# 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 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 uni-axial 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

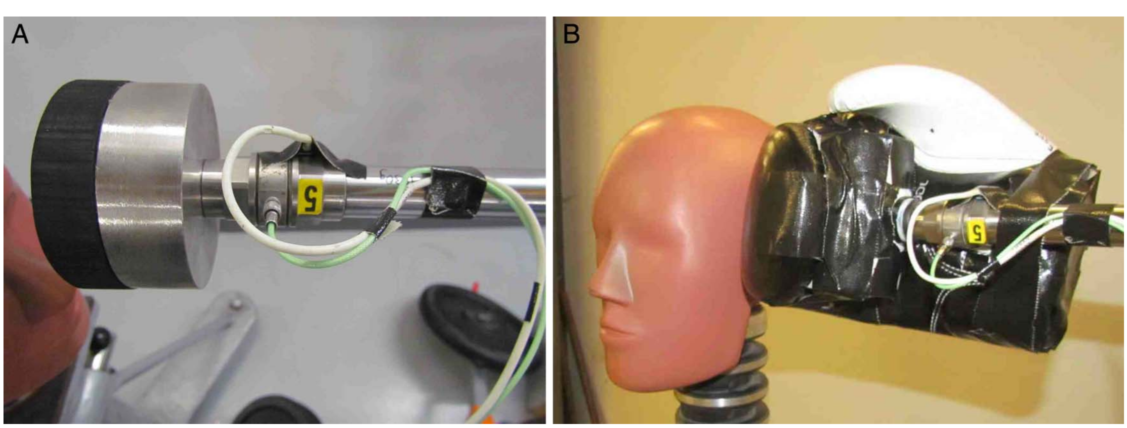


**Figure 1** The disc-pad interface (left) and fist-glove interface (right). A cylindrical mallet head (fist) was attached to the end of the impactor arm and then glove wrapped tightly around the fist. The Kistler force link with numeral '5' is shown (green cable) and the mounting point for accelerometer (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 $\alpha_{Hdy}$ for centre-front impacts was 1484 rad/s$^2$ for headguard tests and 1694 rad/s$^2$ for bare headform tests. Peak $\alpha_{Hdx}$ 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 $\alpha_{Hdx}$ (rad/s$^2$) | Mean | | | 2461* | 4048 | | | 3747* | 5765 |
| | SD | | | 64 | 320 | | | 796 | 794 |
| Peak $\alpha_{Hdy}$ (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 $\alpha_{Hdx}$ (rad/s$^2$) | Mean | 2617 | 6347 | 6186 | 6414 |
| | SD | 29 | 2729 | 490 | 238 |
| Peak $\alpha_{Hdy}$ (rad/s$^2$) | Mean | 2413 | 2879 | 2186 | 2097 |
| | SD | 205 | 99 | 158 | 15 |
| Peak $\alpha_{Hdz}$ (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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**Supplementary Material**

## Appendix A: Biomechanics of boxing punches

There have been few biomechanical studies of boxing. A review of the literature was undertaken to provide a guide to the test conditions applied in projects one to three.

A review process, using PubMed, was carried out to identify peer-reviewed articles investigating the biomechanics of punches to the head during boxing matches. PubMed is a free database, maintained by the United States National Library of Medicine at the National Institutes of Health, which primarily accesses citations from the MEDLINE database, in addition to other biomedical literature. The keyword search terms were a Boolean combination of “boxing”, “punch”, “biomechanics” and “kinematics”. Only English language peer-reviewed journal papers, conference proceedings, theses and books were considered.

The primary PubMed search strategy returned 122 articles (table A1), which was reduced to 28 articles after excluding articles based on the relevancy of their titles. After reading the abstracts of the 28 articles, a further 10 articles were excluded for various reasons: seven martial arts articles, two unrelated articles one foreign language article and one article detailing an assault case.

**Table A1: Inclusion and exclusion of articles during search strategy.**

| Search | Level | Articles | | |
|---|---|---|---|---|
| | | Number | Excluded | Included |
| Primary | PubMed | 122 | | 122 |
| | Title | 28 | 94 | |
| | Abstract | 17 | 11 | |
| | Full text | 9 | 8 | |
| Total | | 9 | | |

# Table A2: Biomechanics of boxing punches (articles from primary strategy).

| Source | Method | Type | Level | Weight class/ body mass | n | Punch (hand) | Fist Speed | Fist Force | Fist Mass |
|---|---|---|---|---|---|---|---|---|---|
| | | | | [kg] | | | [m/s] | [N] | [kg] |
| Atha et al. (1985) | Single punces to instrumented target mass | Professional | Not reported | Heavy | 1 | Cross | 8.9 | 4096 | |
| Whiting et al. (1988) | Video analysis of single punces with glove | | Proficient | 67.6 (13.4) | 4 | Jab | 5.9 (1.1) | | |
| | | | | | | Hook | 8.0 (2.4) | | |
| Smith (2000) | Single punces to "head" of pear-shaped bag | Amateur | Elite | | 7 | Jab | | 2847 (225) | |
| | | | | | | Cross | | 4800 (227) | |
| | | Amateur | Intermediate | | 8 | Jab | | 2283 (126) | |
| | | | | | | Cross | | 3722 (133) | |
| | | Amateur | Novice | | 8 | Jab | | 1604 (97) | |
| | | | | | | Cross | | 2381 (116) | |
| Viano et al. (2005) | Single punces to Hybrid III ATD head (with neck/torso) | Amateur | Olympic | 76.2 (22.1) | 11 | Cross (forehead) | 8.2 (1.5) | 3419 (1381) | 1.67 (0.28) |
| | | | | | | Cross (jaw) | 9.2 (1.7) | 2349 (962) | |
| | | | | | | Hook | 11 (3.4) | 4405 (2318) | |
| | | | | | | Uppercut | 6.7 (1.5) | 1546 (857) | |
| Walilko et al. (2005) | Single punces to Hybrid III ATD head (with neck/torso) | Amateur | Olympic | Fly | 3 | Cross | 9.2 (1.8) | 3336 (559) | 2.31 (1.06) |
| | | | | Light-welter | 1 | | 7.6 (1.0) | 2910 (835) | 2.70 (1.04) |
| | | | | Middle | 1 | | 11.9 (1.4) | 2625 (543) | 0.81 (0.19) |
| | | | | Super-heavy | 2 | | 8.3 (1.8) | 4345 (280) | 4.97 (2.44) |
| Smith (2006) | Single punces to "head" of pear-shaped bag | Amateur | Elite | | 29 | Jab | | 1722 (700) | |
| | | | | | | Cross | | 2643 (1273) | |
| | | | | | | Hook (lead) | | 2412 (813) | |
| | | | | | | Hook (rear) | | 2588 (1040) | |
| Piorkowski et al. (2011) | Single punces to Hybrid II ATD head | | Varying | | 10 | Jab | 7.22 (0.72) | | |
| | | | | | | Cross | 8.22 (1.08) | | |
| | | | | | | Hook (lead) | 10.61 (1.07) | | |
| | | | | | | Hook (rear) | 11.01 (2.21) | | |
| | Combination punches to Hybrid II ATD head | | Varying | | 10 | Jab | 5.67 (1.09) | | |
| | | | | | | Cross | 6.28 (1.31) | | |
| | | | | | | Hook (lead) | 8.59 (1.81) | | |
| | | | | | | Hook (rear) | 9.42 (2.53) | | |
| Fife et al. (2013) | Single punces to Hybrid III ATD head (with neck/torso) | Amateur | Olympic | 76.5 (22.1) | | Cross (forehead) | 8.25 (1.50) | | |
| | | | | | | Cross (jaw) | 9.24 (1.70) | | |
| | | | | | | Hook | 11.03 (3.37) | | |
| | | | | | | Uppercut | 6.67 (1.53) | | |
| Nakano et al. (2014) | Single punces to instrumented target mass | Amateur | Varsity | | 9 | Jab, cross | 8.7 (0.9) | 2146 (473) | |

From the literature (table A2) it was found that the mean impact speeds of the gloves and/or fists ranged from 5.7 m/s to 11.9 m/s. Straight punches, *i.e.* jabs and crosses, recorded values throughout the entire range; however, the mean impact speed range for hook punches was towards the upper bound of the range (8.0-11.0 m/s). Only two studies reported impact speed values for uppercut punches, which both recorded means of 6.7 m/s.

The impact force of gloved punches ranged from 1.5 kN to 4.8 kN. As with speed, the impact force varied between punch types with crosses, on average, producing the highest impact forces. This result is expected due to the cross, commonly referred to as the "power" punch, being thrown with the dominant side and including much more rotation of the torso than other punches. The literature also demonstrates that punches thrown in competition or in combination during laboratory experiments have approximately half the impact force of single maximal-effort punches; however, single maximal-effort punches are an indication of the worst case scenario.

Few studies reported the effective mass of the fist, with values ranging from 0.81 kg to 4.97 kg; however, the lowest effective mass value was reported for a single subject by Walilko et al. with the next highest mean effective mass being approximately twice that value (1.67 kg).

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**Appendix B: Additional punch machine and instrumentation details.**

The design parameters for the punch machine were: Mass – adjustable between 2.5 kg and 4 kg; Speed up to 10 m/s; Orientation – adjustable to any head impact vector and contact site; Interface – variety including fist-glove impactor head; and, Repeatability – test speed and impact force.

The punch machine was driven by a pair of 305 mm long extra heavy duty Raymond die springs (model #SEH5048) with a stiffness of 30.8 N/mm. Two 800 mm long 12 mm round steel shafts were inserted into the springs, which were fixed at the ends with shaft supports. In front of the springs were two linear bearings, which were connected by a steel plate to form the "carriage". The carriage was also fixed to the 800 mm long 20 mm impacting shaft, which operated through a pair of linear bearings in series. The end of the 20 mm shaft was drilled and tapped with an M12 thread so that a grub screw could connect the shaft to the force link. The carriage was winched back by a 4:1 hand winch, with an internal brake, via a cable running through a pulley. A flag on the carriage was used to measure the displacement of the springs from the unloaded position. A quick-release snap shackle was fixed to the end of the cable and released by a cord. The impactor struck a buffer positioned to stop the impactor after the head had separated from the impact interface. All parts were mounted onto a 20 mm thick piece of timber, which was reinforced with two pieces of steel angle. The impactor was mounted to two height-adjustable weighted stands. There was minimal movement of the stands during an impact. Since completing the testing reported in this paper, the rig has been rebuilt with a steel frame and integrated height adjustable stand.

Preliminary system tests showed that the coefficient of variation (CV) for the impact speed was 4.7% averaged across three target speeds in 27 tests. Spring displacement and velocity were highly correlated ($r^2$=0.96). The tests showed that the CV for the measured impact force was 3.2% averaged across three test speeds in 15 tests with the same impactor mass.

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 $F_m$, the linear acceleration of the impactor shaft ($a_I$) and the estimated effective mass ($m_e$) of the components between the force transducer and contact point. Preliminary tests indicated that the best estimate of the effective mass was 0.2 kg. $F_c$ is the force applied to the head, i.e. what the boxer would 'feel' when punched. In preliminary tests the difference between the $F_m$ and $F_c$ was observed to be approximately 5%.

## Appendix C: Test impact orientations

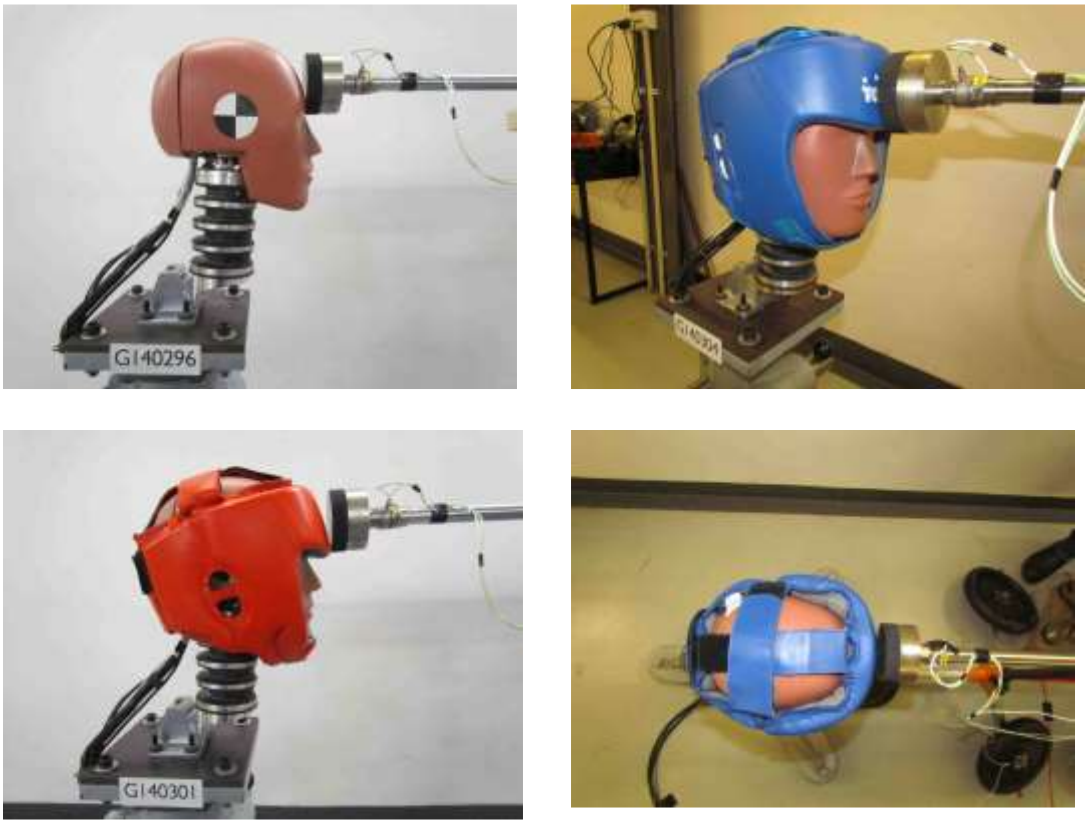


**Figure C1: Centre-front forehead impacts with disc-pad interface. There is some parallax error in the photographs that suggests that the impactor was not aligned horizontally. The impactor was aligned horizontally in all tests.**


**Figure C2: Left lateral impacts with disc-pad interface.**

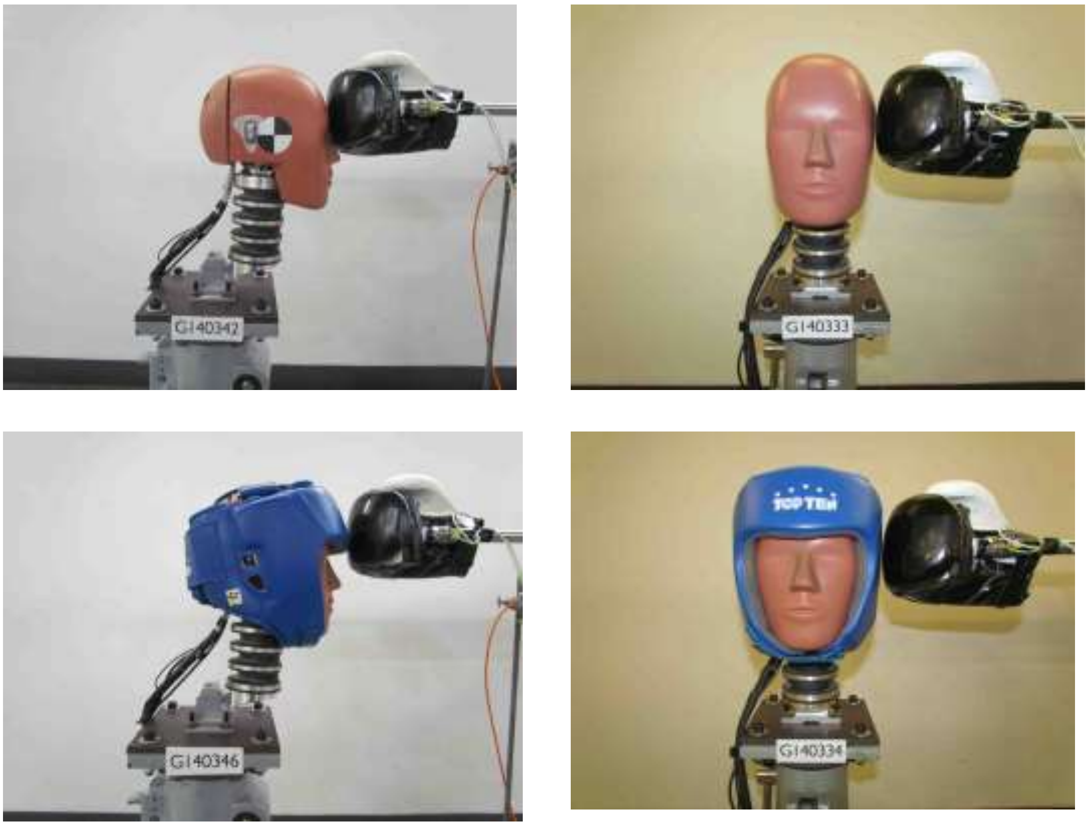


**Figure C3: Centre-front forehead and lateral impacts with glove-fist interface.**


**Figure C4: 45°forehead impacts.**

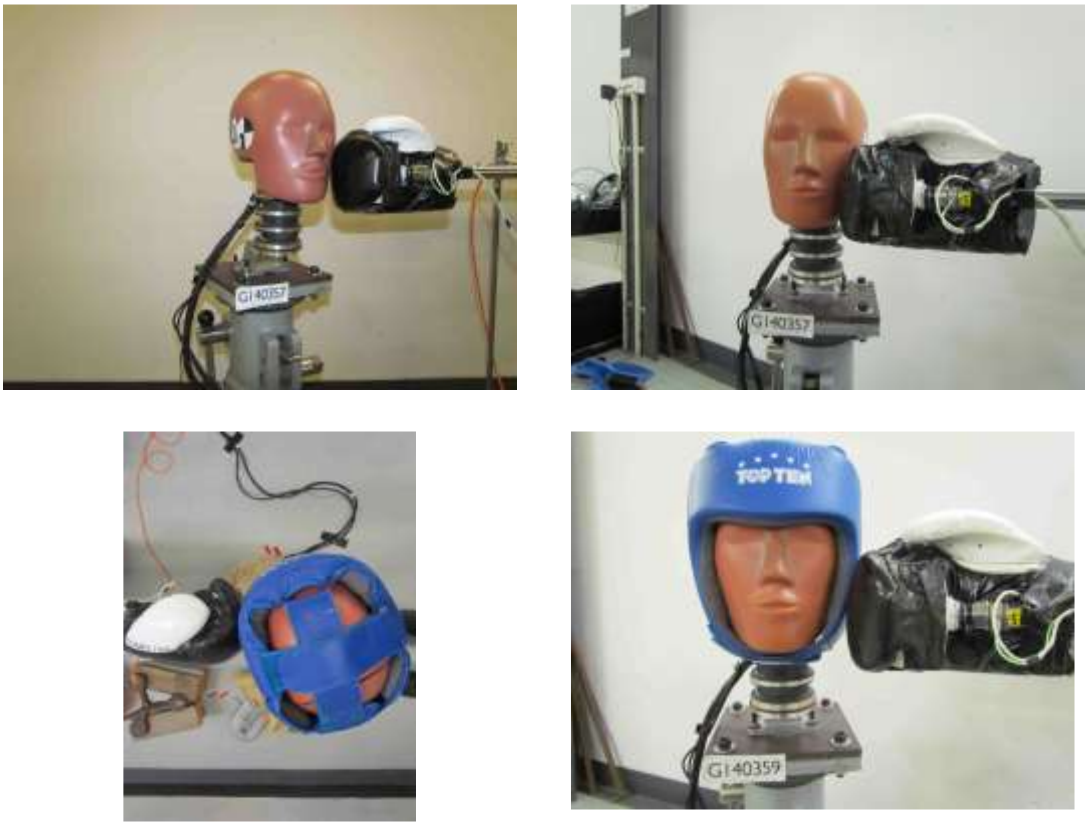


**Figure C5: 60°jaw impacts. The impact axis was aligned to be 60° from the mid-saggital plane measured in the horizontal plane.**

## Appendix C

### Disc-pad results

There were minor differences between the impact performance of the two headguard models. AIBA do not specify headguard performance requirements and neither model claimed compliance with a helmet standard, e.g. ASTM F2397 – 09.

Twenty-two (22) tests were conducted at 4.11 m/s using the semi-rigid disc-pad interface after two preliminary tests at 4.99 m/s (tables C1 and C2). The test locations and impact orientations were: Centre-front forehead oriented in the sagittal plane on the anterior-posterior axis, and lateral above the ear oriented in the coronal plane left to right on the medial-lateral axis. At least three impacts were performed in each test condition. The combined data (tables C3 and C4) show an overall reduction in peak resultant head acceleration, $HIC_{15}$, peak measured force and peak contact force in the range of 59% to 84% associated with the headguard compared to the bare headform tests. These tests show the effect of the headguard only, without the influence of gloves. Exemplar time-histories for the disc-pad impacts are presented below.

**Table C1: Head impact responses by headguard model and impact direction in 4.11 m/s disc-pad tests. Linear head acceleration and impact force responses presented.**

| Test Characteristics | Velocity | 4.11 m/s | | | |
|---|---|---|---|---|---|
| | Location | Centre-front | | Left Lateral | |
| | Headguard | Adidas (AIBA) | Top Ten (AIBA) | Adidas (AIBA) | Top Ten (AIBA) |
| Peak $Ra_{Hd}$ (g) | n. | 3 | 3 | 5 | 3 |
| | Mean | 46 | 39.33 | 49.6 | 43.67 |
| | SD | 7.81 | 1.53 | 9.07 | 1.53 |
| $HIC_{15}$ | n. | 3 | 3 | 5 | 3 |
| | Mean | 37 | 29.33 | 41.8 | 35.67 |
| | SD | 7.81 | 1.53 | 10.52 | 1.53 |
| Peak $F_m$ (N) | n. | 3 | 3 | 5 | 3 |
| | Mean | 1720.33 | 1546 | 1750.4 | 1546.67 |
| | SD | 290.41 | 35.51 | 299.77 | 51.5 |
| Peak $F_c$ (N) | n. | 3 | 3 | 5 | 3 |
| | Mean | 1846 | 1646 | 1867 | 1652.67 |
| | SD | 304.86 | 41.57 | 323 | 55.54 |

**Table C2: Head impact responses by headguard model and impact direction in 4.11 m/s disc-pad tests. Angular head kinematic responses presented. The "y" axis angular kinematics are most relevant for the centre front impacts and the "x" axis angular kinematics for the lateral impacts. "y" axis equates to head flexion-extension (or pitch) and "x" axis equates to lateral flexion (or roll).**

| Test Characteristics | Velocity | 4.11 m/s | | | |
|---|---|---|---|---|---|
| | Location | Centre-front | | Left Lateral | |
| | Headguard | Adidas (AIBA) | Top Ten (AIBA) | Adidas (AIBA) | Top Ten (AIBA) |
| Peak $\omega_{Hdx}$ (rad/s) | n. | 3 | 3 | 5 | 3 |
| | Mean | 0.1 | 0.4 | 14.3 | 14.4 |
| | SD | 0.4 | 0.1 | 0.7 | 0.2 |
| Peak $\omega_{Hdy}$ (rad/s) | n. | 3 | 3 | 5 | 3 |
| | Mean | 18.6 | 17.9 | -2.7 | -2.9 |
| | SD | 0.4 | 0.4 | 0.2 | 0.1 |
| Peak $\alpha_{Hdx}$ (rad/s$^2$) | n. | 3 | 3 | 5 | 3 |
| | Mean | 487.3 | -80.2 | 2482.6 | 2214.6 |
| | SD | 153.2 | 325.3 | 437.5 | 77.7 |
| Peak $\alpha_{Hdy}$ (rad/s$^2$) | n. | 3 | 3 | 5 | 3 |

| | | | | | |
|---|---|---|---|---|---|
| | Mean | 1922.4 | 1888.9 | 182 | 337 |
| | SD | 215.1 | 71.9 | 271.5 | 73.4 |
| Peak $R\alpha_{Hdx,y}$ (rad/s$^2$) | n. | 3 | 3 | 5 | 3 |
| | Mean | 1923.67 | 1890.67 | 2494.6 | 2233 |
| | SD | 215.63 | 69.21 | 435.3 | 81.17 |

**Table C3: Descriptive statistics for disc-pad tests. Impact locations combined. Linear acceleration and force data presented.**

| Test Characteristics | Velocity | 4.11 m/s | | |
|---|---|---|---|---|
| | Headguard | Adidas | Top Ten | None |
| | No. tests | 8 | 6 | 8 |
| Peak $Ra_{Hd}$ (g) | Mean | 48 | 42 | 135 |
| | SD | 8 | 3 | 7 |
| $HIC_{15}$ | Mean | 40 | 33 | 199 |
| | SD | 9 | 4 | 13 |
| Peak $F_c$ (N) | Mean | 1859 | 1649 | 4483 |
| | SD | 294 | 44 | 262 |

Differences between headguard impact performance by model (Adidas versus Top Ten) and impact location on linear and angular head acceleration and force related parameters were small and non-significant (table C3). Impacts to the Top Ten headguard produced generally lower peak head responses and impact forces.

Differences in linear and angular head accelerations and impactor forces between headguard and bare headform tests by impact location were large and all significant (table C4). Head kinematics in these tests were approximately planar, e.g. a forehead punch producing head extension (x-axis rotation). The resultant of the x and y angular accelerations ($R\alpha_{Hdx,y}$) for the headguard tests was approximately half the bare headform test value for both impact conditions.

**Table C4 Head impact responses by headguard/bare headform and impact direction in 4.11 m/s disc-pad tests. The data for the two headguard models are combined. "y" axis equates to head flexion-extension (or pitch) and "x" axis equates to lateral flexion (or roll).**

| Test Characteristics | Velocity | 4.11 m/s | | | |
|---|---|---|---|---|---|
| | Direction | Centre-front | | Left Lateral | |
| | Headguard | Both | None | Both | None |
| | No. tests | 6 | 4 | 8 | 4 |
| Peak Ra$_{Hd}$ (g) | Mean | 43* | 132 | 47* | 139 |
| | SD | 6 | 6 | 8 | 7 |
| HIC (15) | Mean | 33* | 200 | 40* | 198 |
| | SD | 7 | 16 | 9 | 11 |
| Peak F$_c$ (N) | Mean | 1746* | 4715 | 1787* | 4251 |
| | SD | 223 | 102 | 270 | 80 |
| Peak □$_{Hdx}$ (rad/s$^2$) | Mean | | | 2382* | 6409 |
| | SD | | | 361 | 746 |
| Peak □$_{Hdy}$ (rad/s$^2$) | Mean | 1906* | 4541 | | |
| | SD | 145 | 721 | | |
| Peak R□$_{Hdx,y}$ (rad/s$^2$) | Mean | 1907* | 4588 | 2397* | 5526 |
| | SD | 144 | 691 | 358 | 1961 |

NB: * indicates a significant difference in the relevant pair ($p<0.05$). The component Peak $\alpha_{Hdx}$ for centre-front impacts is not relevant, as is Peak $\alpha_{Hdy}$ for left lateral impacts. These components are considered in Peak R$\alpha_{Hdx,y}$

## Appendix D: Selection of head responses from punch tests

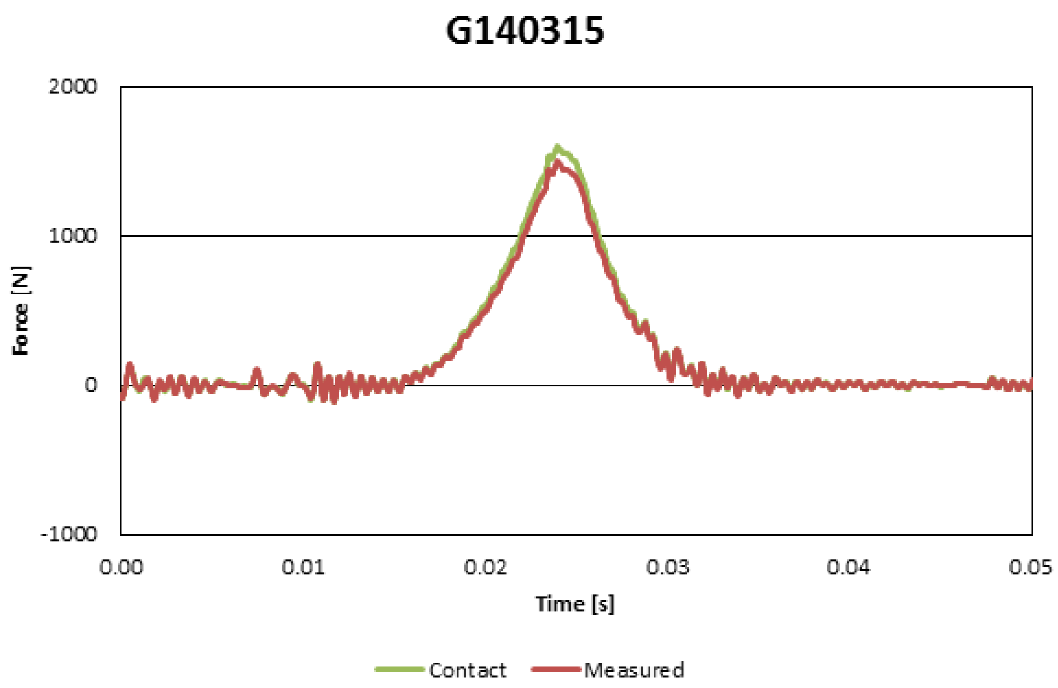


**Figure D1: Time histories for contact and measured forces in a 4.11 m/s left lateral disc-pad impact with headguard.**

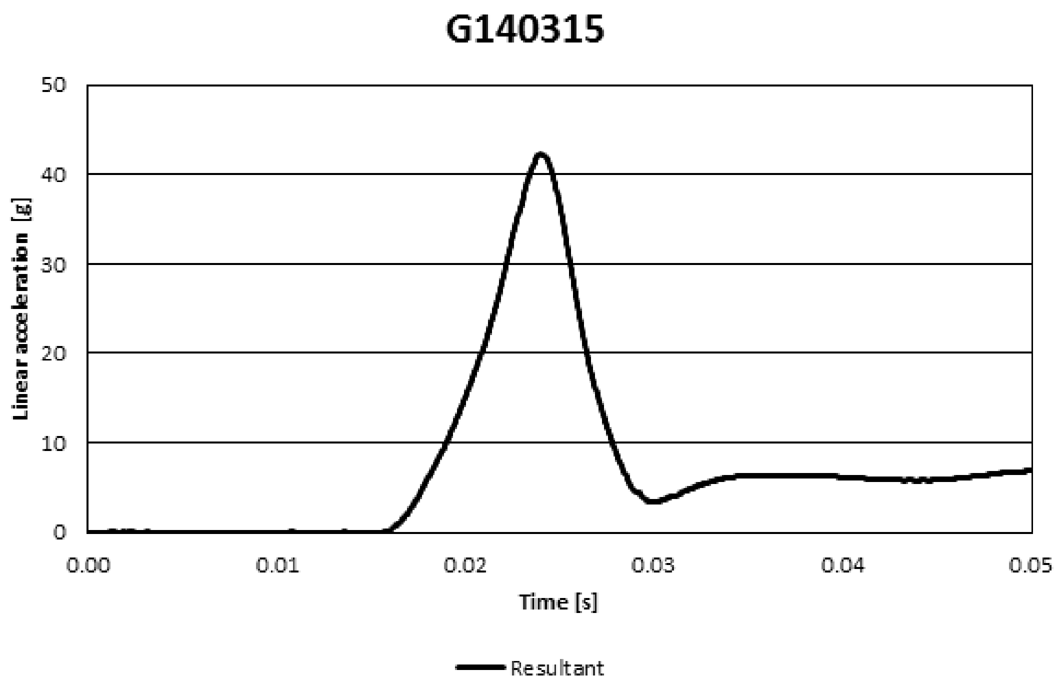


**Figure D2: Time history for resultant headform linear acceleration in a 4.11 m/s left lateral disc-pad impact with headguard.**

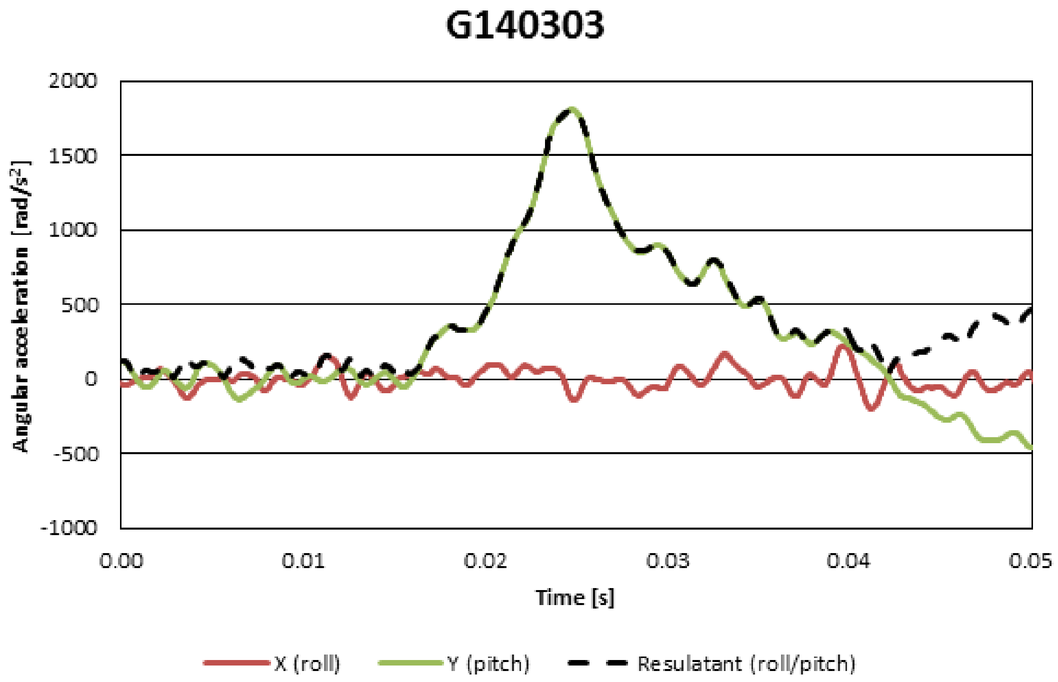


**Figure D3: The head angular acceleration time histories for a 4.11 m/s centre-front disc-pad impact with headguard are presented. The data show that the head is rotated rearward into extension ($\alpha_y$ or pitch). Changes in $\alpha_x$ (or roll) relate to variation in the contact force vector, which pushes the head into either left or right lateral flexion.**

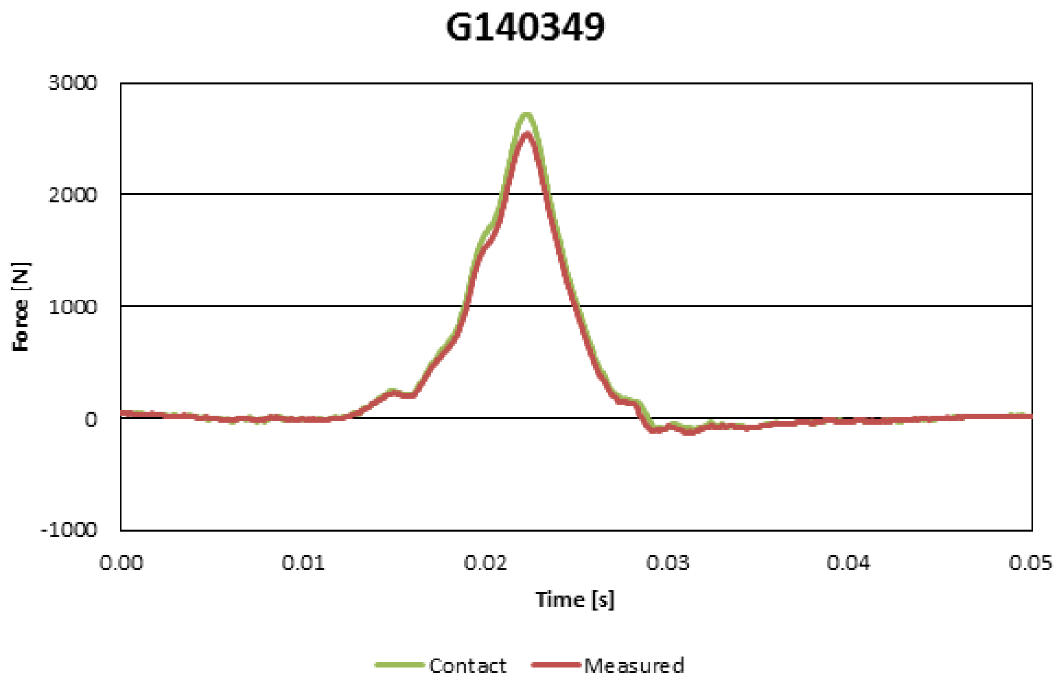


**Figure D4: Time histories for contact and measured forces in a 8.34 m/s centre-front fist-glove impact with headguard.**

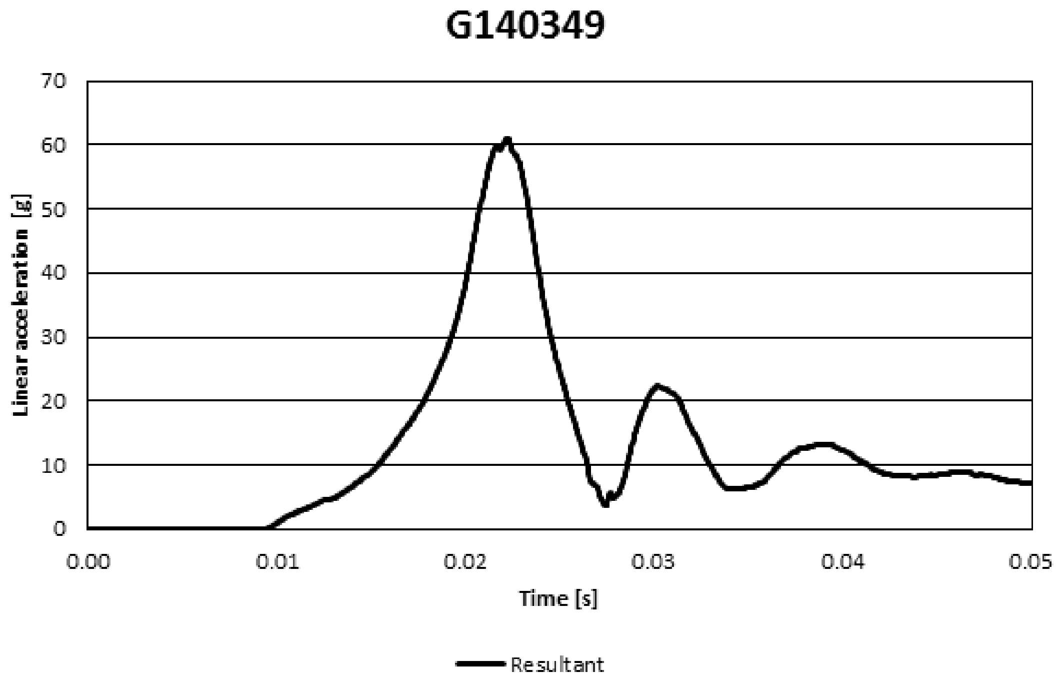


**Figure D5: Time history for resultant headform linear acceleration in a 8.34 m/s centre-front fist-glove impact with headguard.**

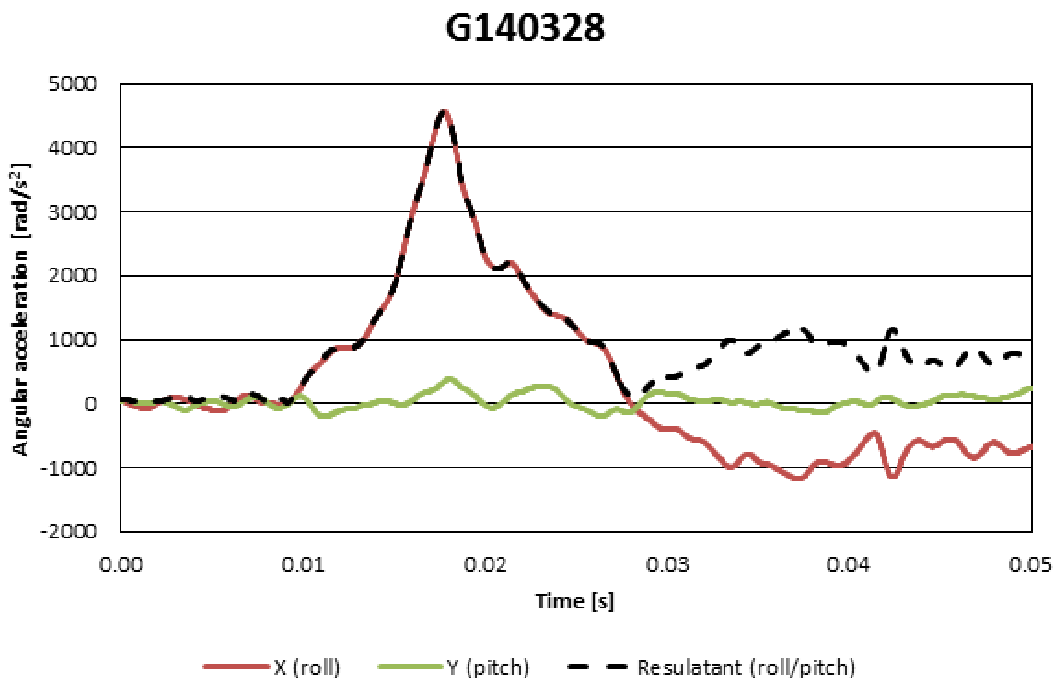


**Figure D6: Head angular acceleration time histories for an 8.34 m/s left lateral fist-glove impact with headguard. The data show that the head is rotated in lateral flexion to the right ($\alpha_x$ or roll). Changes in $\alpha_y$ (or pitch) relate to variation in the contact force vector, which pushes the head into either flexion or extension.**

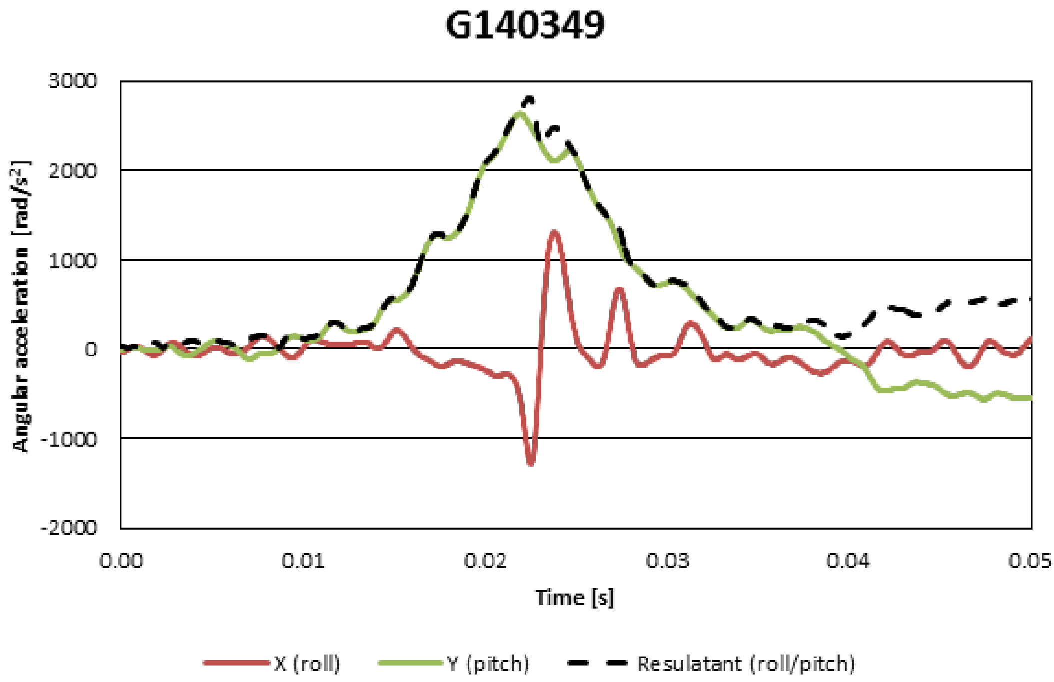


**Figure D7: The head angular acceleration time histories for an 8.43 m/s centre-front fist-glove impact with headguard are presented. The data show that the head is rotated rearward into extension ($\alpha_y$ or pitch). Changes in $\alpha_x$ (or roll) relate to variation in the contact force vector, which pushes the head into either left or right lateral flexion.**

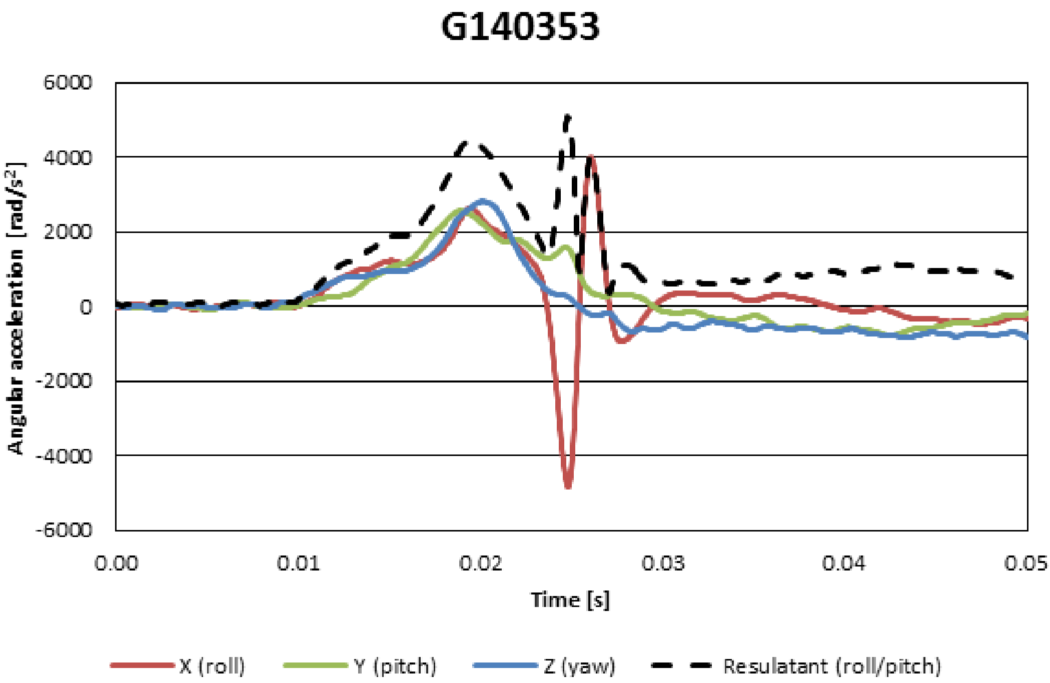


**Figure D8: The head angular acceleration time histories in an 8.34 m/s 45° forehead fist-glove impact with headguard are presented. The data show that the head is initially rotating rearward into extension ($\alpha_y$), into right lateral flexion ($\alpha_x$) and right axial rotation ($\alpha_z$). Changes in $\alpha_x$ relate to variation in the contact force vector, which pushes the head into either left or right lateral flexion.**

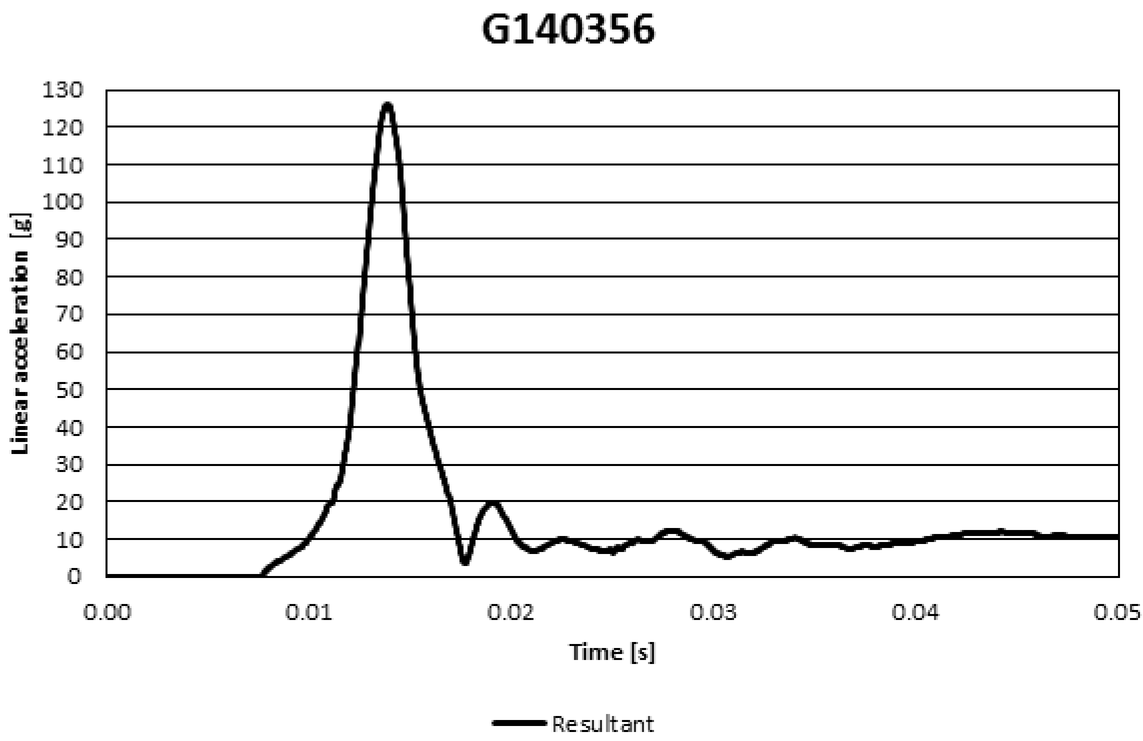


**Figure D9: The head resultant linear acceleration time history in an 8.34 m/s jaw fist-glove impact bare headform.**

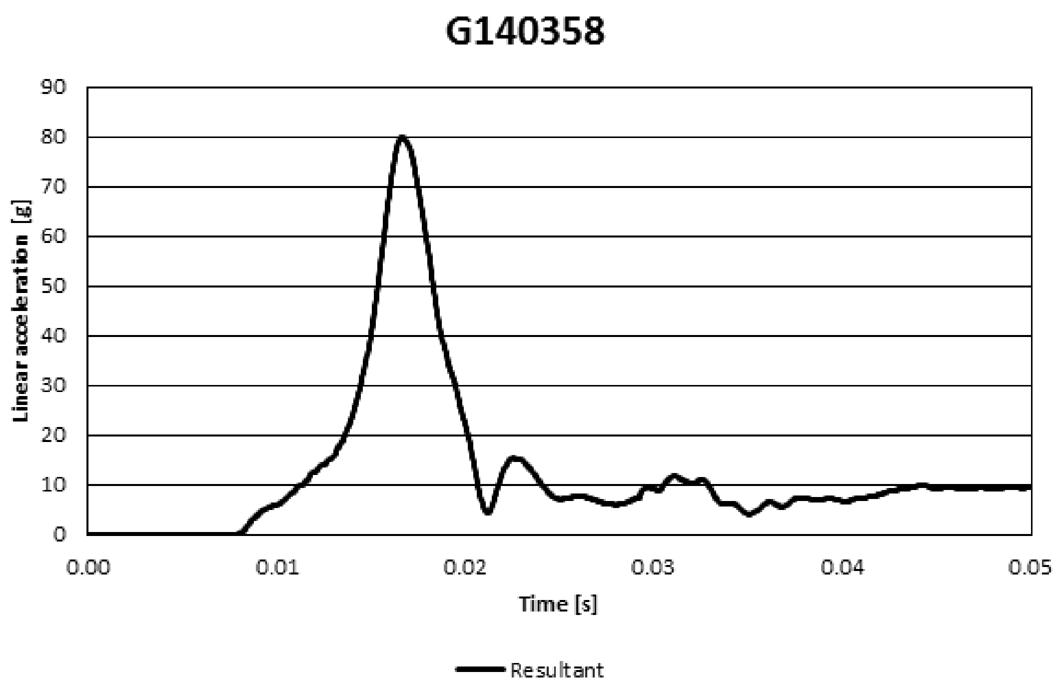


**Figure D10: The head resultant linear acceleration time history in an 8.34 m/s jaw fist-glove impact with headguard.**

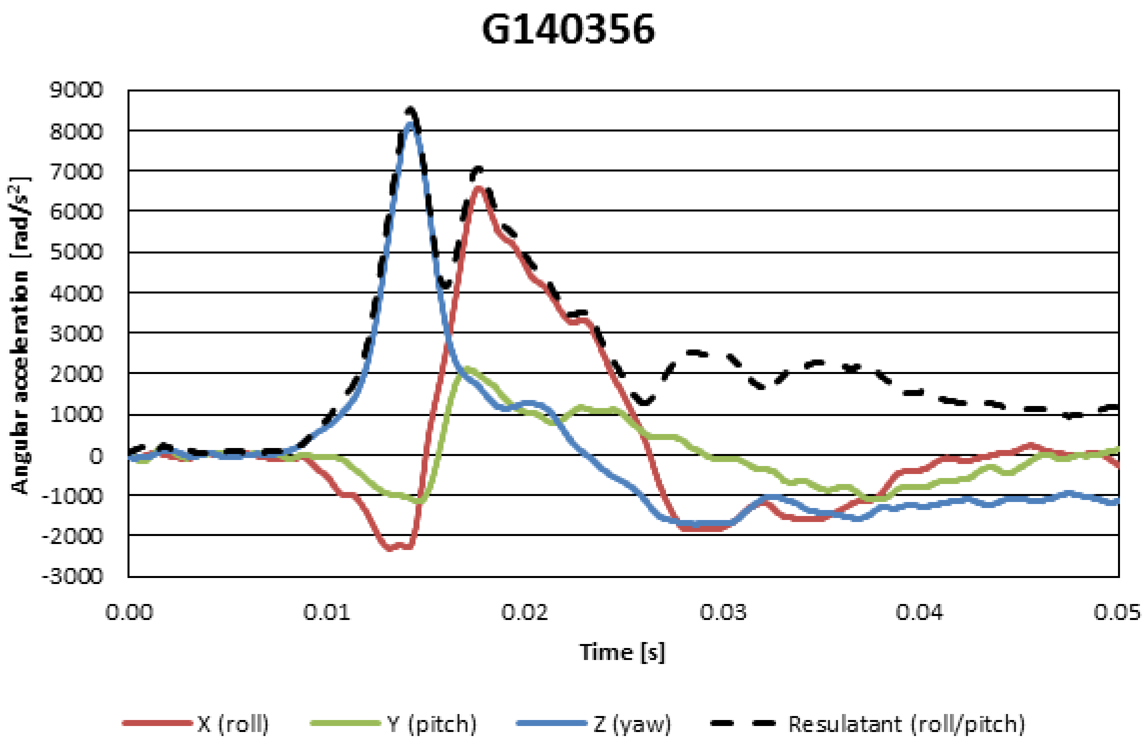


**Figure D11: The head angular acceleration time histories in an 8.34 m/s jaw fist-glove impact bare headform impact. The data show the complex angular acceleration with the dominance of right axial rotation ($\alpha_z$ or yaw).**

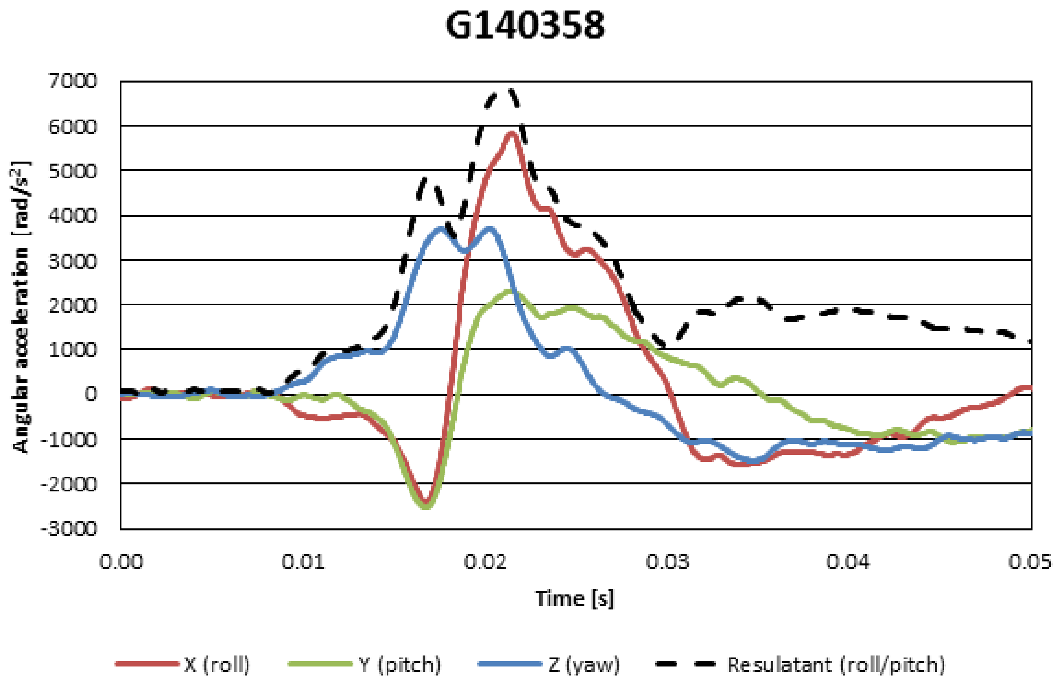


**Figure D12: The head angular acceleration time histories in an 8.34 m/s jaw fist-glove impact with headguard. The data show the complex angular acceleration with the reduced dominance of right axial rotation ($\alpha_z$ or yaw).**

**Table E3: Head impact responses for fist-glove impacts. Linear and angular head kinematic responses, measured and contact forces presented. Only one test was conducted per test condition.**

| | 4.99 m/s | | | |
|---|---|---|---|---|
| | Centre-front | | Left Lateral | |
| | Headguard Model | | Headguard Model | |
| | Top Ten | Bare | Top Ten | Bare |
| Peak $Ra_{Hd}$ (g) | 24 | 35 | 22 | 29 |
| HIC (15) | 15 | 27 | 15 | 22 |
| Peak $F_m$ (N) | 869 | 1477 | 856 | 1196 |
| Peak $F_c$ (N) | 930 | 1582 | 904 | 1288 |
| Peak $\omega_{Hdx}$ (rad/s) | -1 | -1.4 | 15.6 | 18.3 |
| Peak $\omega_{Hdy}$ (rad/s) | 18 | 20.2 | -3.4 | -3.8 |
| Peak $\alpha_{Hdx}$ (rad/s$^2$) | -275.3 | -392.8 | 1214.8 | 1750.1 |
| Peak $\alpha_{Hdy}$ (rad/s$^2$) | 1483.7 | 1693.8 | 330.3 | 417.3 |
| Peak $R\alpha_{Hdx,y}$ (rad/s$^2$) | 1485 | 1700 | 1217 | 1767 |
| Peak $R\alpha_{Hd}$ (rad/s$^2$) | 1491 | 1701 | 1488 | 1794 |

NB: ω is angular velocity and α angular acceleration. "R" is resultant.