Boxing headguard performance in punch machine tests.

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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 [kg]	n	Punch (hand)	Fist Speed [m/s]	Fist Force [N]	Fist Mass [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).

References

Atha, J., M. R. Yeadon, et al. (1985). "The Damaging Punch." British Journal of Sports Medicine 291(6511): 1756-1757.

Whiting, W. C., R. J. Gregor, et al. (1988). "Kinematic Analysis of Human Upper Extremity Movements in Boxing." American Journal of Sports Medicine 16(2): 130-136.

Smith, M. S., R. J. Dyson, et al. (2000). "Development of a Boxing Dynamometer and Its Punch Force Discrimination Efficacy." Journal of Sports Sciences 18(6): 445-450.

Viano, D. C., I. R. Casson, et al. (2005). "Concussion in Professional Football: Part 10 - Comparison with Boxing Head Impacts." Neurosurgery 57(6): 1154-1172.

Walilko, T. J., D. C. Viano, et al. (2005). "Biomechanics of the Head for Olympic Boxer Punches to the Face." British Journal of Sports Medicine 39(10): 710-719.

Smith, M. S. (2006). "Physiological Profile of Senior and Junior England International Amateur Boxers." Journal of Sports Science and Medicine 5(CSSI): 74-89.

Piorkowski, B. A., A. Lees, et al. (2011). "Single Maximal versus Combination Punch Kinematics." Sports Biomechanics 10(1): 1-11.

Fife, G. P., D. O'Sullivan, et al. (2013). "Biomechanics of Head Injury in Olympic Taekwondo and Boxing." Biology of Sport 30(4): 263-268.

Nakano, G., Y. Iino, et al. (2014). "Transfer of Momentum from Different Arm Segments to a Light Movable Target During a Straight Punch Thrown by Expert Boxers." Journal of Sports Sciences 32(6): 517-523.

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

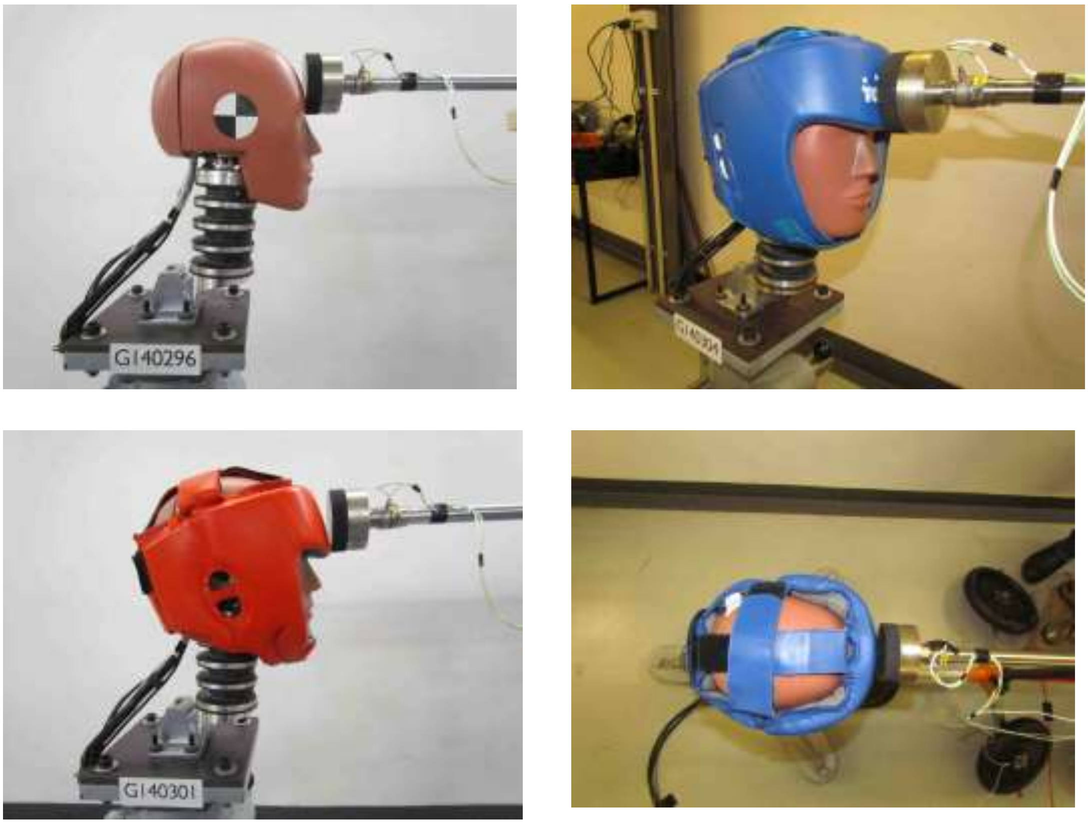

Figure C1: Centre-front forehead impacts with disc-pad interface. There is some parallax error in the photographs that suggests that the impactor was not aligned horizontally. The impactor was aligned horizontally in all tests.

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

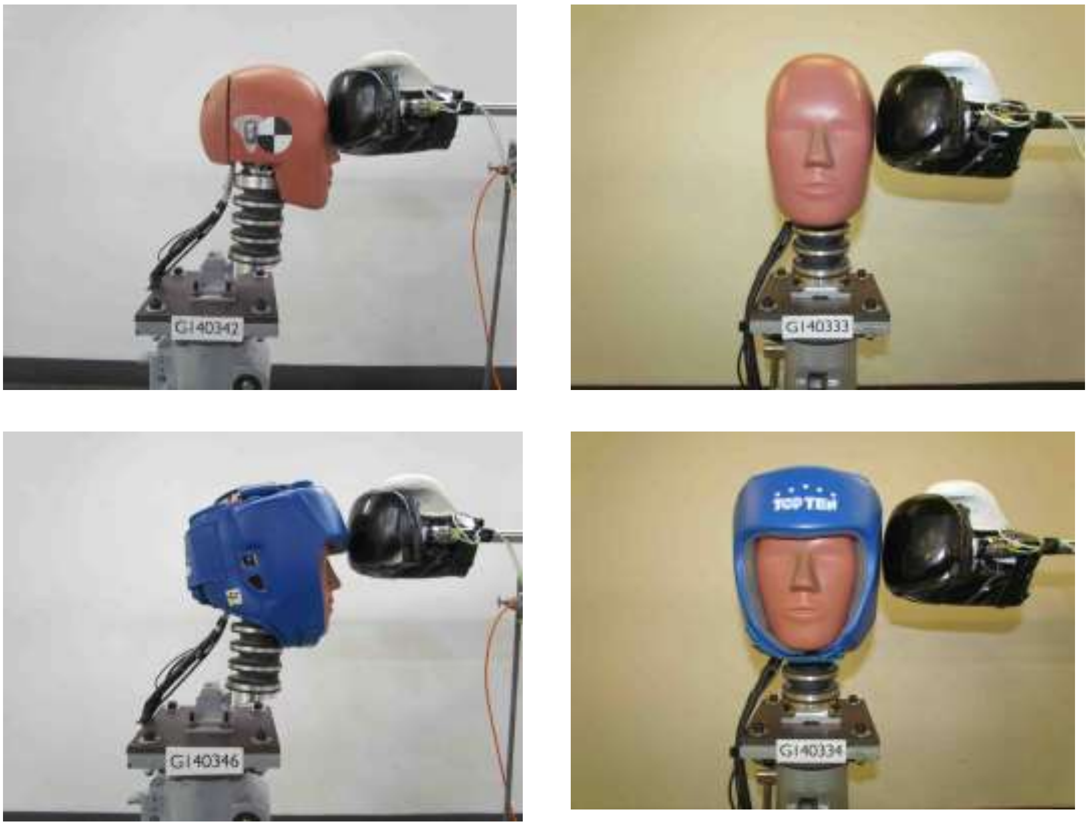

Figure C3: Centre-front forehead and lateral impacts with glove-fist interface.

Figure C4: 45°forehead impacts.

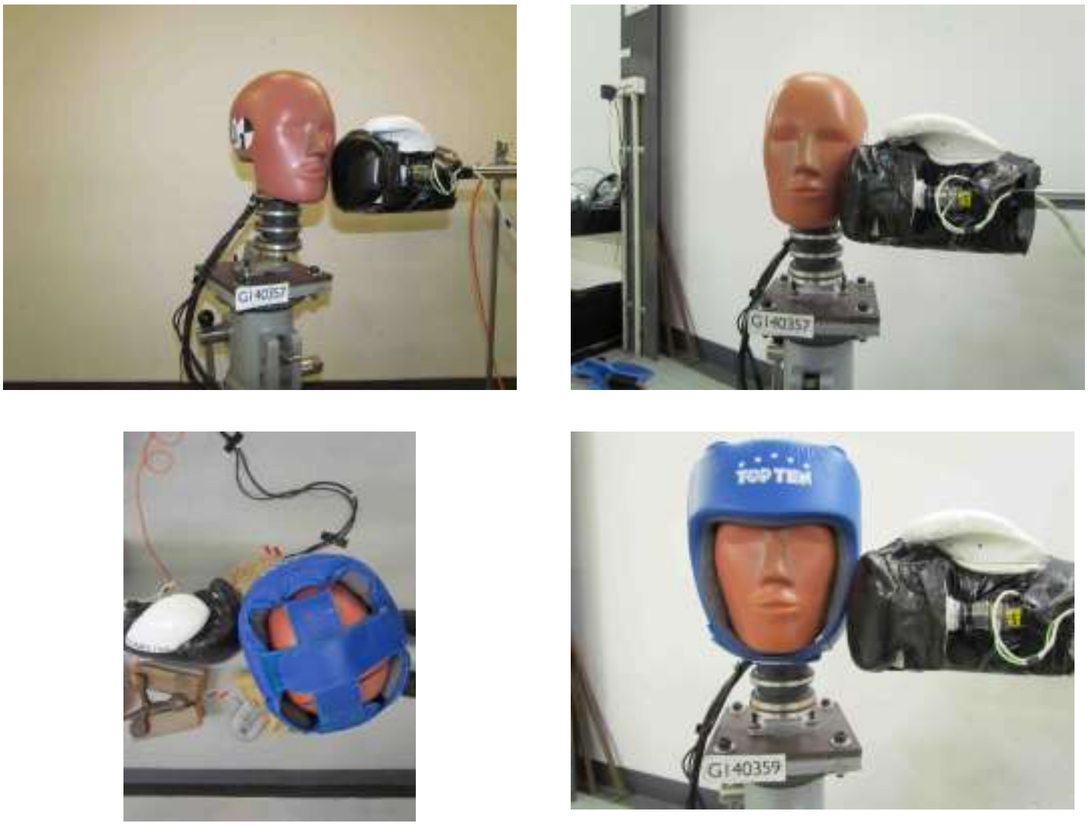

Figure C5: 60°jaw impacts. The impact axis was aligned to be 60° from the mid-saggital plane measured in the horizontal plane.

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 ω_{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 ω_{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 α_{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 α_{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 α_{Hdx} for centre-front impacts is not relevant, as is Peak α_{Hdy} for left lateral impacts. These components are considered in Peak $R\alpha_{Hdx,y}$

Appendix D: Selection of head responses from punch tests

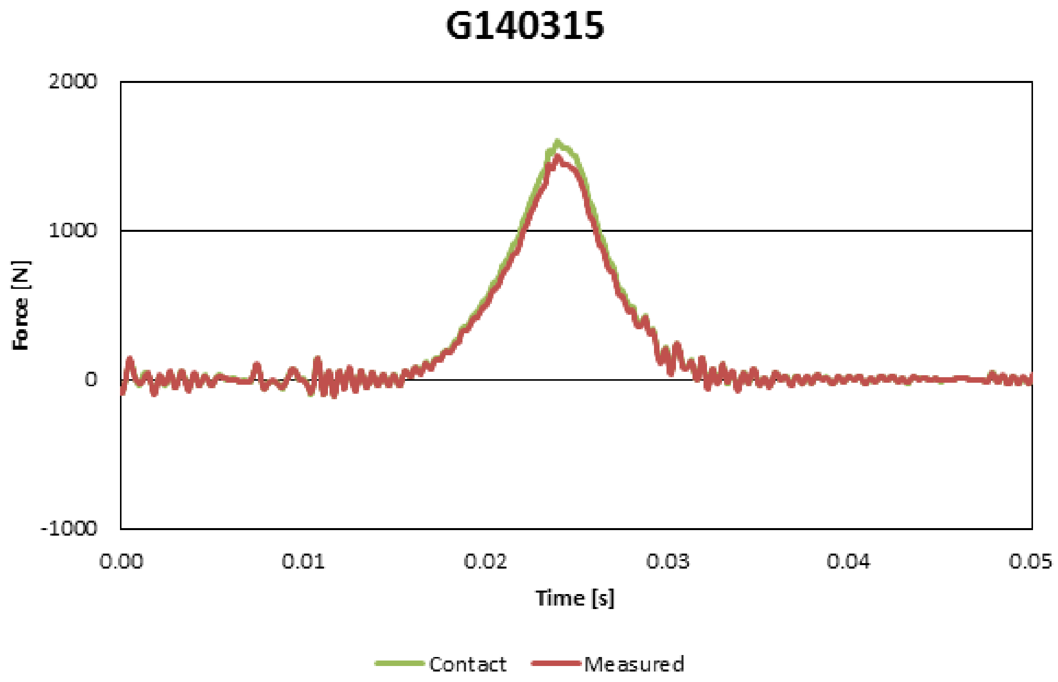

Figure D1: Time histories for contact and measured forces in a 4.11 m/s left lateral disc-pad impact with headguard.

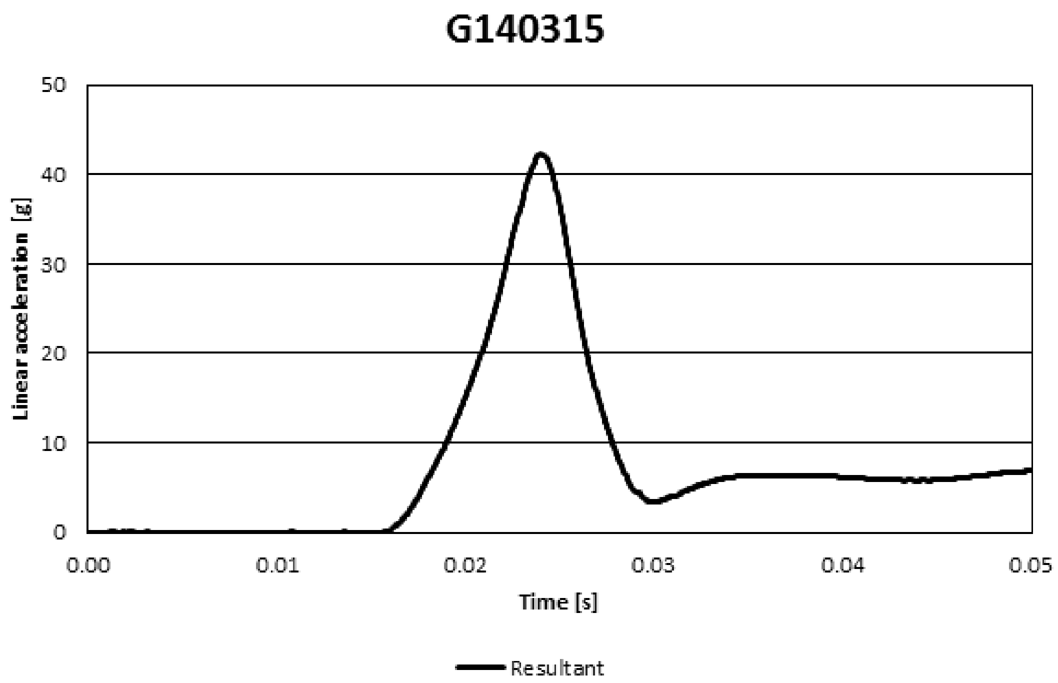

Figure D2: Time history for resultant headform linear acceleration in a 4.11 m/s left lateral disc-pad impact with headguard.

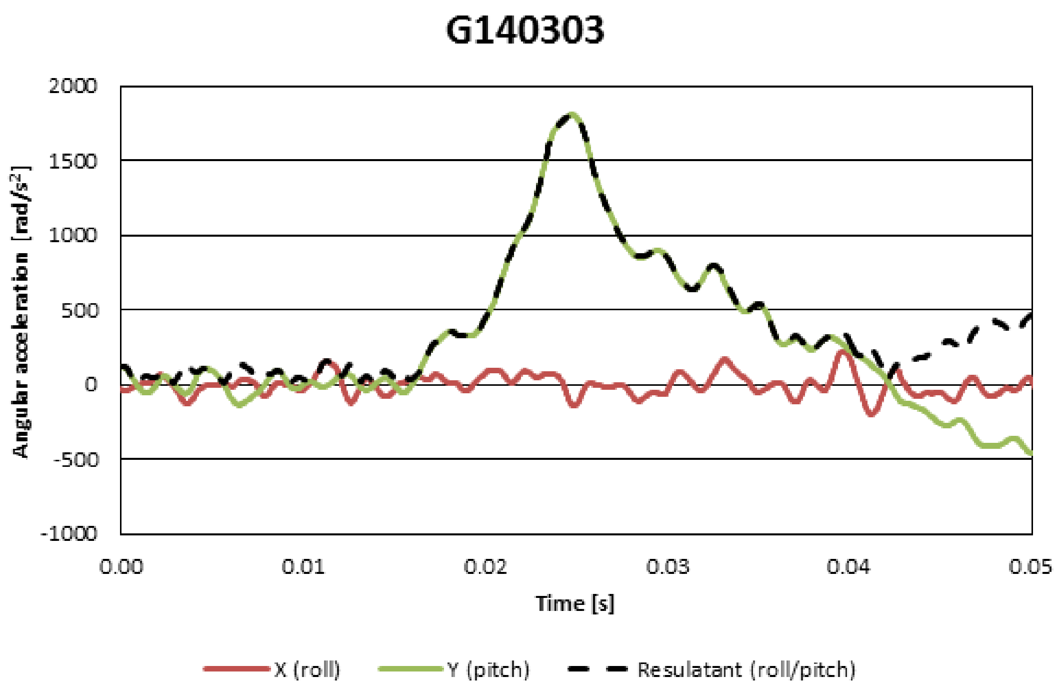

Figure D3: The head angular acceleration time histories for a 4.11 m/s centre-front disc-pad impact with headguard are presented. The data show that the head is rotated rearward into extension (α_y or pitch). Changes in α_x (or roll) relate to variation in the contact force vector, which pushes the head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

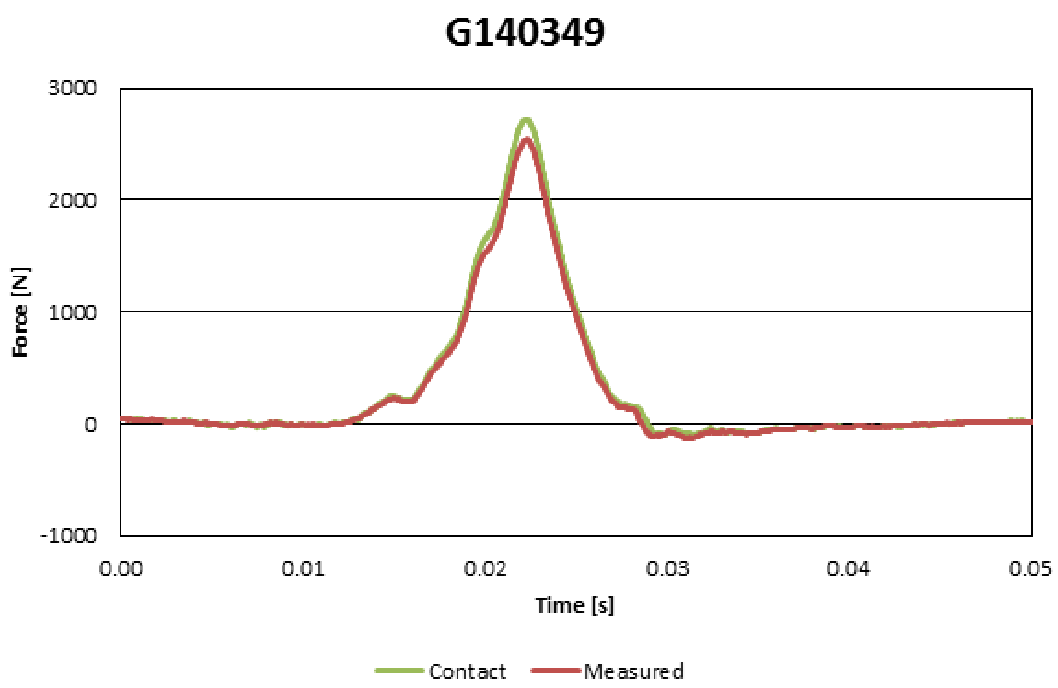

Figure D4: Time histories for contact and measured forces in a 8.34 m/s centre-front fist-glove impact with headguard.

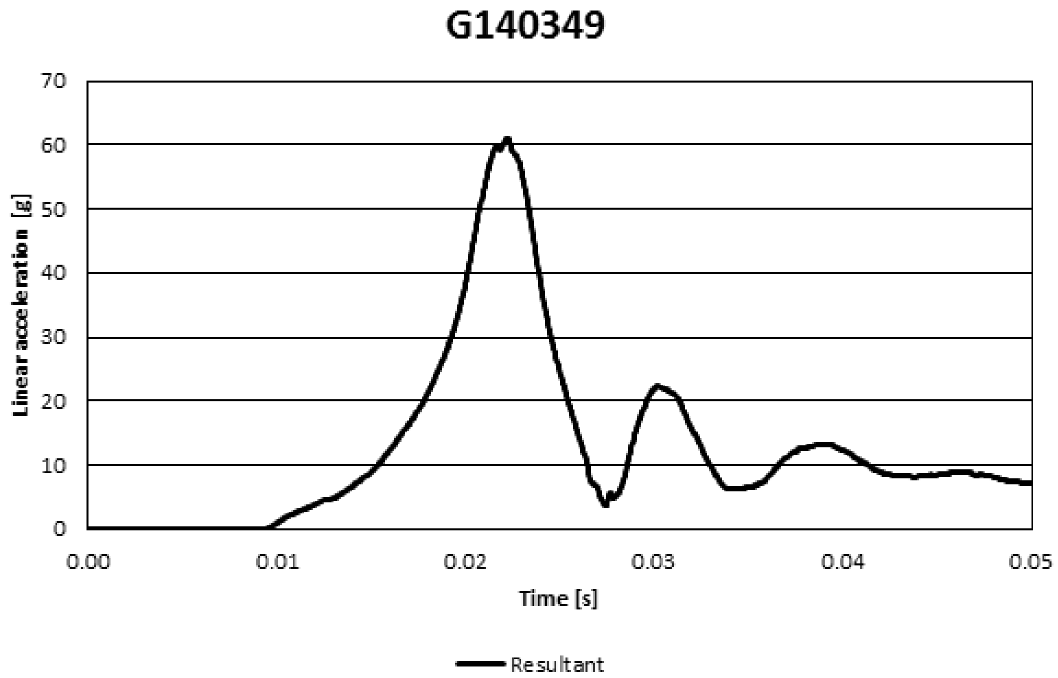

Figure D5: Time history for resultant headform linear acceleration in a 8.34 m/s centre-front fist-glove impact with headguard.

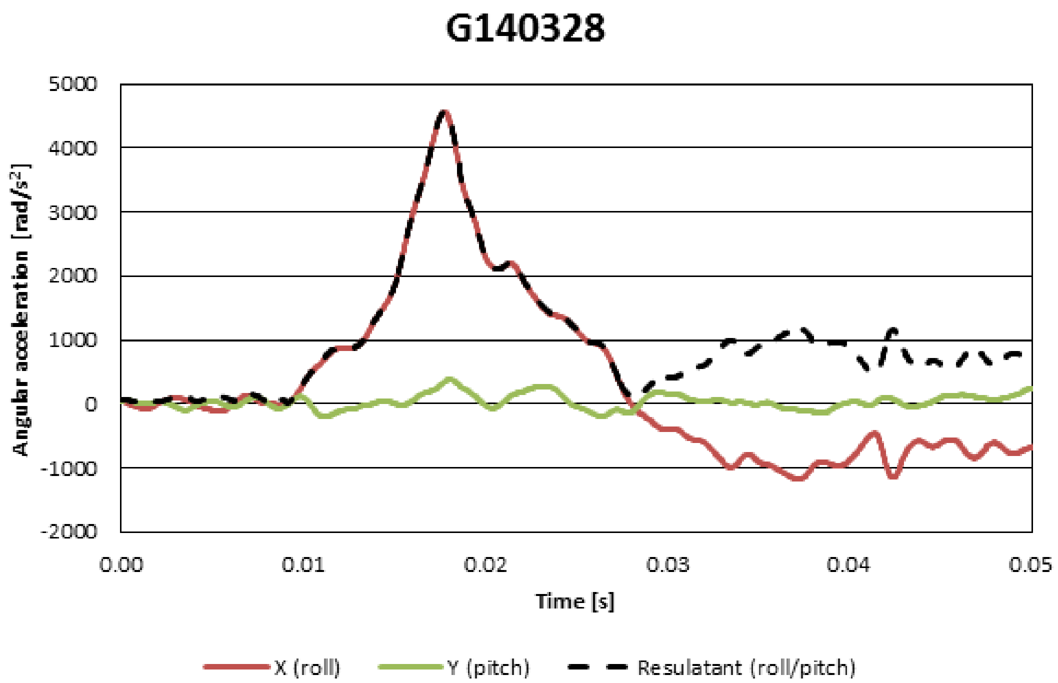

Figure D6: Head angular acceleration time histories for an 8.34 m/s left lateral fist-glove impact with headguard. The data show that the head is rotated in lateral flexion to the right (α_x or roll). Changes in α_y (or pitch) relate to variation in the contact force vector, which pushes the head into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

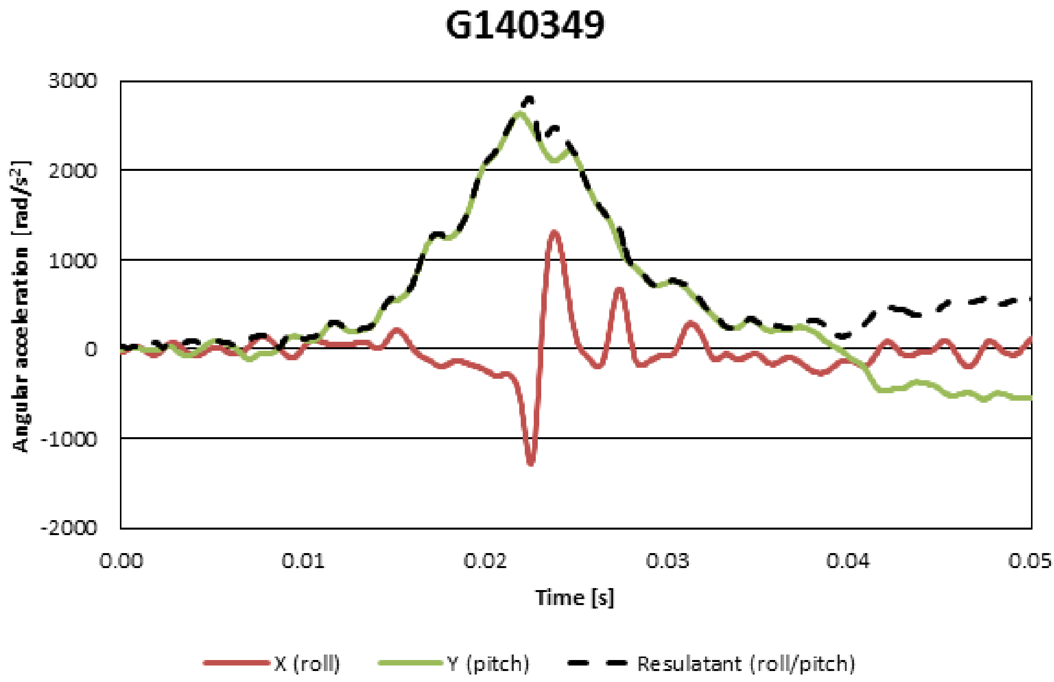

Figure D7: The head angular acceleration time histories for an 8.43 m/s centre-front fist-glove impact with headguard are presented. The data show that the head is rotated rearward into extension (α_y or pitch). Changes in α_x (or roll) relate to variation in the contact force vector, which pushes the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

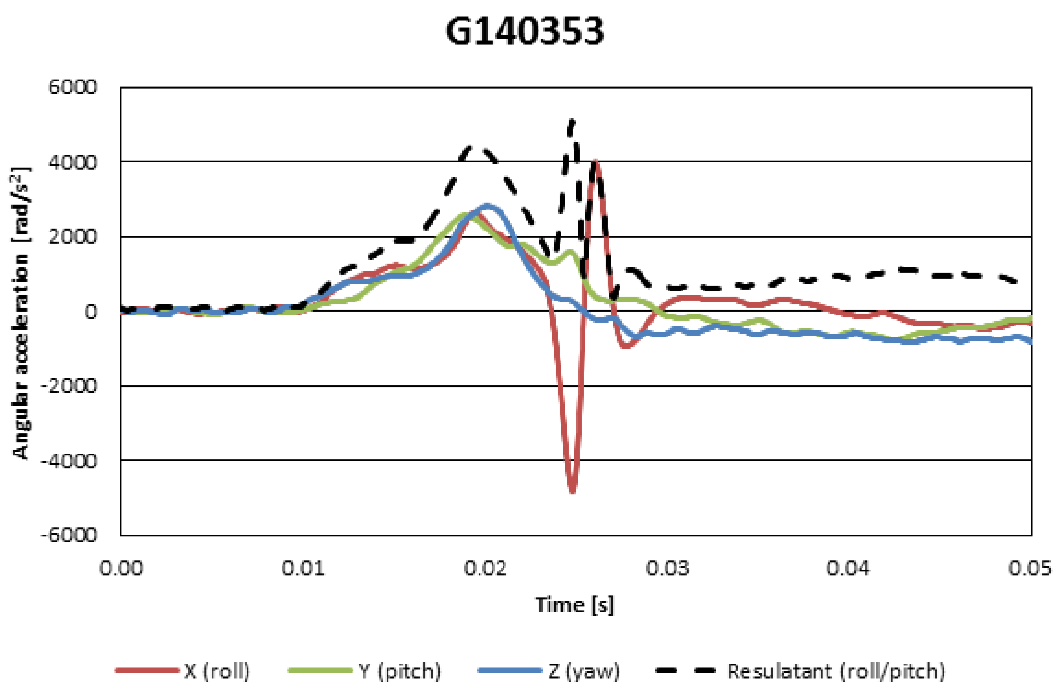

Figure D8: The head angular acceleration time histories in an 8.34 m/s 45° forehead fist-glove impact with headguard are presented. The data show that the head is initially rotating rearward into extension (α_y), into right lateral flexion (α_x) and right axial rotation (α_z). Changes in α_x relate to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

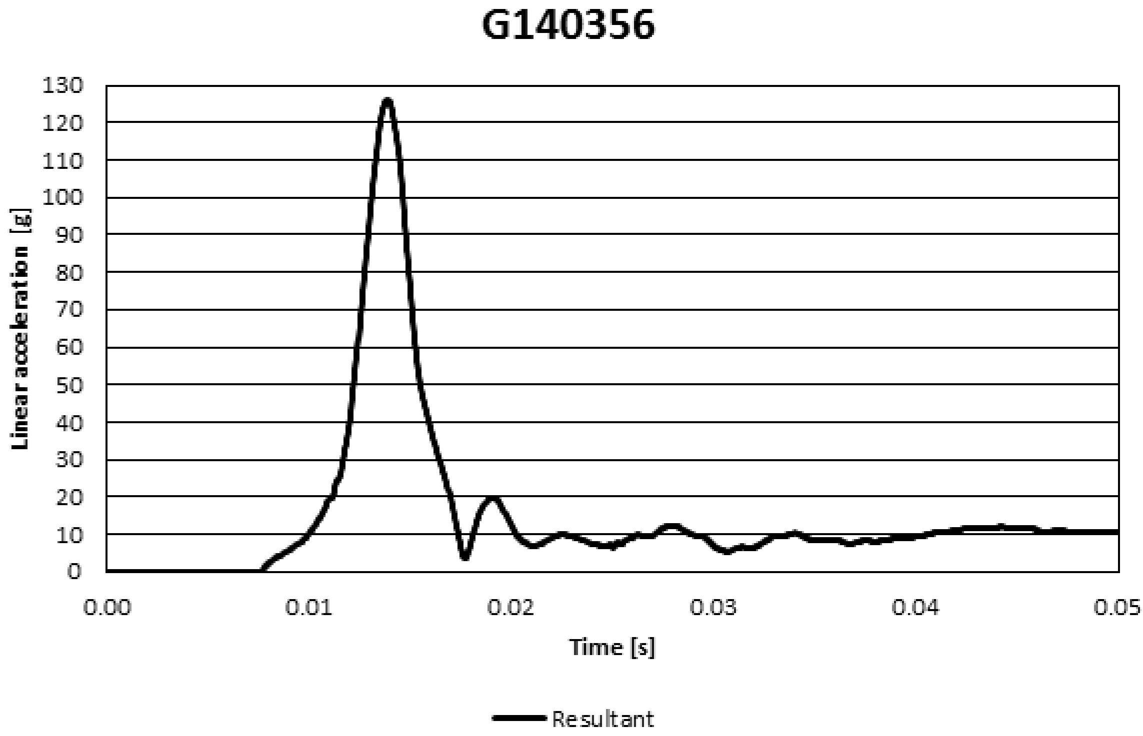

Figure D9: The head resultant linear acceleration time history in an 8.34 m/s jaw fist-glove impact bare headform.

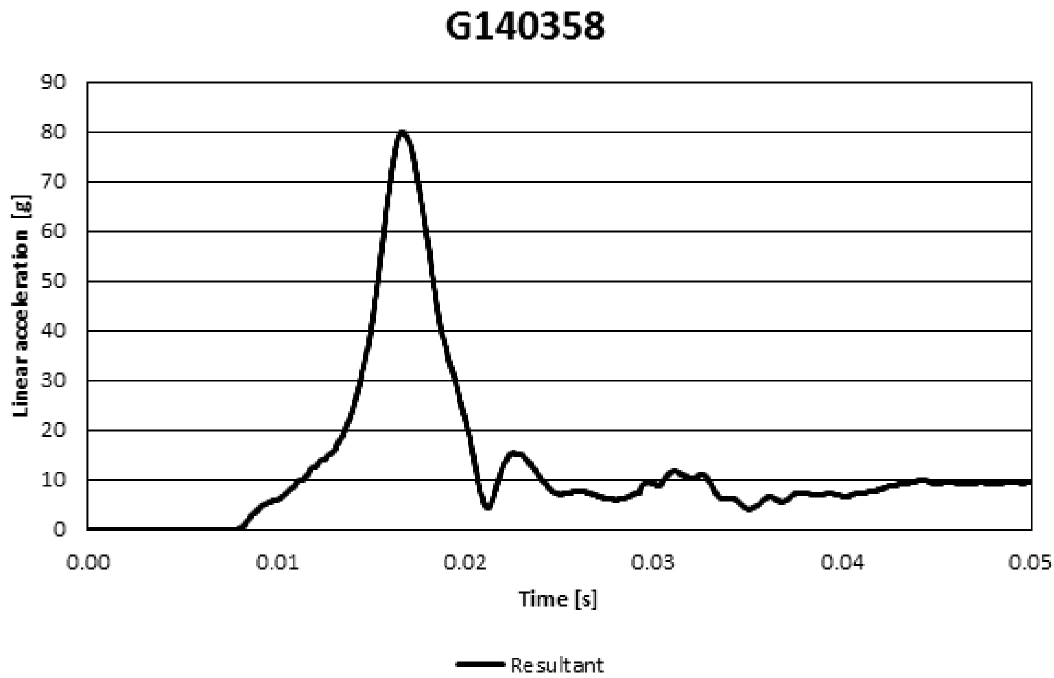

Figure D10: The head resultant linear acceleration time history in an 8.34 m/s jaw fist-glove impact with headguard.

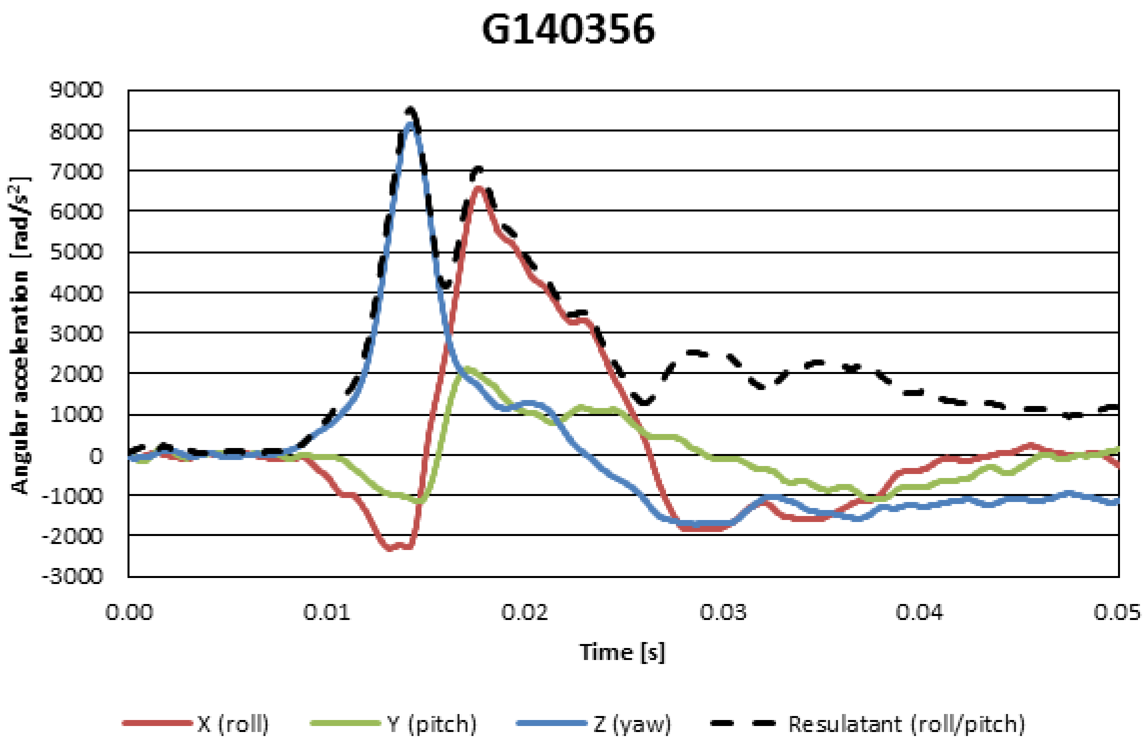

Figure D11: The head angular acceleration time histories in an 8.34 m/s jaw fist-glove impact bare headform impact. The data show the complex angular acceleration with the dominance of right axial rotation (α_z or yaw).

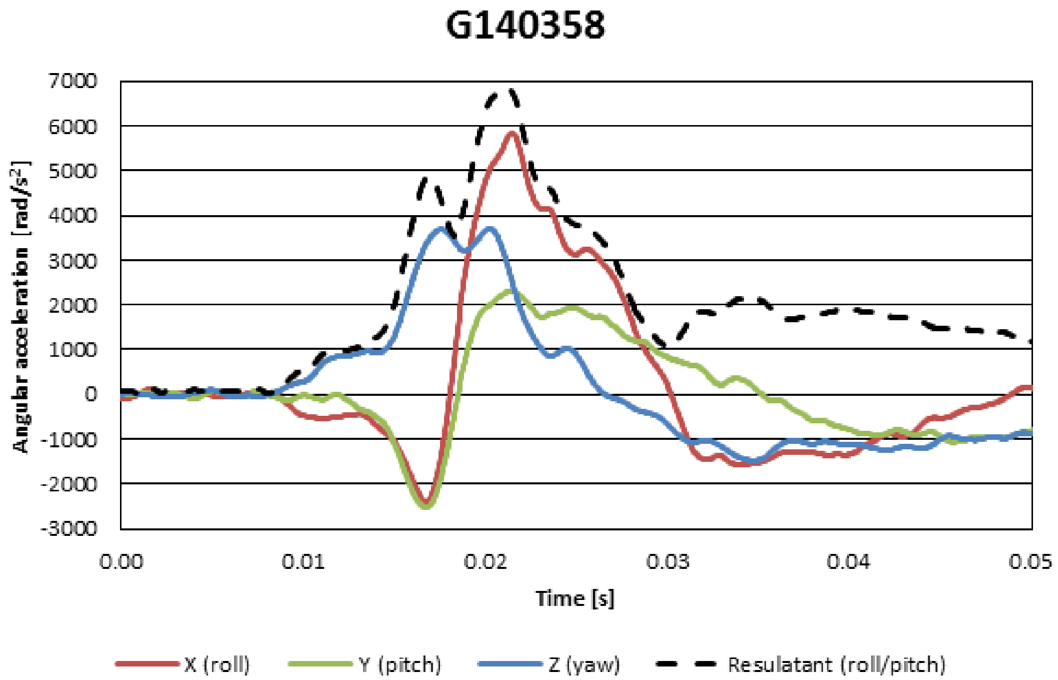

Figure D12: The head angular acceleration time histories in an 8.34 m/s jaw fist-glove impact with headguard. The data show the complex angular acceleration with the reduced dominance of right axial rotation (α_z or yaw).

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 ω_{Hdx} (rad/s)	-1	-1.4	15.6	18.3
Peak ω_{Hdy} (rad/s)	18	20.2	-3.4	-3.8
Peak α_{Hdx} (rad/s^2)	-275.3	-392.8	1214.8	1750.1
Peak α_{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.