Boxing headguard performance in punch machine tests

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ABSTRACT

Background The paper presents a novel laboratory method for assessing boxing headguard impact performance. The method is applied to examine the effects of headguards on head impact dynamics and injury risk.

Methods A linear impactor was developed, and a range of impacts was delivered to an instrumented Hybrid III head and neck system both with and without an AIBA (Association Internationale de Boxe Amateur)-approved headguard. Impacts at selected speeds between 4.1 and 8.3 m/s were undertaken. The impactor mass was approximately 4 kg and an interface comprising a semirigid 'fist' with a glove was used.

Results The peak contact forces were in the range 1.9–5.9 kN. Differences in head impact responses between the Top Ten AIBA-approved headguard and bare headform in the lateral and forehead tests were large and/or significant. In the 8.3 m/s fist-glove impacts, the mean peak resultant headform accelerations for bare headform tests was approximately 130 g compared with approximately 85 g in the forehead impacts. In the 6.85 m/s bare headform impacts, mean peak resultant angular head accelerations were in the range of 5200–5600 rad/s^2 and almost halved by the headguard. Linear and angular accelerations in 45° forehead and 60° jaw impacts were reduced by the headguard.

Conclusions The data support the opinion that current AIBA headguards can play an important role in reducing the risk of concussion and superficial injury in boxing competition and training.

INTRODUCTION

Boxing is a combat sport that is associated with head impact and head injury risks. In 2013, the International Boxing Association (AIBA, Association Internationale de Boxe Amateur), which is responsible for setting the competition rules for boxing at the Olympic games, banned the use of headguards in selected competitions.[1] Headguards are soft padded helmets with no hard shell. AIBA do not specify impact performance tests for boxing headguards nor do they mandate any standard, rather they specify headguard dimensions, for example, mass <450 g.[2] This paper presents a novel method for assessing boxing headguard impact performance and examines the effects of headguards on head impact dynamics.

Head impact dynamics, that is, impact force vector and head linear and angular accelerations, are understood to be mechanically related to head injuries that can occur in combat sports, for example, superficial injury, orofacial fractures and brain injury.[3–11] According to Zhang *et al*,[10] the tolerance levels for mild traumatic brain injury (mTBI) are 6 krad/s^2 and 240 for angular acceleration and the Head Injury Criterion (HIC_{15}), respectively. Rowson *et al*[11] noted a 75% concussion likelihood for a resultant angular acceleration of 6.9 krad/s^2, which is similar to that reported by McIntosh *et al.*[12] McIntosh *et al*[12] reported 50% and 75% concussion likelihood for resultant linear head acceleration as 65 and 89 g, respectively.

Although research has been conducted in which boxers have punched headforms, such tests do not offer the level of experimental control and repeatability required to assess headguards.[4] Some boxing and combat sports headguard tests have been conducted with pendulum impactors.[13 14] A literature review (see online supplementary appendix A) identified that mean impact glove speeds in boxing ranges from 3.0 to 11.9 m/s, and peak impact force in gloved punches ranges from 1.4 to 4.8 kN and varied by punch type. The literature also demonstrates that punches delivered in competition or in combination during laboratory experiments have approximately half the impact force of single maximal-effort punches.[7 15 16]

Boxing headguards have the potential to reduce the impact force by attenuating the impact energy of the punch and distributing the impact force, but must perform over multiple head impact exposures in training and competition.[3 17] Although helmet drop tests are a reliable and repeatable method for testing helmets, in a relatively novel area such as boxing headguards, it may be challenging to interpret the test results in the framework of boxing impacts and related injury risks.[17 18] A second limitation is that the head's angular kinematics cannot be measured in standard drop tests.[3] Therefore, it was decided to design and build a novel linear impactor (punch machine) that could be used to deliver punches to the head of an Anthropometric Test Device. The punch machine was used to: compare the performance of two AIBA-approved headguards; compare headguard performance against bare headform impacts; and, using the punch machine with a glove interface, compare head impact dynamics both with and without an AIBA-approved headguard.

METHODS

Punch machine

A spring driven linear impactor was developed and commissioned through a series of repeatability tests. The impactor is guided by linear bearings and winched back against the resistance of the springs. The displacement of the springs determines the impact speed. Preliminary tests showed that the

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punch machine delivered repeatable and reliable impacts. A detailed description of the punch machine and system tests is presented in online supplementary appendix B. Two impact interfaces were used: a 'fist-glove' and 'disc-pad' (figure 1). The total impactor mass was 3.880 kg for the disc interface and 3.885 kg for the fist-glove impacts, including the glove

Hybrid III head and neck

A calibrated Hybrid III head and neck was used in all tests (figure 2). The head and neck were mounted on a massive stand that permitted vertical and rotational orientation of the head and neck with respect to the impactor. The impactor height and angle were adjustable.

Instrumentation, data acquisition and signal conditioning

The head was instrumented with a triaxial linear accelerometer ($a_{Hdx,y,z}$), three angular velocity sensors ($\omega_{Hdx,y,z}$) and a six-axis upper neck load cell. The head angular accelerations ($\alpha_{Hdx,y,z}$) were derived by differentiating the filtered angular velocity time histories. For a posteriorly directed frontal impact, the main angular motion is extension, that is, +y angular displacement, velocity and acceleration.[19] For a right directed left lateral impact, the main angular motion is right lateral flexion, that is, +x angular displacement, velocity and acceleration. An impact to the left jaw will result in initial axial rotation to the right, that is, +z angular displacement, velocity and acceleration.

The impact force was measured using a Kistler 9331B uniaxial force link mounted between the shaft and impact interface. This force is referred to as the 'measured force' (F_m). An estimate of the contact force (F_c) was derived from F_m, where F_c is what the boxer would 'feel' when punched (see online supplementary appendix B)

All data were acquired at 20 kHz with a TDAS (Seal Beach, California, USA) data acquisition system. The following signals were filtered with a SAE CFC 1000 filter: $a_{Hdx,y,z}$; F_m; a_I; and $F_{Nx,y,z}$. $M_{Nx,y,z}$ were filtered with a SAE CFC 600 filter. Angular velocity and acceleration ($\omega_{Hdx,y,z}$ and $\alpha_{Hdx,y,z}$) were filtered with a CFC 180 filter. Resultant linear and angular accelerations, respectively, Ra_{Hd} and $R\alpha_{Hd}$, were calculated. The 15 ms limited HIC_{15} was calculated. Neck loads were measured but not reported. The signal conditioning processes conformed to SAE J211.[20] A timing gate was positioned to measure the velocity of the impactor just prior to contact.

Figure 2 Hybrid III head and neck configuration. Frontal impact condition shown. The head orientation was checked before each test. The SAE J211 sign convention was applied: +x=anterior; positive rotation around x is right lateral flexion (also referred to as roll); +y=lateral right; positive rotation around y is extension (referred to as pitch); and, +z=inferior; positive rotation around z is right rotation (also referred to as yaw).

Test matrix and headguards

The minimum number of planned tests is presented in table 1. Large-sized Top Ten and Adidas AIBA-compliant headguards were used in all tests. The headguard thickness was in the range of 20–26 mm, density approximately 80 kg/m^3, and mass approximately 0.3 kg. All tests were conducted at the Roads and Maritime Services Crashlab in Sydney. Each headguard was tested once only at an impact location. The impact orientations were: centre-front forehead, lateral, 45° forehead and 60° jaw impacts (see online supplementary appendix C).

Statistical analysis

Descriptive statistics were calculated for the main independent variables: peak linear and angular headform acceleration, peak measured and contact force, and HIC_{15}. t Tests were performed to assess differences between the headguards and between the headguard and bare headform tests.

RESULTS

In total, 64 tests were performed of which three were discarded completely because of test system failures. The coefficient of

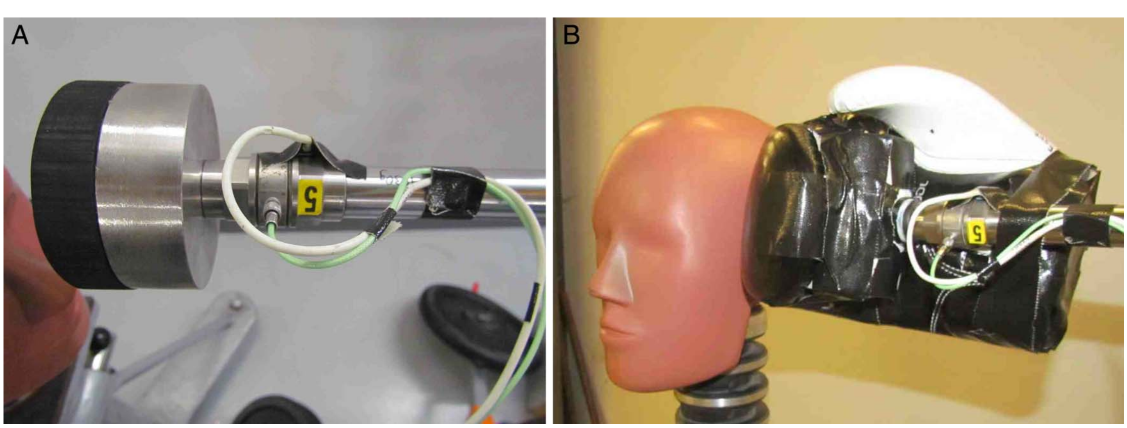

Figure 1 The disc-pad interface (left) and fist-glove interface (right). A cylindrical mallet head (fist) was attached to the end of the impactor arm and then glove wrapped tightly around the fist. The Kistler force link with numeral '5' is shown (green cable) and the mounting point for accelerometer (white cable) that measured a_I. The force link measured the force along the shaft (F_m).

Table 1 Outline of planned tests

Headguard	Speed	Impact interface	Repeat	Orientation	Total
Top Ten, Adidas, None	1	Disc-pad	3	2 (frontal, lateral)	18
Top Ten, None	2	Glove-fist	2	2 (frontal, lateral)	16
Top Ten, None	1	Glove-fist	2	2 (jaw, forehead)	8

The minimum number of tests is described in the table. Additional tests were conducted.

variation for impact velocity—intended versus obtained—was in the range 1–4%. All results with the disc-pad interface are presented in the online supplementary appendix C.

Fist-glove impacts

In total 37 tests were conducted using the fist-glove interface both with and without the Top Ten headguard. Exemplar time-histories for the head impact responses are presented in online supplementary appendix D. Differences in head impact responses between the Top Ten AIBA-approved headguard and bare headform in the fist-glove lateral and centre-front forehead tests were large and/or significant ($p<0.05$; table 2).

At 4.11 m/s, the headguard tests resulted in slightly lower head impact response values than in the bare headform tests (see online supplementary appendix E). For example, peak R_{aHd} (g) was 24 and 22 g, respectively, for centre-front forehead and lateral headguard impacts compared with 35 and 29 g for bare headform impacts. Peak α_{Hdy} for centre-front impacts was 1484 rad/s^2 for headguard tests and 1694 rad/s^2 for bare headform tests. Peak α_{Hdx} for lateral impacts was 1215 rad/s^2 for headguard tests and 1750 rad/s^2 for bare headform tests.

Lateral jaw and 45° forehead impacts at 8.34 m/s were conducted. The tests were multiplanar and emphasised the head z-axis angular kinematics (see online supplementary appendix D). Significance tests were not performed because of the small sample size (table 3). Angular acceleration in the z-axis was reduced with headguards in both test configurations. The bare headform jaw impacts resulted in a mean peak $R\alpha_{Hd}$ of 8605 rad/s^2 and mean peak $R\alpha_{Hdz}$ of 8333 rad/s^2. With the headguard, jaw impacts were reduced to 4335 and 3941 rad/s^2, respectively. The bare headform 45° forehead impacts resulted in a mean peak $R\alpha_{Hd}$ of 8365 rad/s^2 and mean peak $R\alpha_{Hdz}$ of 5619 rad/s^2. With the headguard, these were reduced to 4335 and 2620 rad/s^2, respectively.

DISCUSSION

Test method

The linear impactor built for these tests delivered repeatable impacts. Average peak Fc_c by test condition for all the glove tests was in the range of 1.9–5.9 kN, which overlaps with the target range of 1.4–4.8 kN in similar punch speed ranges. A linear impactor could become the basis for a technical specification for boxing headguards and/or gloves as an alternative to a helmet drop test or pendulum impactor.[3 13 14 21 22] Although the Hybrid III's biofidelity in all possible impact situations is unknown, it has been used to study many impact situations including helmets, boxing and concussive impacts.[13 19 23–25]

Injury risk reduction

In general, the results showed that peak impact force, and linear and angular head accelerations were substantially reduced by headguards compared to the bare headform condition; often at least halved. On the assumption that the system biofidelity is meaningful from the perspective of the boxer, the results of the glove tests were interpreted with respect to the following concussion-oriented injury assessment reference values: peak resultant linear acceleration <75 g, $HIC_{15}<240$, and peak resultant angular acceleration <6000 rad/s^2.[10–12]

Table 2 Head impact responses for glove/fist impacts

Test characteristics	Velocity	6.85 m/s				8.34 m/s			
	Direction	Centre-front		Left lateral		Centre-front		Left lateral	
	Headguard	Top Ten	None	Top Ten	None	Top Ten	None	Top Ten	None
	Number of tests	2	2	3	3	3	4	3	3
Peak Ra_{Hd} (g)	Mean	60*	89	46*	86	88*	131	86*	133
	SD	1	2	1	2	3	5	8	14
HIC (15)	Mean	82*	148	62*	132	183*	322	165*	326
	SD	5	7	2	5	10	15	34	38
Peak F_c (N)	Mean	2693*	3900	1983*	3737	4107*	5462	3820*	5941
	SD	36	49	72	109	230	316	604	212
Peak α_{Hdx} (rad/s^2)	Mean			2461*	4048			3747*	5765
	SD			64	320			796	794
Peak α_{Hdy} (rad/s^2)	Mean	2619*	3746			3620*	4905		
	SD	21	175			161	353		
Peak $R\alpha_{Hdx,y}$ (rad/s^2)	Mean	2826	5582	2470*	4062	3915	7470	3758*	5787
	SD	19	1758	66	320	268	2535	800	802
Peak $R\alpha_{Hd}$ (rad/s^2)	Mean	2871	5617	2849*	5202	4072	7489	4323*	7411
	SD	40	1792	81	55	276	2543	244	812

The 'y' axis angular kinematics are most relevant for the centre front impacts and the 'x' axis angular kinematics for the lateral impacts. The 'y' axis equates to head flexion-extension (or pitch) and 'x' axis equates to lateral flexion (or roll).
*Indicates a significant difference (p<0.05).
HIC, Head Injury Criterion.

Table 3 Head impact responses for 45° forehead and jaw conditions in glove/fist tests

Test characteristics	Velocity / Direction / Headguard / Number of tests	8.34 m/s Left 45° forehead Top Ten 2	None 2	Jaw Top Ten 2	None 3
Peak Ra_{Hd} (g)	Mean	73	113	84	123
	SD	3	0	5	3
HIC (15)	Mean	123	243	129	276
	SD	6	6	12	13
Peak F_c (N)	Mean	2962	4747	4249	5821
	SD	15	175	151	150
Peak α_{Hdx} (rad/s^2)	Mean	2617	6347	6186	6414
	SD	29	2729	490	238
Peak α_{Hdy} (rad/s^2)	Mean	2413	2879	2186	2097
	SD	205	99	158	15
Peak α_{Hdz} (rad/s^2)	Mean	2620	5619	3941	8333
	SD	255	199	342	165
Peak $R\alpha_{Hdx,y}$ (rad/s^2)	Mean	3532	6796	6561	6710
	SD	120	2314	402	227
Peak $R\alpha_{Hd}$ (rad/s^2)	Mean	4335	8365	7173	8605
	SD	189	1900	506	113

Linear head acceleration and impact force responses presented.
HIC, Head Injury Criterion.

In the 8.34 m/s glove impacts, the mean peak resultant headform accelerations for bare headform tests exceeded 75 g for lateral (133 g) and centre-front impacts (131 g). With the headguard, mean peak resultant headform accelerations were 86 g in the lateral impacts and 88 g in the centre-front impacts. Mean HIC_{15} exceeded 240 for the 8.34 m/s impacts and was less than 240 with the headguard. This suggests that the struck boxer without a headguard would be concussed, and a proportion of those wearing headguards might be concussed. In the 6.85 m/s glove impacts, the mean peak resultant headform accelerations for bare headform tests exceeded 75 g for lateral impacts (86 g) and centre-front impacts (88 g). By contrast, with the headguard, mean peak resultant headform accelerations were less than 75 g. In the 6.85 m/s impacts, mean HIC_{15} was less than 240 for both headguard and bare headform conditions. This suggests that a proportion of those not wearing headguards would be concussed, and boxers wearing headguards would not be concussed in equivalent punches.

In the lateral and centre-front 8.34 m/s bare headform impacts, peak resultant angular head accelerations exceeded 6000 rad/s^2. With headguards, peak resultant angular accelerations were below 4500 rad/s^2. In the 6.85 m/s bare headform impacts, peak resultant angular head accelerations were slightly below 6000 rad/s^2 (mean 5200–5600 rad/s^2), and was almost halved by the headguard. Therefore, the angular acceleration results indicate a much lower likelihood that boxers wearing headguards would be concussed compared to those not wearing headguards.

In the lateral and centre-front 4.99 m/s fist-glove impacts, the IARVs were not exceeded for the headguard or bare headform conditions. This suggests that concussion is unlikely in these impacts.

Average peak F_c for bare headform impacts was in the range 3.7–5.9 kN, depending on location and velocity, compared to 1.9–4.2 kN for headguard tests. F_c is applied over a large surface area because of the glove and, therefore, F_c is unlikely to correspond directly to experimental data on facial fracture forces.[26–29] The force data (F_c) suggest that the likelihood and severity of laceration would be reduced by the headguard plus glove, as reflected in practice.

Differences indicative of a protective effect of headguards in the 8.34 m/s jaw and 45° forehead impacts were also observed. In the bare headform, jaw and forehead impacts, 75 g was exceeded but not with the headguard. By contrast, with the headguard, mean peak resultant headform accelerations were close to 83 g, or <75 g. In the bare headform, jaw and forehead impacts a HIC_{15} of 240 was exceeded but not with a headguard; 6000 rad/s^2 was clearly exceeded for both jaw and 45° forehead bare headform impacts. With headguards, peak resultant headform angular acceleration was 7173 rad/s^2 in the jaw impact and 4335 rad/s^2 in the 45° forehead impact. This strongly suggests that the boxer without a headguard, who was punched on the forehead or jaw in equivalent punches would be concussed, and a proportion of those wearing headguards might be concussed. It is important to note that the z-axis (yaw) angular acceleration was reduced by approximately 50% with a headguard in the jaw impacts. The test results do not show that headguards will increase the risk of head and brain injury.

CONCLUSIONS

In totality, the data support the opinion that current AIBA headguards can play an important role in reducing the risk of concussion and superficial injury in boxing competition and training. The results indicate that for slower punches, that is, <5 m/s with the punch machine, the benefits offered by a headguard over and above a glove are small. In the range of punch speeds between 5 and 9 m/s, an AIBA-approved headguard, in combination with a glove, will offer a large level of protection to the boxer's head. The tests in the range of 5–9 m/s correspond well with observed punch speeds and energies.

What are the new findings?

- ▸ Laboratory impact tests show that a boxing headguard in combination with a glove offers a level of protection to the head and brain in a wide range of impacts.
- ▸ The optimal benefits of current AIBA (Association Internationale de Boxe Amateur)-compliant headguards are realised in midrange speed punches (5–8.5 m/s) where the impact test results suggest that the headguard will reduce the likelihood of concussion and superficial head wounds.
- ▸ In low-speed punches (<4 m/s) the addition of a headguard may have only a limited benefit, and in high-speed punches (>9 m/s) the headguard effects in terms of reducing the likelihood of concussion may be limited.
- ▸ The headguard reduced the magnitude of angular head accelerations, including in impacts to the lateral jaw.

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