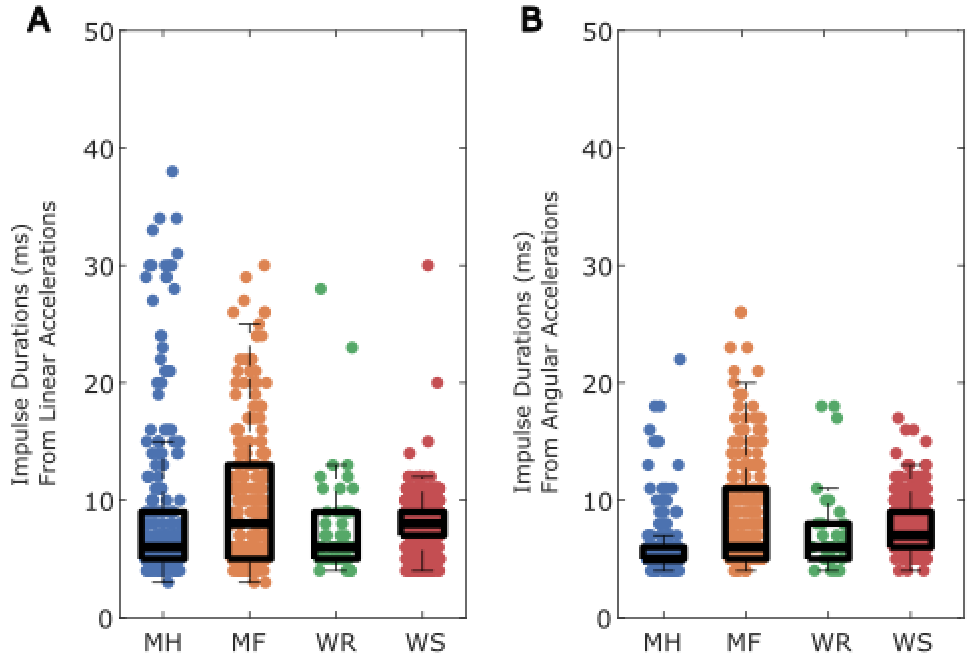

Figure 3: Linear (A) and angular (B) impulse duration comparisons

DISCUSSION

Cross-sport comparisons of peak kinematics highlights MF to exhibit the highest peak linear and angular accelerations, which may be associated with high concussion incidence found in football (Broglio et al., 2009). WS consistently displayed the lowest peak kinematics, which could be attributed to the high ball-to-head impacts in soccer as compared to player-to-player (Kirkendall et al., 2001). Interestingly, while MH may have involved higher speed on-ice collisions with not just other players but also higher-mass objects such as the board, it involved the second lowest median PLA, but was more comparable to MF in the distributions of peak angular velocity and acceleration. In contrast, WR involved relatively higher PLAs, yet lower PAVs and PAAs. In general, peak kinematics showed statistically significant variations across the four datasets, and the linear/angular comparisons did not always show the same trends, indicating complexities in sport-specific characteristics of peak kinematics distributions.

Furthermore, we observed interesting directionality patterns in our study. As expected, WS involved mostly anterior-posterior head linear accelerations (57.8% dominance), as expected from frontal soccer headers. Yet both coronal (side-to-side) and sagittal (front-to-back) rotations showed some dominance in WS, and this variation may depend on the target for the redirected soccer ball. The other three sports had higher dominance in left-right linear accelerations, which may imply more impacts to the side of the head. This may also be slightly surprising for American football, as past studies using helmet sensors have indicated frontal and rear impacts to be the most common (Pellman et al., 2003). On the other hand, rotational plane dominance showed varying patterns,

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with nearly 50% of MF impacts having coronal dominance, MH showing some sagittal dominance, and a mix of coronal and sagittal dominance for WR. Notably, there were few inferior-superior impacts and horizontal rotation dominant impacts across all sports. Animal and modeling studies have shown potential directional dependence in brain injury risk, with the coronal (Gennarelli et al., 1986) and horizontal (Weaver et al., 2012) planes proposed as more vulnerable. As shown in our analysis, coronal head rotations may be more prominent in American football compared with other sports.

As observed in each sport and noted in prior studies, the impacting objects and surfaces can be very different across sports (e.g., helmet-helmet in American football versus head-ball in soccer). Thus, it was generally surprising to find very similar median impulse durations for impacts across the four populations. For example, while it was anticipated that the presence of helmets and padding would attenuate impacts and increase the impact duration, helmeted sports (MH and MF) showed similar median impulse duration as unhelmeted sports (WR and WS), which may bring into question whether helmets are effectively mitigating the majority of impacts. However, helmeted sports did demonstrate a larger range of impulse durations and had some longer impulse duration impacts. Further examination of the impulse duration findings may bring insight into fundamental contact mechanics during sports head impacts.

Given our sample, it is difficult to speculate main factors leading to biomechanical differences between sports, since sex and sport factors cannot be isolated. Previous literature has highlighted sex-differences attributed to females having smaller neck girth and less neck strength resulting in higher head impact kinematics (Bretzin et al., 2017). Nonetheless, our results showed higher impact kinematics in the two men's teams compared with the two women's teams. In the future, we will aim to expand our dataset to better match sports teams for more controlled investigation of the influence of sex, equipment, and playstyle on head impact biomechanics. Another notable limitation of the current study is the lower sample size of women's rugby impacts, which may be expanded in future work. In addition, while we designed a universal processing pipeline to minimize sampling and processing differences across datasets, there may be other factors such as unknown sampling variability and sensor-skull coupling variability that could pose confounding variables. Future work may further investigate potential sensor differences and determine best protocols to combine datasets for meta-analyses.

CONCLUSIONS

In summary, our study is one of the first to compare head impact biomechanics across multiple sports using real-world head impact data all gathered from iMG sensors and processed through a universal processing pipeline. We observed impact magnitude and direction differences between sports with injury risk implications. In addition, we note unexpected impulse duration similarities across sports despite large differences in impact conditions, which warrants further investigation of the impact mechanisms. This line of research can contribute insight to inform injury risk differences across sports populations, with potential sport-specific strategies in injury prevention.

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