HEAD IMPACTS DURING SPARRING: DIFFERENCES AND SIMILARITIES BETWEEN MOUTHGUARD, SKIN, AND HEADGEAR SENSORS

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The timely identification of concussions is essential to ensuring athlete safety. In contact sports, many devices are available to measure head impacts, but concerns remain regarding their ability to accurately estimate the number and magnitude of those impacts. This study measured head impacts during boxing sparring simultaneously with three sensors – a mouthguard, a skin patch and a headgear patch – and video analysis. The objective was to assess and compare the number, quality, and magnitude of impact events across sensor types. All sensors had issues related to decoupling from the skull, although the mouthguard appeared to generate better estimates than the patches of the number of impacts and impact-induced head kinematics.

KEYWORDS: Concussion, kinematics, acceleration, combat sport, boxing.

INTRODUCTION: Identifying when a contact sports athlete potentially sustains a concussion is essential for proper care and there is a need for objective and reliable tools to assist with this challenging task (Mihalik et al. 2017). To meet this need, head impact sensors have been developed on the assumption that impact-induced head kinematics are a causative factor of concussion (Holbourn 1943, Ji et al. 2014). These sensors typically consist of accelerometers and/or gyroscopes moulded into a mouthguard or a small widget that can be adhered to the skin or embedded in an athlete's headgear. Each configuration has strengths and weaknesses that influence a user's instrument choice.
A common weakness of wearable head impact sensors is their varying levels of coupling with the skull. The poor fit of the mouthguard, the scalp's elasticity, and the headgear sliding on the head are common causes of relative motion between the sensors and the skull (Wu et al. 2016). As a result of this relative motion, sensors overestimate the linear and angular accelerations of the skull (Siegmund et al. 2015, Wu et al. 2016, Kuo et al. 2018). Additionally, because these sensors are typically triggered using a linear acceleration threshold, erroneously large kinematics can also lead to spurious recordings and overestimates of the number of impacts sustained (Siegmund et al. 2015, Wu et al. 2016).
An imprecise quantification of the number and magnitude of head impacts hinders the advancement of our understanding of concussive injury (Wu et al. 2017, Patton et al. 2020). Therefore, there is a need to assess the capacity of the sensors to accurately estimate exposure to head impacts during sports participation. This study was designed to simultaneously record head acceleration events using a mouthguard, a skin patch, and a headgear patch to assess and compare their exposure estimates during boxing sparring.

METHODS: Amateur boxers (4 females, 3 males) competing under AIBA rules participated in this observational cohort study. The participants were observed during boxing sparring sessions composed of multiple 3-minute rounds of sparring against various opponents in a similar weight class. Each participant simultaneously wore an instrumented mouthguard (Hybrid from Prevent Biometrics Inc., Edina, MN; Figure 1A, sampling at 3200 Hz), a patch taped to the skin on their right mastoid process (CSx Systems Ltd, Auckland, New Zealand; Figure 1B, accelerometer sampling at 3200 Hz and gyroscope at 8000 Hz), and a similar patch adhered to the back of their headgear (Figure 1C). All sensors were set to record an

acceleration event any time the linear acceleration signal reached 10 g on any axis. Acceleration events recorded by the sensors outside of the sparring rounds were automatically excluded. All remaining events were included, irrespective of the manufacturer's classification as valid or spurious.
Sparring sessions were videoed from three angles (Figures 1D and 1E) and the footage of 115 rounds was reviewed by a single rater (author ELF) using Nacsport Elite (Nacsport, Canary Islands, Spain). The rater identified all contact events to the participants' head and characterised them using definitions agreed upon with a combat sports expert (SL). A subset of data underwent intra-rater reliability analysis (ELF and SL) using proportions of total agreement in sequence (Cooper et al. 2007). The same subset was used to assess the inter-rater reliability between ELF and SL. The proportions of total agreement in sequence reached 90.2% for ELF, 75.0% for SL, and 80.8% for ELF-SL. Additionally, the location of the impact on the head was categorized into bins (front, left, right, back) from the videos.

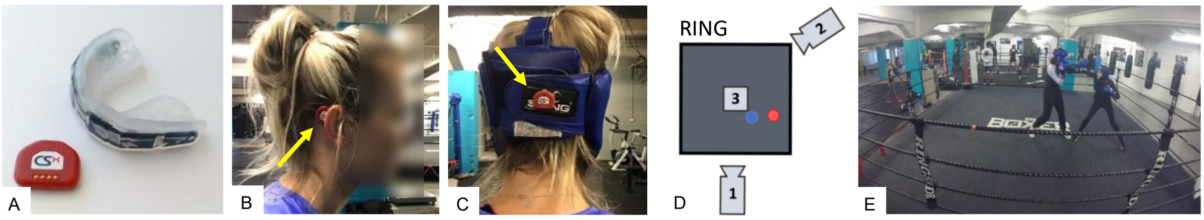

Figure 1: (A) CSx patch and Prevent Biometrics Hybrid mouthguard; (B) location of the skin patch; (C) location of the headgear patch; (D) placement of cameras around the ring; (E) example of footage from camera 1.

Video footage and sensor data were synchronised using one clearly identifiable impact, and a two-way video verification was conducted. If an acceleration event could be matched with a video event, it was marked as a true positive (TP), otherwise as a false positive (FP); video events not associated with an acceleration event were marked as false negatives (FN). For each sensor, the sensitivity [TP/(TP+FN)] and positive predictive value [PPV, TP/(TP+FP)] were calculated with their 95% confidence intervals (CI) and were determined as different when the 95% CIs did not overlap.
For a subset of video-verified events, the raw linear acceleration and angular velocity time series data were assessed against a set of defined criteria to determine if they were representative of head motion ('good') or sensor motion (i.e., decoupled from the skull, 'bad'). The proportions and 95% CI of 'good' recordings were calculated and compared. Peak linear and angular accelerations (PLA and PAA, respectively) at the head's centre of gravity were calculated. Differences between sensors in the distribution of PLA and PAA were assessed with a Kruskal-Wallis analysis of variance, completed with post-hoc tests with a Dunn-Sidák correction. In the absence of a true gold standard, the mouthguard was considered the reference for any comparison.

RESULTS: Over 115 rounds of sparring for individual participants (~6 hours of activity), there were 695 mouthguard, 1578 skin patch, 1690 headgear patch, and 2960 video events. As a result, the sensors' sensitivity to contacts to the head was 21.8% for the mouthguard, 47.3% for the skin patch, and 50.6% for the headgear patch. All sensors were more likely to be triggered when contact to the head was made to the side where the sensor was located (Table 1); this was particularly evident for the patches. Totals of 2, 9, and 12 events from the mouthguard, skin patch, and headgear patch, respectively, were false positive events, resulting in a positive predictive value over 99.2% for all sensors.
For each sensor, 442 events (26-64% of each dataset) were assessed for quality. Large proportions, particularly for the patches, exhibited evidence of skull/sensor decoupling (Table 2). Additionally, for all sensors, impacts landing on the sensor's side of the head also led to higher proportions of such 'bad' signals (Table 2). For all video-verified head impacts assessed as 'good' (N = 235 for the mouthguard, 89 for the skin patch, and 113 for the headgear patch),

the distribution and median PLA and PAA differed between sensors (Figure 2).

Table 1: Sensitivity values and 95% confidence intervals for each sensor at various head impact locations, as determined from video analysis. The skin patch was located on the right side, the headgear patch at the back.

	Sensitivity (95% CI)		
	Mouthguard	Skin patch	Headgear patch
All events (N = 2960)	21.8% (20.3 - 23.3)	47.3% (45.5 - 49.1)	50.6% (48.8 - 52.4)
Front (N = 2028)	19.6% (17.9 – 21.4)	42.6% (42.3 – 52.3)	45.8% (43.6 – 48.0)
Left (N = 398)	28.3% (24.1 – 33.1)	47.2% (42.3 – 52.3)	59.5% (54.5 – 64.4)
Right (N = 461)	26.0% (22.1 – 30.3)	64.0% (59.4 – 68.3)	59.6% (55.0 – 64.1)
Back (N = 73)	19.2% (11.2 – 30.2)	74.0% (62.2 – 83.4)	78.1% (66.6 – 86.8)

Table 2: Proportions of ‘good’ acceleration events and 95% confidence intervals for each sensor at various head impact locations, as determined from video analysis.

	Proportions of ‘good’ events (95% CI)		
	Mouthguard	Skin patch	Headgear patch
All events (N = 442)	53.2% (48.4 – 57.8)	20.1% (16.6 – 24.2)	25.6% (21.6 – 29.9)
Front (N = 260)	40.0% (34.0 – 46.2)	24.2% (19.2 – 30.0)	36.1% (30.4 – 42.3)
Left (N = 84)	70.2% (59.1 – 79.6)	25.0% (16.5 – 35.7)	11.9% (6.2 – 21.0)
Right (N = 88)	73.9% (63.2 – 82.5)	5.7% (2.1 – 1.3)	10.2% (5.1 – 18.7)
Back (N = 10)	70.0% (35.4 – 93.5)	0.0% (0.1 – 2.7)	0.0% (0.9 – 26.8)

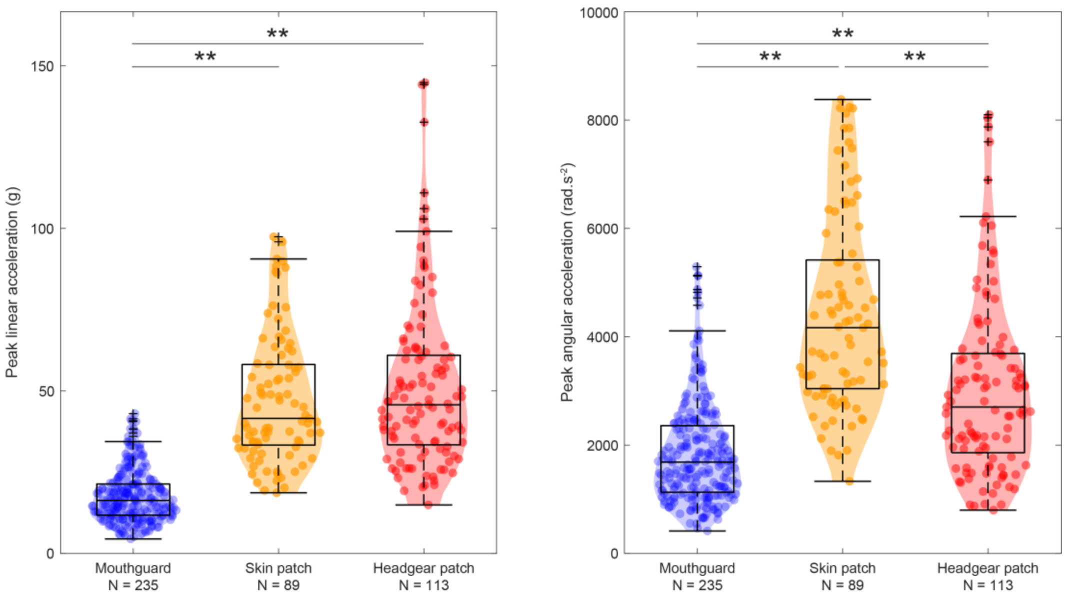

Figure 2: Distribution of peak linear and angular accelerations for a subset of ‘good’ events representative of head motion. Asterisks indicate differences between sensors (p < 0.001).**

DISCUSSION: The patches, whether attached to the skin on the mastoid process or to the boxers’ headgear, recorded the same number of events, with comparably low proportions of valid signals and similar distributions of PLA values. The patches were twice as sensitive (48-52%) to contacts to the head as the mouthguard (23%), but also more sensitive to the location of the impact. However, both patches showed that only a small proportion (20-26%) of recordings reflected good coupling between the skull and the sensor, against 53% for the mouthguard.

Consistent with the literature (Siegmund et al. 2015, Wu et al. 2016), we observed evidence of physical decoupling in the case of the skin and headgear patches and visualised the independent motion of the sensor on the raw kinematic traces for all three sensors. Our results suggest that the number of head impacts may be overestimated as a sensor moves at a faster rate than the skull, triggering a recording while a better-fitted sensor may have measured sub-threshold accelerations. The number of impacts may be particularly inflated for impact locations close to the sensor, creating over-estimates in the dataset.

Overall, for the analysis of acute exposure to head impacts in boxing, the mouthguard was the best option out of the three sensors, as our results suggested it was better coupled to the skull, when compared to the patches. However, the mouthguard's ability to record all potentially injurious head impacts in boxing requires further investigation. Furthermore, its moderate proportion of recordings with issues, associated with the frequency of impacts to a boxer's face, suggests it should not be used as a "black box" for boxing head impacts.

The patches did not provide enough data of acceptable quality to validate their use for the analysis of head impact kinematics in boxing. Considering the consistency of our findings with the recent literature regarding skin-based sensors coupling issues (Rooks, Dargie, and Chancey 2019), caution is warranted for the use of patches and interpretation of patches' kinematic data in exposure analyses. Nonetheless, the headgear patch could be used as an impact counter in boxing because of its high sensitivity to head impacts and its ease of use (interchangeable, no issues with adherence due to sweat). As impacts to the back of the head are not legal blows and only represented 2.5% of all events, the patch's location at the back of the headgear limits the effects of its sensitivity to impact location.

CONCLUSION: Tight coupling of the sensor to the skull is key to a sensor's ability to measure the number, magnitude, and direction of impacts to the head. Further work is needed to continue refining these tools so that they more accurately record the number and magnitude of head impacts. In the meantime, instrumented mouthguards appear to be better than skin or headgear patches for studying boxing head impacts.

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