# Characterizing Head Impact Exposure in Men and Women During Boxing and Mixed Martial Arts

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**Background:** The accumulation of subconcussive impacts has been implicated in permanent neurological impairment. A gap in understanding the relationship between head impacts and neurological function is the lack of precise characterization and quantification of forces that individuals experience during sports training and competition.

**Purpose:** To characterize impact exposure during training and competition among male and female athletes participating in boxing and mixed martial arts (MMA) via an instrumented custom-fit Impact Monitoring Mouthguard (IMM).

**Study Design:** Cross-sectional study; Level of evidence, 3.

**Methods:** Twenty-three athletes (n = 4 women) were provided a custom-fit IMM. The IMM monitored impacts during sparring and competition. All training and competition sessions were videotaped. Video and IMM data were synchronized for post hoc data verification of true positives and substantiation of impact location. IMM data were collected from boxing and MMA athletes at a collaborating site. For each true-positive impact, peak linear acceleration and peak angular acceleration were calculated. Wilcoxon rank sum tests were used to evaluate potential differences in sport, activity type, and sex with respect to each outcome. Differences in impact location were assessed via Kruskal-Wallis tests.

**Results:** IMM data were collected from 53 amateur training sessions and 6 competitions (session range, 5-20 minutes). A total of 896 head impacts (men, n = 786; women, n = 110) were identified using IMM data and video verification: 827 in practice and 69 during competition. MMA and boxers experienced a comparable number of impacts per practice session or competition. In general, MMA impacts produced significantly higher peak angular acceleration than did boxing impacts ($P < .001$) and were more varied in impact location on the head during competitions. In terms of sex, men experienced a greater number of impacts than women per practice session. However, there was no significant difference between men and women in terms of impact magnitude.

**Conclusion:** Characteristic profiles of head impact exposure differed between boxing and MMA athletes; however, the impact magnitudes were not significantly different for male and female athletes.

**Keywords:** head impact; head impact power; peak linear acceleration; peak angular acceleration; boxing; mixed martial arts

Concussion is defined as "a complex pathophysiological process affecting the brain induced by traumatic biomechanical forces."[26] Subconcussive impacts in athletes pose a unique challenge: they do not result in the clinical manifestations observed in concussions, and individuals are typically asymptomatic until a certain threshold is reached.[2,12,25,35,43] A history of concussion or exposure to subconcussive impacts has been associated with long-term and irreversible neurological consequences, including chronic traumatic encephalopathy and other neurodegenerative diseases.[30,33,39,44] Despite the critical implications of a potential link between cumulative subconcussive impacts and permanent neurological damage, an accurate and reliable method of quantifying head impact exposure in athletes is lacking.[1,6,11,13,31] Consequently, specific thresholds for unsafe levels of impact exposure remain elusive, with limited objective guidance to inform participation in contact sports for athletes, in particular those participating in multiple contact sports or those with a history of concussion.

The literature is replete with attempts to quantify the head impact biomechanics of athletes[1,6,11,13,31] and military personnel[7,16,23] over the past 50 years. The most frequently used head impact sensor system to date is the Head Impact Telemetry System (HIT System), typically affixed within a Riddell helmet (BRG Sports).[5,6,8,9,14,28,29] The HIT System data have provided the mean numbers of head impacts per player per season, primarily among high school and collegiate football players, but have yet to identify a variable that accurately predicts concussive injury using

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biomechanical impact measures.[9] A limitation of the system is the placement of accelerometers within a helmet, which is prone to variation relative to the head's center of gravity (CG). The HIT System operates under the assumption that the skull and helmet move as a single rigid unit; however, the impact sensors may not be closely coupled to the skull.[1,21,38] Each entity may experience a different acceleration, particularly depending on the fit of the helmet and variations in padding. Validation studies have quantified the uncertainty of data collected via the HIT System.[1,21,38] Reported error margins are as large as 32% ± 43% (mean ± SD) for peak linear acceleration (PLA) and 35% ± 36% for peak angular acceleration (PAA) when comparing HIT System results with head sensor data collected in vitro (via anthropomorphic devices) and ex vivo (via postmortem human subjects), both of which allow for rigid sensor attachment to the skull.[31,38]

Additional wearable impact-measuring systems have been developed and utilized in research.[22,27,31,34,41] Devices containing accelerometers and gyroscopes have been affixed to the skin using an adhesive (ie, behind the ear),[27,36,37,42] fixed within a headband[17,31,34] or cap,[24,45] or integrated in a mouthguard.[10,19,20,22,32,46] These devices attempt to improve upon the limitations of the HIT System associated with poor sensor-skull coupling and use in nonhelmeted sports (ie, soccer). However, the accuracy of impact data recorded using these novel devices has also been challenged. McCuen et al[27] demonstrated error rates of approximately 50% for PLA and PAA as detected via a skin patch worn behind the ear during women's high school and collegiate soccer when compared with data from in vitro validation. In a recent meta-analysis, O'Connor et al[31] revealed numerous issues with biomechanical skin patches and current mouthguards, with head impact data often confounded by (1) motion around the skin patches, (2) an inaccurate fit of the mouthguards, and (3) the accumulation of saliva causing mouthguard malfunction, resulting in error rates of approximately 50% for available devices.[22,34]

Compounding the issue of questionable accuracy of wearable devices, the majority of previous studies using these devices to monitor head impacts in athletes have lacked a secondary verification process of recorded impact data.

Post hoc video verification of all recorded impact events is necessary to identify actions that may have been erroneously recorded as head impact events, such as running, jumping, or handling of the monitoring device. The absence of video verification puts into question the validity of impact counts and subsequent analyses of impact data in previous works, as identified by a recent HIT System study that pointed to potential errors in on-field data sets attributed to a lack of video review.[40] In a recent analysis of close to 9000 impact events recorded via skin patch sensors worn during collegiate soccer, Press and Rowson[34] reported that secondary video verified only 19% as true-positive head impacts. Thus, relying on head impact monitoring devices alone may lead to an exaggerated representation of the nature of actual impact events during sports. Video review is also critical to accurately describe impact location on the head and inform correlations related to acceleration magnitudes and location.

The previously reported high error rates with the HIT System and alternative wearable impact devices, combined with a lack of second-level video verification of impact data, limit their use in threshold determination and concussion monitoring in vivo.[27,31] To address the unmet need of an instrument that accurately and precisely measures head impacts during sports, we developed and tested an Impact Monitoring Mouthguard (IMM) system in vitro and in vivo for this project, and it has subsequently been commercialized.[3,4,18] The IMM utilizes a flexible circuit embedded within a custom mouthguard that contains 4 accelerometers, each producing 3 channels of data, with a custom algorithm that translates the impact kinematics data—linear and angular accelerations and velocities—to the head CG in real time.

In vitro testing of American football and boxing impacts using Hybrid III (Humanetics, Detroit, MI) head forms has revealed consistently rigid coupling between the IMM and the aluminum dentition before, during, and after impacts of PLAs up to 120$g$.[3,4] Additionally, results of benchtop linear drop and dynamic rotation testing of individual components of the IMM have demonstrated uncertainties of 3.8% and 3.3% for the data collected via IMM accelerometers and gyroscopes, respectively, as compared with reference data.[3,4] When the Hybrid III head forms were used to assess IMM results within the impact acceleration profiles of American football and boxing, IMM data were correlated with reference data for PLA, PAA, and peak angular velocity ($R^2 \geq 0.98$ for each metric).[3,4,18] Improved coupling and error margins <5% represent a substantial improvement over other impact dosimeters.[3,4]

Given the popularity of the helmet-bound HIT System and the relative popularity of various sports in the past decade, the majority of available research regarding impact

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Ethical approval for this study was obtained from Cleveland Clinic (17-1110).

counts and magnitudes collected during sport participation has included populations of athletes participating in American football, distantly followed by ice hockey and soccer, with even fewer data on snow sports, lacrosse, rugby, and boxing. Although accurate impact data on combat sport athletes are limited, Stojsih et al[41] outfitted a population of amateur boxers with a modified version of the HIT System in padded headgear. During controlled 2-minute sparring sessions, mean numbers of impacts of 42 ± 27 and 32 ± 18 were recorded for 19 male and 4 female athletes, respectively, clearly identifying boxing practices as a source of substantial doses of subconcussive impacts. With the recent advent of reliable mouthguard-based impact dosimeters, one-on-one combat sports such as boxing and mixed martial arts (MMA) offer an ideal environment to observe and record ample head impact data and perform second-level video verification analysis.

The primary aim of this study was to characterize head impact exposure during the training and competition of boxers and MMA athletes by utilizing an instrumented custom-fit mouthguard capable of accurately quantifying impact dose. A secondary exploratory aim of this project was to evaluate potential sex differences during sparring in impact exposure profiles in each sport, including number, magnitude, and location of impacts on the head.

## METHODS

A single-center prospective observational study was conducted under the guidance and approval of the study site's institutional review board. Before the study procedures, all participants signed an informed consent document and a video release form for video recording to be implemented during data capture.

Data were collected on amateur boxers and MMA athletes: 19 men and 4 women. All participants were adults (mean age, 26 ± 4 years) voluntarily participating in local sparring and sanctioned competitions in Ohio over a 6-month period (December 2017–May 2018). Inclusion criteria included male and female boxers or MMA athletes aged 18 to 40 years, with upcoming sparring or scheduled sanctioned competitions and ability to provide informed consent.

Upon enrollment into the study, 23 participants were instrumented with an IMM, which has been described and validated.[3,4,18] All mouthguards fit snugly on the participants' upper dentitions, and adjustments could be made if necessary for comfort of fit before use in sparring or competition. Participants wore the IMMs while research personnel captured time-stamped video recordings for all sparring sessions (n = 54) and competitions (n = 6). Many of the athletes represented in this data set participated in boxing and MMA events. Data were collected from 54 sparring practices (14 boxing, 40 MMA) and 6 competition events (4 boxing, 2 MMA) over the 6-month study period.

Rather than a prescribed sparring protocol per the study, training sessions were captured in the natural setting of the athletes and the facility and were unstructured in terms of duration. Typical training sessions (5 to 20 minutes total) entailed multiple bouts of sparring between 2 teammates for 5 to 7 minutes each, separated by rest and hydration breaks. Competitions were composed of standard 5-minute rounds for MMA and 3-minute rounds for boxing. While sparring, all athletes used boxing gloves and standard MMA or boxing headgear. During competition, athletes used sport-specific gloves according to governing body regulations. Protective headgear is not worn by athletes during MMA fighting; however, boxers wear protective headgear according to governing regulatory policies. Recorded impacts included hand to head (boxing and MMA), head to floor (boxing and MMA), head to cage (MMA), and foot to head (MMA).

Video recordings were utilized during data analysis for the identification of false-positive impacts (eg, biting or throwing the mouthguard) and for the confirmation of impact location on the head. Before the start of the match, research personnel video recorded a timestamp (www.time.gov) onto the video footage for synchronization to the athlete's IMM data during analysis. Video instrumentation was positioned above the participants to capture their movements.

The sensing elements of the IMM were 4 triaxial accelerometers (200*g* full-scale range, 3200-Hz sampling rate). The trigger threshold for recording an event was a linear acceleration of 15*g* in the raw signal. The complete event record comprised 10 milliseconds before the trigger and 40 milliseconds after it in addition to a time stamp. Up to 64 events were stored in the IMM's on-board nonvolatile memory before wireless offload via Bluetooth was necessary. Estimates of PLA, PAA, and impact location were displayed in real time to research personnel via an Apple iPad application to ensure proper data collection and to provide feedback regarding impact intensity. All data were transmitted via Bluetooth to the app, and the IMM itself contained no wires for data transmission or storage. The resultant time traces of the head CG acceleration were computed in postprocessing from the time traces of the IMM accelerometers.

Before postprocessing, all raw acceleration signals were digitally filtered using a low-pass 300-Hz corner frequency second-order Butterworth filter and a zero-phase forward-and-reverse filtering process. The $X$, $Y$, and $Z$ components of the head CG linear and angular acceleration vectors were computed from the individual accelerometer signals as functions of time. The directions were defined per SAEJ211/1 standard ($X$ = forward, $Y$ = to the right, $Z$ = down; reference point = head CG). For each impact, PLA (in $g$) and PAA (in rad/s$^2$) were computed per the postprocessing signal to characterize an event.

Impact location estimate was based on azimuth and elevation of a vector from head CG to the impact location on the head (vector *CGL*). Elevation angle was defined as an angle between vector *CGL* and its projection $CGL_{xy}$ onto the horizontal plane passing through the head CG. Azimuth was defined as an angle in that horizontal plane between the projection $CGL_{xy}$ and the x-axis of the head, with 0° pointing to the front, 90° pointing to the left, –90° pointing to the right, and 180° or –180° pointing to the rear. The crown zone was defined as elevation >55.6°; chin zone, as elevation –30° or lower; front zone, as azimuth from –45° to

TABLE 1
Head Impact Severity Metrics by Nonexclusive Subgroups of Sex, Sport, and Activity Type[a]

| Sex: Activity | Athletes | Sessions Recorded | Total True-Positive Impacts | Impacts per Athlete per Session | PLA, *g* | PAA, rad/s$^2$ |
|---|---|---|---|---|---|---|
| **Male** | | | | | | |
| Boxing | | | | | | |
| Competition (boxing gloves) | 3 | 4 | 49 | 12.3 ± 10.4 | 17.1 (13.2-22.9) | 1642 (1338-2298) |
| Sparring (boxing gloves) | 5 | 10 | 184 | 18.4 ± 13.1 | 19.7 (14.7-25.2) | 1534 (1221-2078) |
| Total | 6 | 14 | 233 | 16.6 ± 12.3 | 19.4 (14.4-24.6) | 1592 (1251-2126) |
| MMA | | | | | | |
| Competition (MMA gloves) | 2 | 2 | 20 | 10.0 ± 4.2 | 37.9 (29.2-48.6) | 3773 (3103-4658) |
| Sparring (boxing gloves) | 15 | 28 | 533 | 19.0 ± 20.5 | 17.5 (13.8-24.3) | 1766 (1359-2373) |
| Total | 15 | 30 | 553 | 18.4 ± 19.9 | 17.7 (13.9-25.1) | 1795 (1368-2464) |
| Total | 19 | 44 | 786 | 17.9 ± 17.7 | 18.1 (14.0-24.9) | 1731 (1335-2357) |
| **Female** | | | | | | |
| Boxing | | | | | | |
| Competition (boxing gloves) | 0 | 0 | 0 | — | — | — |
| Sparring (boxing gloves) | 3 | 4 | 19 | 4.8 ± 3.5 | 16.0 (12.5-24.2) | 2019 (1457-2479) |
| Total | 3 | 4 | 19 | 4.8 ± 3.5 | 16.0 (12.5-24.2) | 2019 (1457-2479) |
| MMA | | | | | | |
| Competition (MMA gloves) | 0 | 0 | 0 | — | — | — |
| Sparring (boxing gloves) | 4 | 12 | 91 | 7.6 ± 5.4 | 17.6 (13.4-24.7) | 1796 (1323-2822) |
| Total | 4 | 12 | 91 | 7.6 ± 5.4 | 17.6 (13.4-24.7) | 1796 (1323-2822) |
| Total | 4 | 16 | 110 | 6.9 ± 5.1 | 17.1 (13.3-24.6) | 1811 (1339-2796) |

[a]Values are presented as n, mean ± SD, or median (interquartile range). MMA, mixed martial arts; PAA, peak angular acceleration; PLA, peak linear acceleration. Dashes represent data not available.

45°; left zone, as azimuth from 45° to 142.5°; right zone, as azimuth from –45° to –142.5°; and rear zone, as azimuth from 142.5° to 180° and from –142.5° to –180°.

A recorded event was considered a true positive after video verification if the recording was triggered via a head movement attributed to a head or body impact. All other recorded events were considered false positives. Event signals with a short burst of acceleration (eg, caused by a bite) were eliminated via custom filtering, based on amplitude comparison between the original signal and a 100-Hz low-pass filtered comparison signal. Recorded events with a filtered magnitude of CG acceleration <10*g* were considered on par with activities of daily living and excluded from data analysis.[15]

All head impact data were divided into the following nonexclusive groups: sport (boxing vs MMA), activity type (sparring vs competition), impact location (crown, chin, front, rear, left, right), and sex (male vs female).

## Statistical Analysis

The 2 major outcomes of interest were the PLA and PAA of each true-positive impact. Descriptive statistics of these outcomes were reported via their median and interquartile range as a function of activity type, sport, and sex. Differences in mean numbers of impacts per session were evaluated using Welch *t* tests. The Wilcoxon rank sum test—a nonparametric test to assess differences in distributions of observations obtained between 2 separate groups—was used to evaluate differences in activity type, sport, impact location, and sex with respect to each outcome, separately. Effect estimates—the effect of a given predictor (sport, activity type, or sex) on the outcome metric (PLA or PAA)—were quantified using the Hodges-Lehmann estimator, consistent with the Wilcoxon rank sum test. The Hodges-Lehmann estimator is the median of all possible differences in outcome between 2 observations, each selected from one of the groups being compared (eg, PLA in boxing impacts vs MMA impacts). Differences in PLA and PAA were compared across impact locations using the Kruskal-Wallis test, a nonparametric 1-way analysis of variance method. All hypotheses tests were performed at 5% level of significance. Statistical analysis was completed using R statistical software (version 3.6.2; R Project).

## RESULTS

Table 1 displays descriptive metrics of number and magnitude of all video-verified impacts for various nonexclusive combinations of predictors: sport, activity type, and sex. The number of video-verified true-positive impacts was 896 (786 male, 110 female). Impacts were skewed toward lower magnitudes of PLA and PAA (Figure 1).

Boxing sparring and competition sessions of men and women (18 events total) resulted in a total of 252 impacts (233 male, 19 female), representing 28% of the true-positive data set. In comparison, MMA sessions (42 total) totaled 644 true-positive impacts (553 male, 91 female), 72% of the total data. The total numbers of impacts experienced per athlete per session were comparable across boxing (14.0 ± 12.0) and MMA (15.3 ± 17.7; $t$ = –0.340; $P$ = .738). Interestingly, the mean forces imparted by impacts differed between sports (Figure 2A). Although PLA was generally higher for boxing

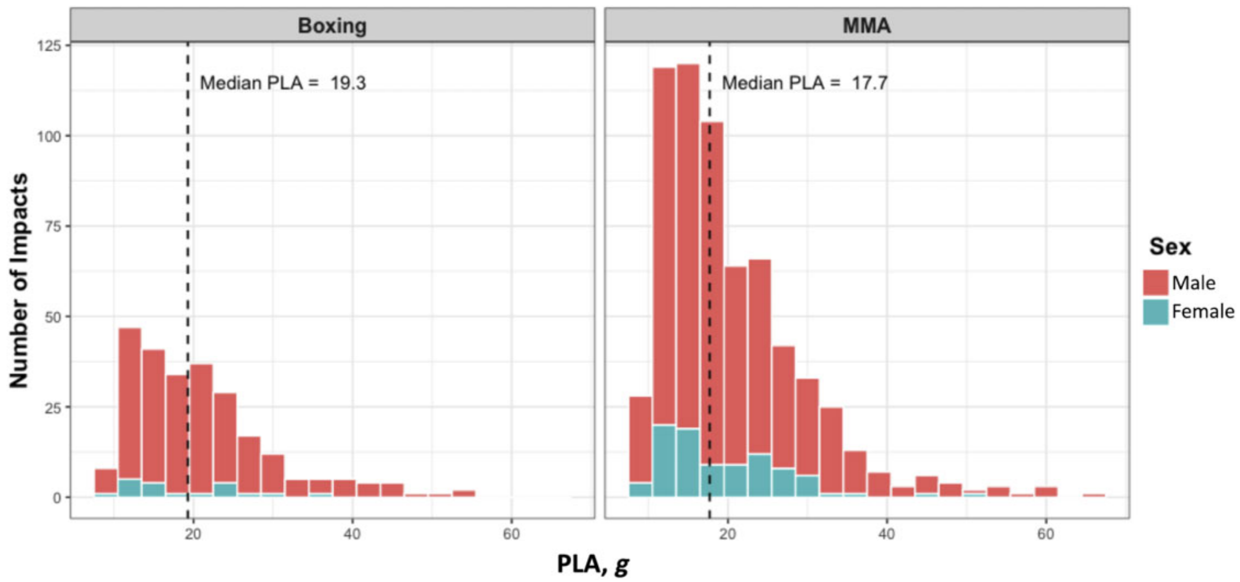


**Figure 1.** Distribution of PLA values for boxing and MMA impacts by sex. MMA impacts represented 72% of the video-verified data set, and male impacts represented 88%. Distributions of PAA values (not shown) were similarly right skewed, with the majority of true-positive impacts having low linear and angular accelerations. MMA, mixed martial arts; PAA, peak angular acceleration; PLA, peak linear acceleration.

impacts (median, 19.3*g*) than MMA impacts (median, 17.7*g*), a Wilcoxon test indicated that this trend was not statistically significant ($U$ = 84,376; $P$ = .35). Conversely, PAA was significantly higher for MMA impacts (median, 1796 rad/s$^2$) than boxing impacts (median, 1596 rad/s$^2$; $U$ = 69,294; $P$ < .001; Hodges-Lehmann effect estimate, 174 rad/s$^2$ higher for MMA than boxing [95% CI, 74-277 rad/s$^2$]) (Table 2). Maximum values of PLA and PAA in this data set occurred in male athletes participating in MMA: 65.1*g* PLA during a competition and 6912-rad/s$^2$ PAA during sparring.

The distributions of impact location were similar for boxing and MMA sparring sessions. However, boxing competitions resulted in a majority of impacts to the front zone of the head, and MMA competitions involved impacts more evenly dispersed among all impact zones (Figure 3). When combining all boxing and MMA impacts, PLA and PAA differed significantly by impact location ($P$ < .001 for each location). Impacts to the rear of the head imparted the highest linear and angular accelerations as compared with impacts to any other zone. The rear of the head was also the second-least common impact location in terms of number of impacts per athlete per session (2.2 ± 2.7), and impacts to the front of the head were most common (9.6 ± 11).

To compare impacts incurred during sparring versus competition, we combined boxing and MMA impacts, but only male data were analyzed owing to a lack of female competition data (Figure 2B). Although the mean number of impacts per session was larger for sparring practices (18.9 ± 18.6) than competition events (11.5 ± 8.4), the difference was not statistically significant ($t$ = –1.617; $P$ = .127). Competition impacts had significantly higher values of PLA (median, 21.9*g*) than did sparring impacts (median, 17.9*g*; $U$ = 29,381; $P$ = .01; Hodges-Lehmann effect estimate, 2.9*g* higher for competition impacts [95% CI, 0.6-5.4*g*]). Competition impacts also had higher PAA (median, 2248 rad/s$^2$) as compared with sparring impacts (median, 1704 rad/s$^2$; $U$ = 31,760; $P$ < .001; Hodges-Lehmann effect estimate, 456 rad/s$^2$ higher for competition impacts [95% CI, 217-737 rad/s$^2$]).

The head impact profiles of male and female athletes were characterized and compared, with analysis limited to sparring impacts because of a lack of female competition data. The majority of the data set represents male impacts (786 total impacts, 88% of all true-positive impacts), as women (n = 4) contributed sparring data from 16 sessions (4 boxing, 12 MMA; 110 total impacts, 12% of impact data). Women experienced an average of 4.8 ± 3.5 head impacts per boxing sparring session, as compared with the male average of 18.4 ± 13.1 impacts per session ($t$ = –3.045; $P$ = .011). Similarly, female MMA sparring sessions resulted in a mean 7.6 ± 5.4 impacts, as opposed to 19.0 ± 20.5 impacts during male MMA sparring sessions ($t$ = –2.744; $P$ < .01). Despite this disparity in total number of impacts, PLA and PAA values were statistically comparable between the sparring impacts experienced by women and men (PLA, $U$ = 36,870, $P$ = .29; PAA, $U$ = 42,936, $P$ = .13). Although not reaching the threshold of statistical significance, impacts experienced by women generally had higher PAA, whereas impacts experienced by men had higher PLA (Figure 2C).

## DISCUSSION

Analysis of the present video-verified data set revealed an expected concordance between linear and angular

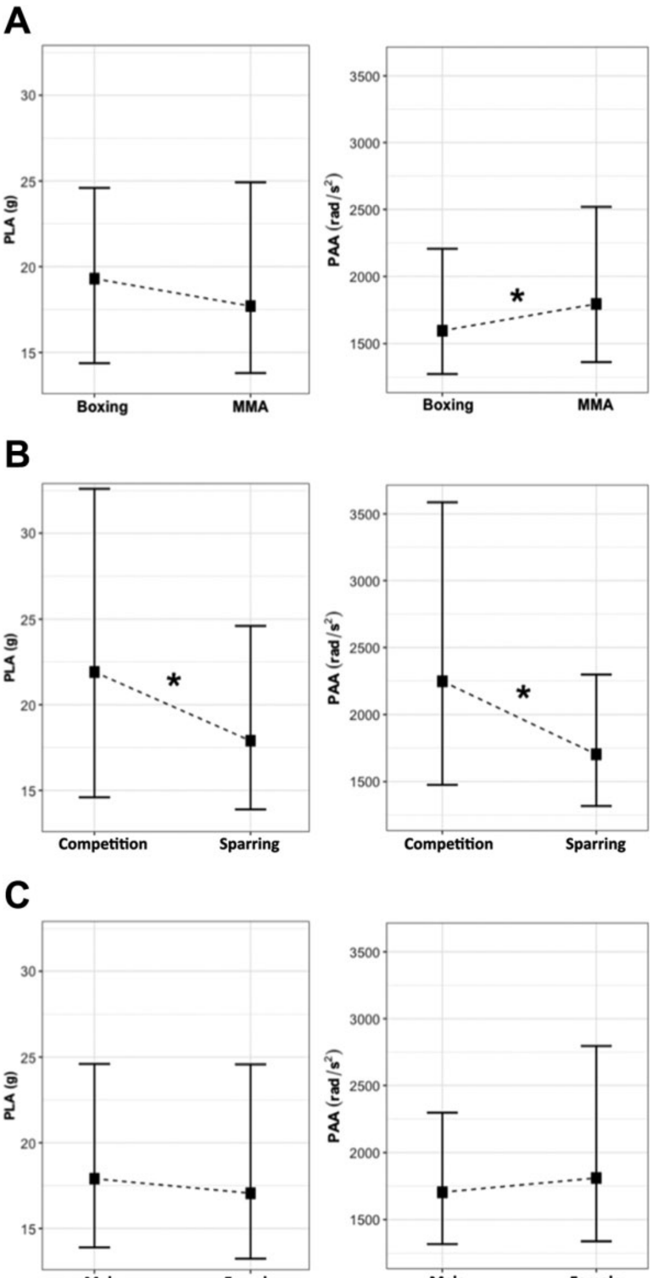


**Figure 2.** Median PLA and PAA for (A) boxing vs MMA impacts using the full data set, (B) competition vs sparring impacts using only male data, and (C) male versus female impacts using only sparring data. Error bars represent interquartile ranges. *Statistically significant difference between groups ($P < .05$). MMA, mixed martial arts; PAA, peak angular acceleration; PLA, peak linear acceleration.

acceleration metrics: most high-magnitude impacts were likely to impart high values of linear acceleration and angular acceleration. The distributions of linear and angular accelerations were skewed toward lower values, as most impact data represented sparring- rather than competition-level intensity. Impacts sustained during competitions were significantly higher in PLA and PAA as compared with those sustained during sparring. These differences may be partly attributable to the differences in glove type worn during sparring versus competitions. Boxing gloves were worn during boxing competitions, boxing sparring, and MMA sparring sessions, whereas MMA gloves were worn only during sanctioned MMA competition events. Data recorded during MMA glove use were limited, but results suggested that boxing gloves may offer protective value in lessening the forces of head impact intensity relative to MMA gloves. This supports recommendations to practice boxing and MMA exclusively using boxing gloves and to consider redesigning MMA gloves with additional padding to more closely mimic the structure of boxing gloves.

TABLE 2
Results of Wilcoxon Rank Sum Test to Evaluate Differences in PLA and PAA by Sport, Activity Type, and Sex[a]

| Impact Metric | PLA, *g* | PAA, rad/s$^2$ |
|---|---|---|
| Sport | | |
| *U* statistic | 84,376 | 69,294 |
| *P* value | .35 | **.00067** |
| Estimated median difference[b] (boxing – MMA) | 0.5 | –174 |
| 95% CI | –0.50 to 1.50 | –277 to –74 |
| Activity type[c] | | |
| *U* statistic | 29,381 | 31,760 |
| *P* value | **.01** | **.0001** |
| Estimated median difference[b] (competition – sparring) | 2.9 | 456 |
| 95% CI | 0.6 to 5.4 | 217 to 737 |
| Sex[c] | | |
| *U* statistic | 36,870 | 42,936 |
| *P* value | .29 | .13 |
| Estimated median difference[b] (male – female) | 0.7 | –120 |
| 95% CI | –0.60 to 2.0 | –286 to 36 |

[a]*P* values exceeding the $\alpha = 5\%$ threshold for statistical significance are in bold. MMA, mixed martial arts; PAA, peak angular acceleration; PLA, peak linear acceleration.

[b]Hodges-Lehmann point estimate of the median difference from a sample of each population being compared, with a 95% CI for that estimate.

[c]Comparison based on male data only, as no female competition data were collected.

Impact profiles differed between boxing and MMA events. When sparring and competition sessions were combined, PAAs were higher in MMA impacts than boxing impacts. Although linear accelerations tended to be higher in boxing impacts, there was no significant difference in PLA between sport groups ($P = .35$). These differences in the linear and angular metrics relative to sport may be attributable to the contrasting styles of boxing and MMA strategies and differences in glove type. These differences were also reflected in general patterns of impact location mapping between boxers, who experienced a larger proportion of impacts to the front of the head, and MMA athletes, who were more prone to impacts spread across location

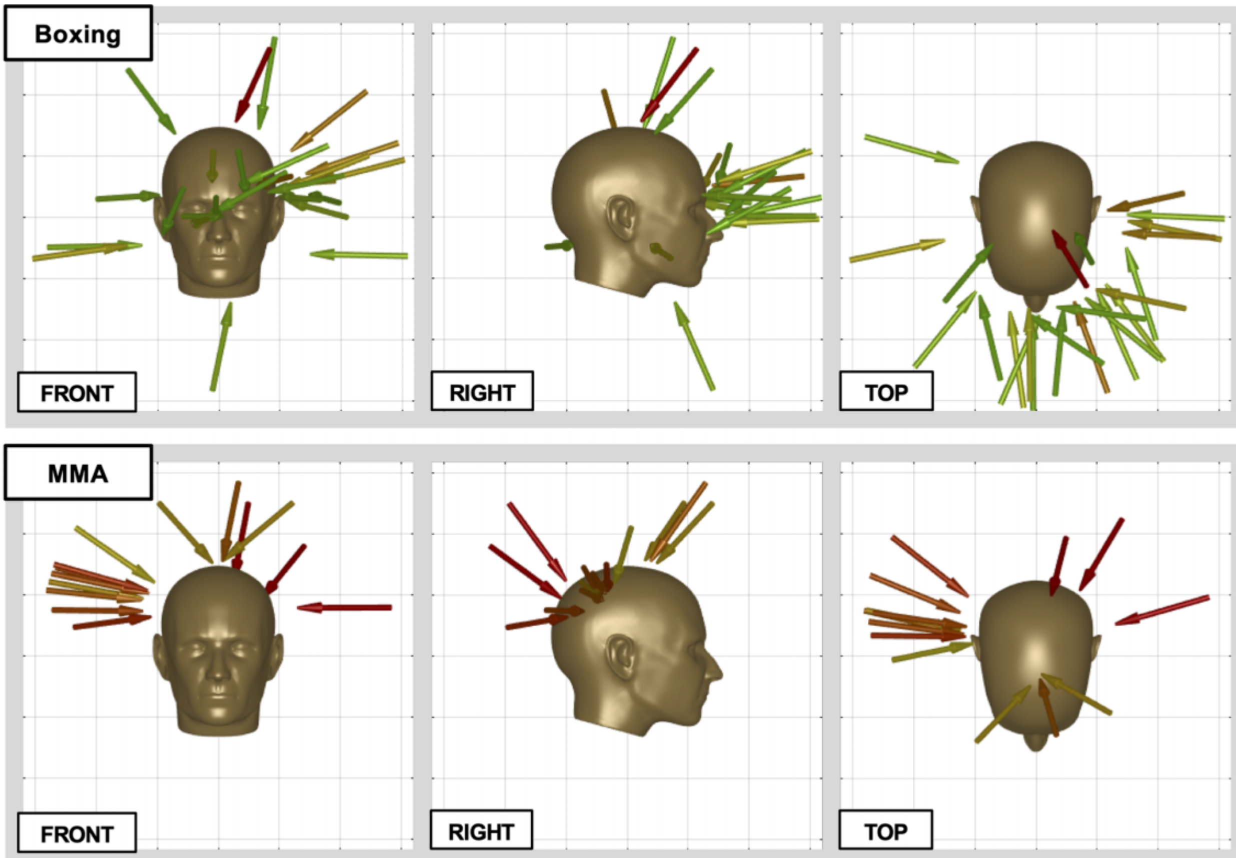


**Figure 3.** Representative examples of characteristic head impact profiles for a single male athlete participating in a competitive boxing match versus a competitive MMA match. In general, boxers experienced a majority of impacts to the front region of the head, whereas MMA impacts were more distributed across impact zones during competitions. Arrows are color coded on a continuous scale based on the PLA value of each impact: green to red, 10*g* to 66*g*. MMA, mixed martial arts; PLA, peak linear acceleration.

zones during competitions. Significant differences existed in PLA and PAA by zone of impact (chin, crown, front, left, rear, or right). Rear impacts were associated with the highest values of linear and angular forces and were more likely to be experienced during MMA competition events, where athletes are subject to direct blows to the back of the head from the opponent and where contact between the head and the floor or cage is likely. Rear impacts represent a particular challenge, as a lack of visibility makes anticipating and bracing for these impacts difficult, likely leading to reduced muscular control of the neck and higher magnitudes of linear and angular forces experienced by the athlete's head. The present findings highlight a potentially higher risk of injury for MMA athletes relative to boxers, as angular accelerations have been proposed to cause higher rates of deleterious effects over time.[33]

The secondary aim of this study was to characterize head impact exposure for female boxers and MMA athletes as compared with their male counterparts. Given the limited female participation (n = 4) and lack of data from female competition events, it was difficult to draw definitive conclusions from this data set. On average, women sustained fewer impacts per athlete per sparring session when compared with men. Despite this disparity in the number of head impacts, there were no statistically significant differences in the linear and rotational magnitudes of impacts experienced by male and female athletes (PLA, $P = .29$; PAA, $P = .13$). Interestingly, median PAA values were higher for impacts experienced by women than those experienced by men. This trend in linear and rotational accelerations may be indicative of anatomic differences between the sexes: smaller neck circumference or lower neck muscle mass in female athletes may reduce their ability to brace for and control head impacts that impart high rotational forces. In addition, the substantial discrepancy in the number of impacts experienced per sparring session between male and female athletes highlights potential differences in practice techniques that should be investigated to identify possible solutions to improve the safety of boxing and MMA for all athletes. Despite sample size limitations, these data currently represent the only female boxing or MMA head impact data available as collected via an instrumented mouthguard and definitively identify female combat sport athletes as a population warranting further study.

The results of this study have potential implications regarding the concussion risk assumed by boxers and MMA athletes participating in sparring and competition events. Unfortunately, there is currently a paucity of reliable in vivo impact information available from combat sport participation, and studies of concussion risk and impact thresholds more commonly utilize populations of American football players. Zhang et al[47] leveraged concussion severity data collected by the National Football League to propose novel impact threshold values relative to the likelihood of occurrence of mild traumatic brain injury (mTBI). Using video recordings for accident reconstruction and information on resultant concussive episodes in combination with computer modeling, the authors reported probabilities of mTBI occurrence at different linear and angular accelerations: 25% probability of mTBI with 66$g$ PLA and 4600-rad/s$^2$ PAA, 50% with 82$g$ PLA and 5900-rad/s$^2$ PAA, and 80% with 106$g$ PLA and 7900-rad/s$^2$ PAA. The values suggested a framework that can be applied beyond football. The maximum values of PLA (65.1$g$) and PAA (6912 rad/s$^2$) recorded in the present population of boxers and MMA athletes fit reasonably within these stratifications. Since the present study pertained to the characterization of subconcussive impacts and their potential effect during a time of combat sports and brain vulnerability, more work is warranted to understand how potential PLA and PAA threshold values may fluctuate via prior cumulative exposure within some critical window. Additionally, decisions regarding acceleration thresholds and other parameters of the filtering process should be subject to sensitivity analyses in future work. Finally, the IMM should be tested in male and female athletes of a variety of ages and sports to establish its validity and reliability in diverse populations.

### Limitations

The unequal sample sizes of female and male participants and the small number of competition events included in the analysis are limitations of the present work. In addition, the results of this work support conducting large-scale replication studies to verify IMM error margins in vivo and establish impact profiles for broader populations of male and female boxers and MMA athletes, but the video verification process required to establish a final true-positive impact data set may not be easily scalable. Until it is established that head impact sensor data produce trustworthy outputs, video verification should be utilized to establish the validity of dosimeter equipment, and the results of this work can inform future data-processing algorithms to accurately differentiate between true- and false-positive impact events.

## CONCLUSION

Subconcussive impacts and cumulative impact exposure represent especially challenging aspects of injury management, as they rarely cause acute clinical manifestations but may instigate a cascade of deleterious and permanent neurological effects that present decades after the exposure window. High-fidelity dosimeters are needed to accurately quantify head impact exposure in sports so that this information can be used to inform eventual recommendations for “safe” impact doses. Additionally, the differing characteristics of head impact exposure for boxing versus MMA events, sparring- versus competition-level intensity, and male versus female athletes can inform training styles and glove utilization. Finally, these results emphasize the importance of including female athletes in head impact research moving forward.

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