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Investigation of Rotational Head Accelerations in Bicycle Helmet Testing

Prepared for: Protective Headgear Manufacturers Association

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PREFACE

This report describes the test method and results of bicycle helmet impact testing that was conducted to investigate rotational head accelerations. This report constitutes the final deliverable for this project.

Any opinions expressed in this report are those of Biokinetics and Associates Ltd., and do not necessarily reflect those of the Protective Headgear Manufacturers Association.

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1. *INTRODUCTION*

Diffuse axonal injury (DAI) is a generic term for a brain injury type that ranges from mild concussion (without loss of consciousness) to severe concussion, coma and even death. Of all the physical measures of brain response to impact, DAI is thought to correlate most strongly to shear strain of brain tissue. This shear is caused when the skull is accelerated faster than the encased brain tissue in a rotational fashion. In the case of an impact that is directed through the centre of gravity of the head, the skull will accelerate as a whole, without rotation. Brain tissue will be pressed into the skull near the impact site, and pulled from the skull on the opposite side. Alternatively, the skull may be impacted off-centre, causing it to twist and generate rotational acceleration. In this scenario, the brain tissue inside the skull is strained as the brain is aggressively pulled around to catch up with the skull. Both mechanisms are believed to contribute to DAI, however, it is believed that rotational acceleration correlates more strongly.

So far, the helmet impact conditions that affect rotational head accelerations are not well understood. Some impact circumstances, or equivalent laboratory test conditions, might have a more significant effect on resulting rotational accelerations than others. The aim of this current study is to investigate the effects of a selected set of test parameters on the magnitudes and relative proportions of linear and rotational head accelerations, measured in a laboratory environment. It is not the intention of this study to investigate effects that helmet design may play in resulting linear or angular accelerations.

2. *TEST EQUIPMENT AND SET-UP*

2.1 HEADFORM

A Hybrid III crash test dummy head was used for this testing, which represents the head size of a 50th percentile adult male. It was modified by the addition of head skin extensions, which were designed for motorcycle crash testing with helmet usage, to allow for a better fit of the chin straps. The Hybrid III head is normally instrumented with a tri-axial linear accelerometer cluster mounted inside the skull at the centre of gravity. However, this particular head was extensively modified to allow the installation of nine accelerometers in a 3-2-2-2 configuration.

This configuration refers to three accelerometers at the centre of gravity, and three pairs of accelerometers mounted at the inner surface of the skull along the X, Y and Z axes. (Note that convention is the X-axis pointing forwards from the centre of gravity, the Y-axis pointing towards the left ear, and the Z-axis pointing upwards.) The idea is to measure acceleration in each direction at three positions: the centre of gravity and two other locations outboard of the centre of gravity. In this fashion, if the outboard accelerometers measure different acceleration than that at the centre of gravity, then the headform must be accelerating in rotation. By knowing the precise distance between these accelerometers, it is possible to relate these independent linear accelerometer measurements to rotational acceleration. While it might suffice to measure this outboard acceleration at only one outboard location, it has been found beneficial to have a redundant extra measurement for reliability.

2.2 DROP TEST APPARATUS

The Hybrid III headform was suspended from a sliding carrier by a hook at the base of the skull, such that the crown of the head was always pointing down. This hook could be swivelled such that the head could be oriented facing any direction horizontally. This carrier was guided by the two wires of a typical twin-wire impact test rig. The impact anvil was an inclined platform of typical roadway asphalt, mounted in a steel frame which allowed adjustment of the platform angle.

When the headform contacted the inclined asphalt surface, it was caused to rotate in the direction of the slope. This caused the hook to disengage with the carrier, allowing the headform to move freely under the influence of the impact. The carrier was arrested immediately after this disengagement by rubber stops that were clamped to the guide wires. A schematic of the test set-up is depicted in Figure 2-1.

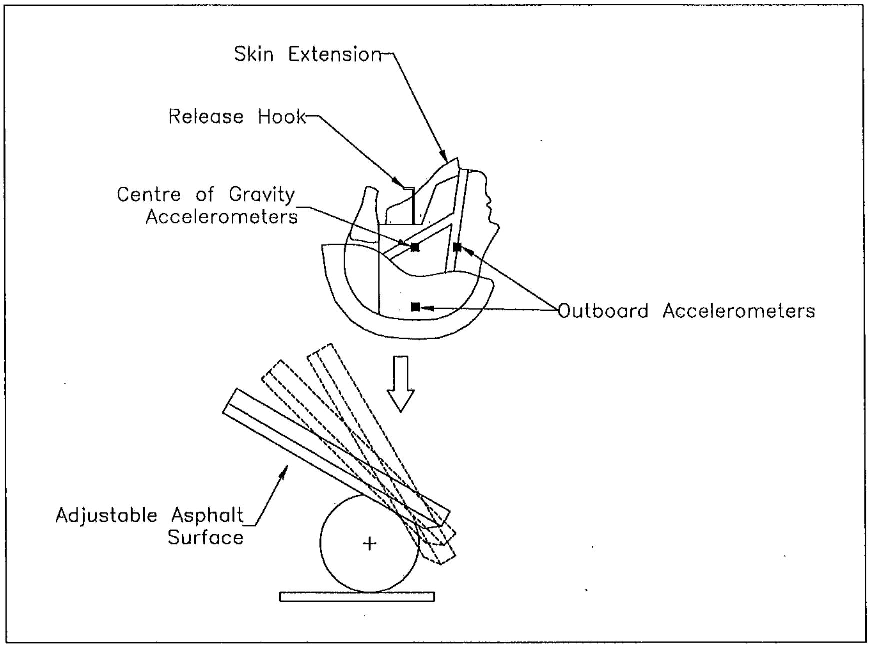

Figure 2-1 : Impact Test Configuration

2.3 Accelerometers and Signal Conditioning

The accelerometers were Endevco® model 7264A-2000 piezo-resistive devices. Signal conditioning and excitation voltage was supplied by three Endevco® model 136 tri-input rack-mounted amplifiers. These units were capable of 1000 Hz low pass filtering to SAE J211 specifications, but filtering was not conducted for two reasons.

First, the filter modules were not phaseless filters. This means that the signal is shifted slightly in time due to filtering. For linear headform acceleration measurements, this is not a problem, since all time histories at a particular point will still be in phase. However, when subtracting accelerations between the centre of gravity and outboard positions, there was concern that phase-shifts might distort the resulting rotational acceleration measurements. Secondly, since Hybrid III headform is damped by a rubber skin, as well as a helmet, it was not considered that filtering was absolutely necessary. This notion was supported by the raw signal traces, which did not show excessive noise. So, for these reasons, filtering was not used in this test programme.

2.4 DATA COLLECTION, PROCESSING AND PRESENTATION

Data collection was accomplished by two parallel National Instruments® model AT-MIO-16L-9 data acquisition boards, mounted in a PC. Data was collected at 10 kHz for 70 ms.

The data collection, storage and processing was managed by customized Labview® software that was created by Biokinetics. The computer algorithms that processed the nine-accelerometer data were based on FORTRAN sub-routines written by the National Highway Traffic Safety Administration (NHTSA) for automotive crash testing with the Hybrid III dummy.

The Biokinetics-Labview software was configured for this study to provide linear X, Y, Z and resultant acceleration plots, as well as rotational X, Y, Z and resultant rotational acceleration plots, for each impact test. This data is provided in Appendix A.

It should be noted that the graphing scale is adjusted for each plot to fit the peak acceleration level. For cases of low accelerations, the signal may appear to be noisy, when in fact this is simply due to the resolution of the minimum digital step. This is set for all testing by the maximum expected acceleration level of the test programme.

3. TEST METHOD

3.1 TEST PARAMETERS

The test parameters of this study included the following:

- Drop height: 3 ft, 4.5 ft, 6 ft
- Impact site: front, rear, left, right
- Anvil angle: 30°, 45°, 60° (from horizontal)
- Chin strap: loose, tight

These combined for a total of 72 impact tests. Each helmet was impacted four times at the sites indicated. A new helmet was used for each other condition, such that no helmet was hit twice at the same site.

3.2 HELMET MODEL

The helmet used throughout this testing was the Bell Sports Inc. "Lynx" model, size small/medium, which provided a good fit with the Hybrid III headform. These helmets were all adjusted with the retention straps the same length to fit the Hybrid III headform identically. All comfort pads inside the helmet were identical for each test sample.

All helmets were supplied by Bell Sports Inc.

3.3 CONDITIONING

All helmets were tested at ambient laboratory conditions.

3.4 TEST PROTOCOL

Each test sample was installed on the Hybrid III head using a template jig that establishes the helmet positioning index. This jig is contoured to match the forehead and nose profile, and was designed for positioning motorcycle helmets in motorcycle crash testing[1].

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[1] Draft Standard for Motorcycles - Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices Fitted to Motor Cycles. Part 6: Full Scale Impact Test Procedures. ISO/DIS 13232-6. Drawing No. 029-2-084.

For "tight" chinstrap configurations, the chinstrap was fastened snugly such that there was no slack. For "loose" configurations, a 5/8 inch diameter rod was inserted under the chin and the chinstrap fastened tightly. Then the rod was removed.

The anvil was set to the desired angle, measured from the horizontal, and the helmeted headform was raised to the desired drop height and oriented to impact the correct location. Note that for all impacts, the crown of the headform was oriented downwards. This was in effort to represent the direction of a glancing blow that a rider might experience should he tumble onto an asphalt surface while riding. The drop height was measured from the point of contact of the helmet with the asphalt.

The carrier assembly was released, the headform unhooked from the carrier upon impact, and the headform was free to tumble unconstrained. A net was installed across the front of the apparatus to prevent the headform from tumbling too far. It was important that the accelerometer cables not be stressed in any way due to the headform rolling too far.

4. TEST RESULTS

Seventy-two tests were conducted to complete the test matrix described in Section 3.1. A summary table of each test configuration, peak linear acceleration and peak resultant acceleration is shown in Figure 4-1. The peak linear and rotational acceleration data traces are shown in Appendix A.

Note that rotational acceleration is given in units of rad/s/s (or rad/s^2), where one radian is equivalent to 57.3 degrees. This is the standard engineering format for rotational acceleration.

Test No.	Anvil Angle	Impact Site	Chinstrap	Drop Height (ft)	Peak Lin Res (G)	Peak Rot Res (rad/s^2)
1	30	front	tight	3	91	3563
2	30	rear	tight	3	85	5308
3	30	left	tight	3	72	7196
4	30	right	tight	3	74	4535
5	30	front	tight	4.5	109	4325
6	30	rear	tight	4.5	117	7555
7	30	left	tight	4.5	102	6321
8	30	right	tight	4.5	137	5543
9	30	front	tight	6	128	6042
10	30	rear	tight	6	138	9063
11	30	left	tight	6	122	7850
12	30	right	tight	6	134	6397
13	30	front	loose	3	99	3767
14	30	rear	loose	3	97	6650
15	30	left	loose	3	83	4369
16	30	right	loose	3	80	4281
17	30	front	loose	4.5	111	4038
18	30	rear	loose	4.5	116	7290
19	30	left	loose	4.5	107	6375
20	30	right	loose	4.5	113	6476
21	30	front	loose	6	141	5128
22	30	rear	loose	6	132	8765
23	30	left	loose	6	118	7026
24	30	right	loose	6	136	7080
25	45	front	tight	3	69	4509
26	45	rear	tight	3	61	5394
27	45	left	tight	3	64	2406
28	45	right	tight	3	76	5091
29	45	front	tight	4.5	84	5349
30	45	rear	tight	4.5	84	6891
31	45	left	tight	4.5	90	3926
32	45	right	tight	4.5	91	3574
33	45	front	tight	6	87	4349
34	45	rear	tight	6	95	8080
35	45	left	tight	6	91	4754
36	45	right	tight	6	112	4397
37	45	front	loose	3	74	3627
38	45	rear	loose	3	58	5232
39	45	left	loose	3	60	2320
40	45	right	loose	3	59	2514
41	45	front	loose	4.5	76	4362
42	45	rear	loose	4.5	77	6885
43	45	left	loose	4.5	79	5911
44	45	right	loose	4.5	82	3221
45	45	front	loose	6	95	6006
46	45	rear	loose	6	90	7035
47	45	left	loose	6	105	4687
48	45	right	loose	6	107	4339
49	60	front	tight	3	38	2351
50	60	rear	tight	3	56	5348
51	60	left	tight	3	46	5346
52	60	right	tight	3	37	2033
53	60	front	tight	4.5	56	4013
54	60	rear	tight	4.5	64	5967
55	60	left	tight	4.5	42	2923
56	60	right	tight	4.5	58	4830
57	60	front	tight	6	48	2422
58	60	rear	tight	6	81	9186
59	60	left	tight	6	39	3277
60	60	right	tight	6	35	2950
61	60	front	loose	3	41	3242
62	60	rear	loose	3	45	4646
63	60	left	loose	3	33	3202
64	60	right	loose	3	47	4312
65	60	front	loose	4.5	61	4605
66	60	rear	loose	4.5	26	3442
67	60	left	loose	4.5	35	1899
68	60	right	loose	4.5	67	3953
69	60	front	loose	6	15	921
70	60	rear	loose	6	78	7895
71	60	left	loose	6	62	3867
72	60	right	loose	6	53	2219

Figure 4-1: Test Results Summary

Graphical presentation of the results for the 30 degree, 45 degree and 60 degree anvils are shown in Figure 4-2, Figure 4-3 and Figure 4-4, respectively.

30 degree Anvil

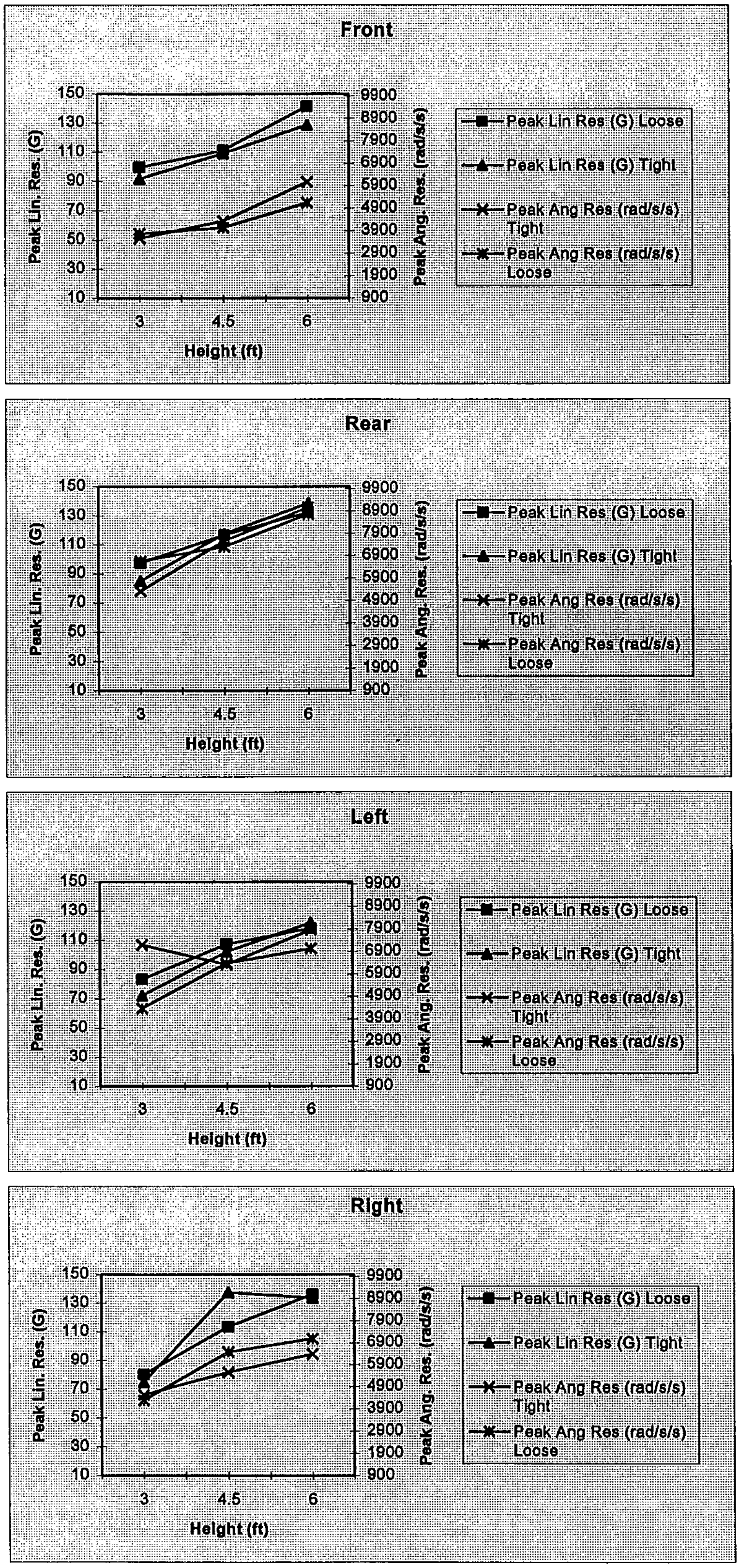

Figure 4-2: Summary of 30 degree anvil results.

45 degree Anvil

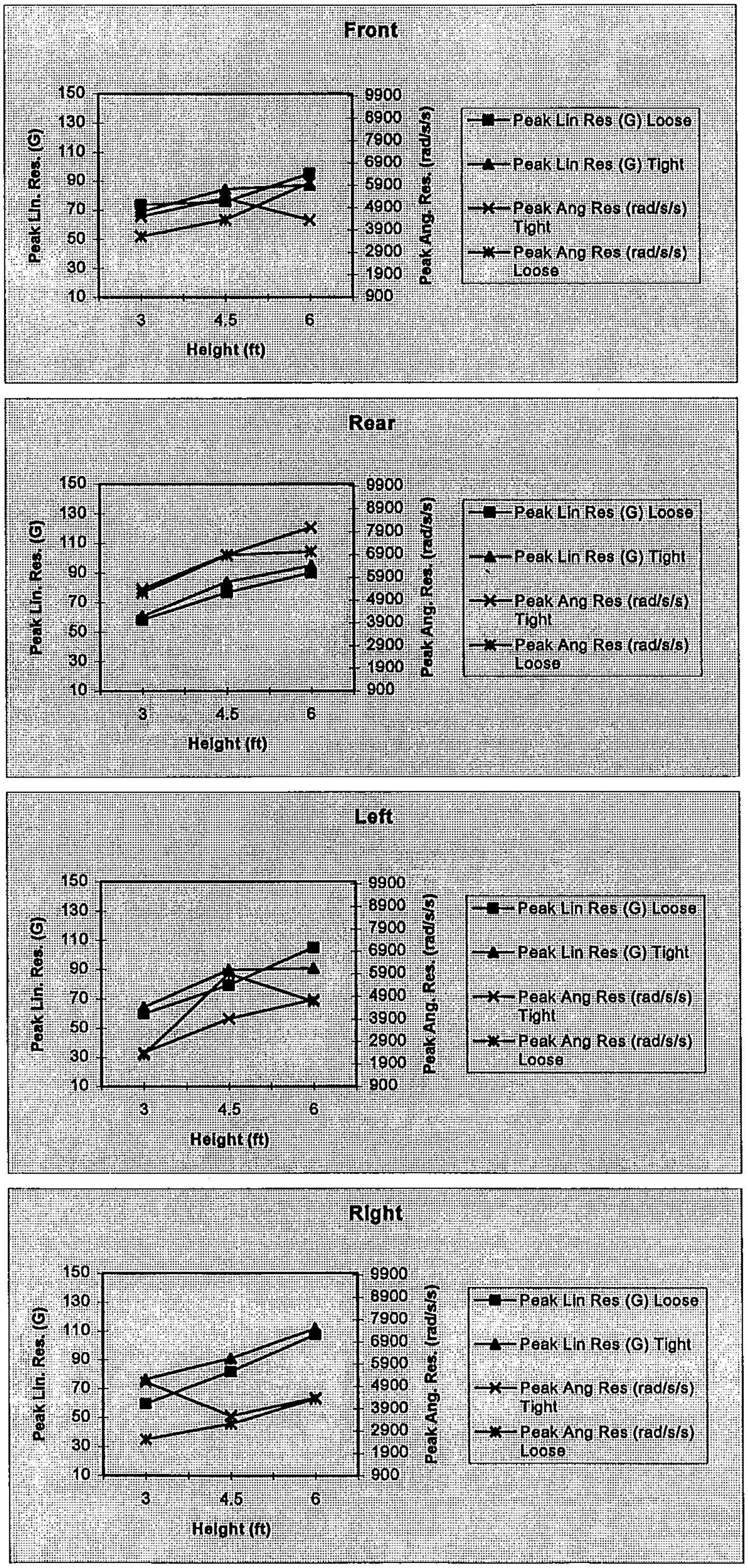

Figure 4-3: Summary of 45 degree anvil results.

60 degree Anvil

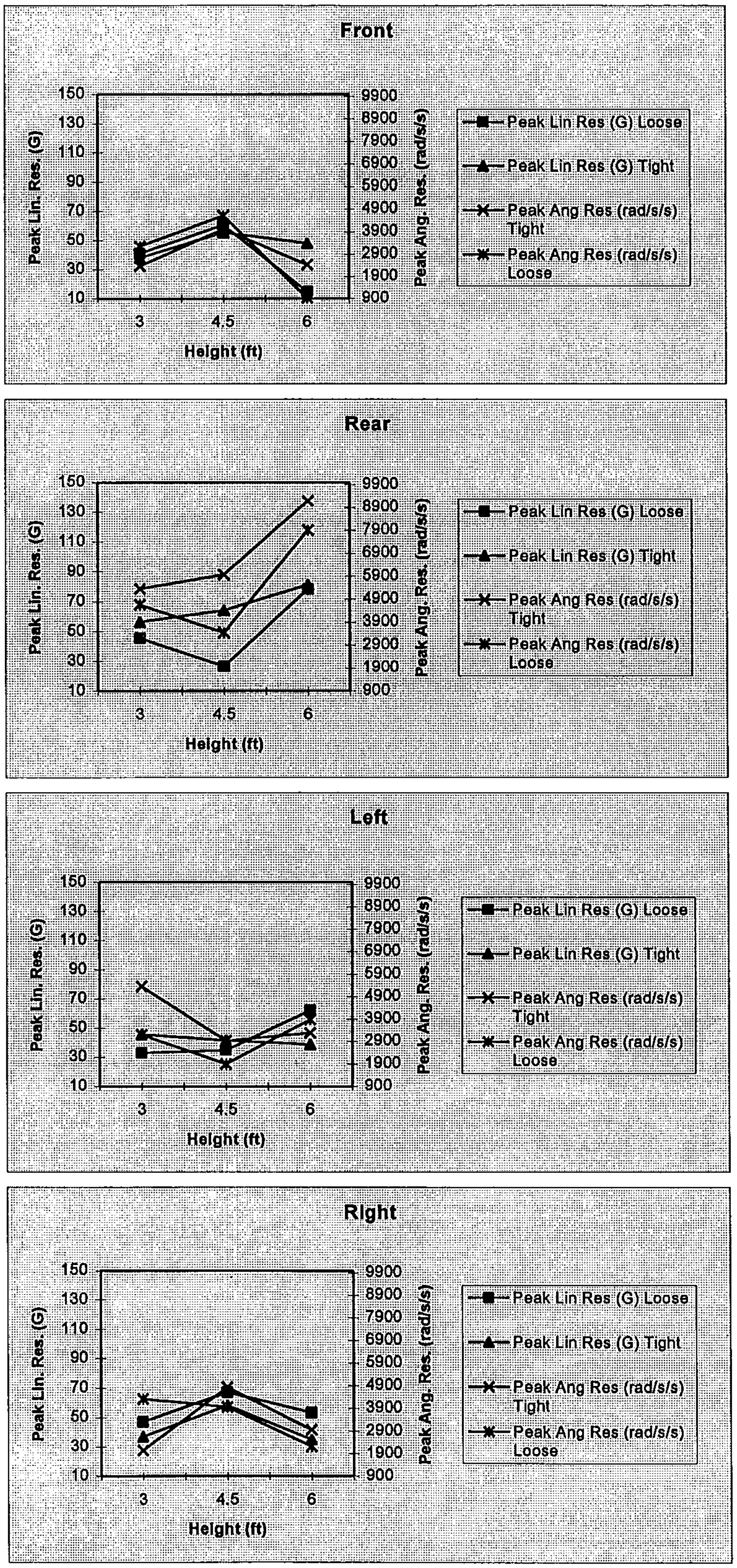

Figure 4-4: Summary of 60 degree anvil results.

5.1 LOOSE VS. TIGHT

The parameter of chinstrap tightness was included to investigate the effect that coupling of the helmet to the headform might have in the inducement of rotational head accelerations. Figure 5-1 through Figure 5-4 below illustrate the effects that chinstrap tightness had on the resulting peak linear and rotational accelerations. The diagonal line in each of these figures represents where the loose and tight conditions display the exact same acceleration levels.

These figures shall also be useful in investigating the relationships between other parameters in following topics.

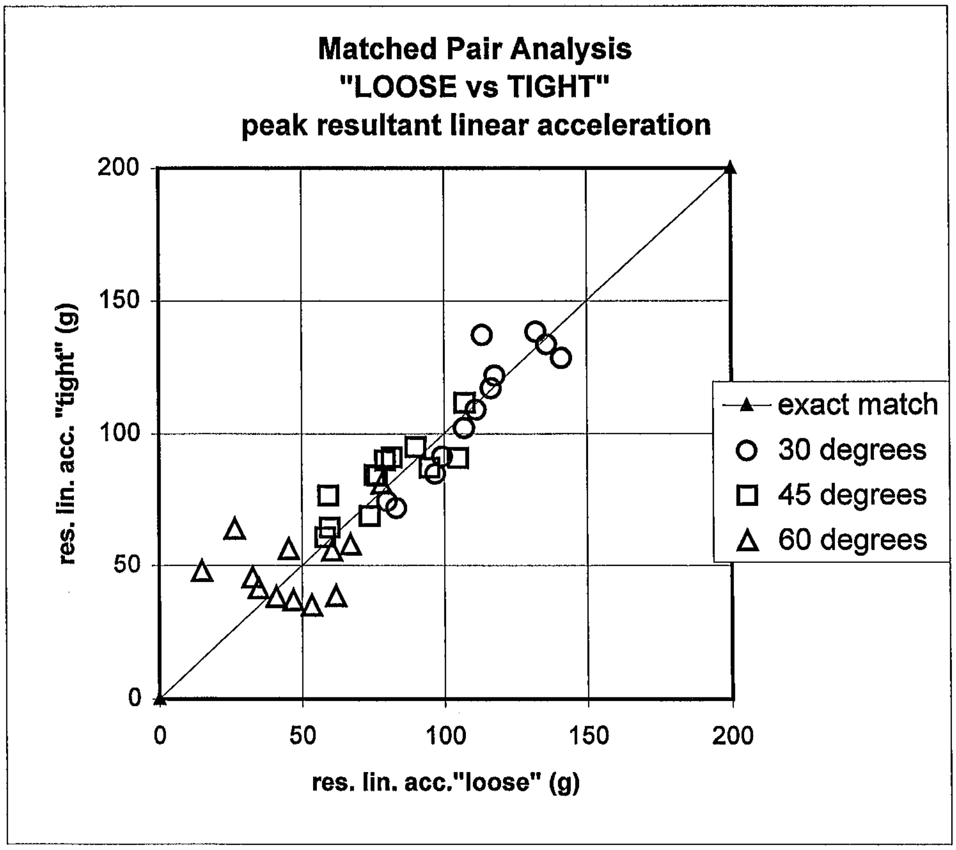

Figure 5-1: Loose vs. tight, linear acceleration, isolating anvil angle.

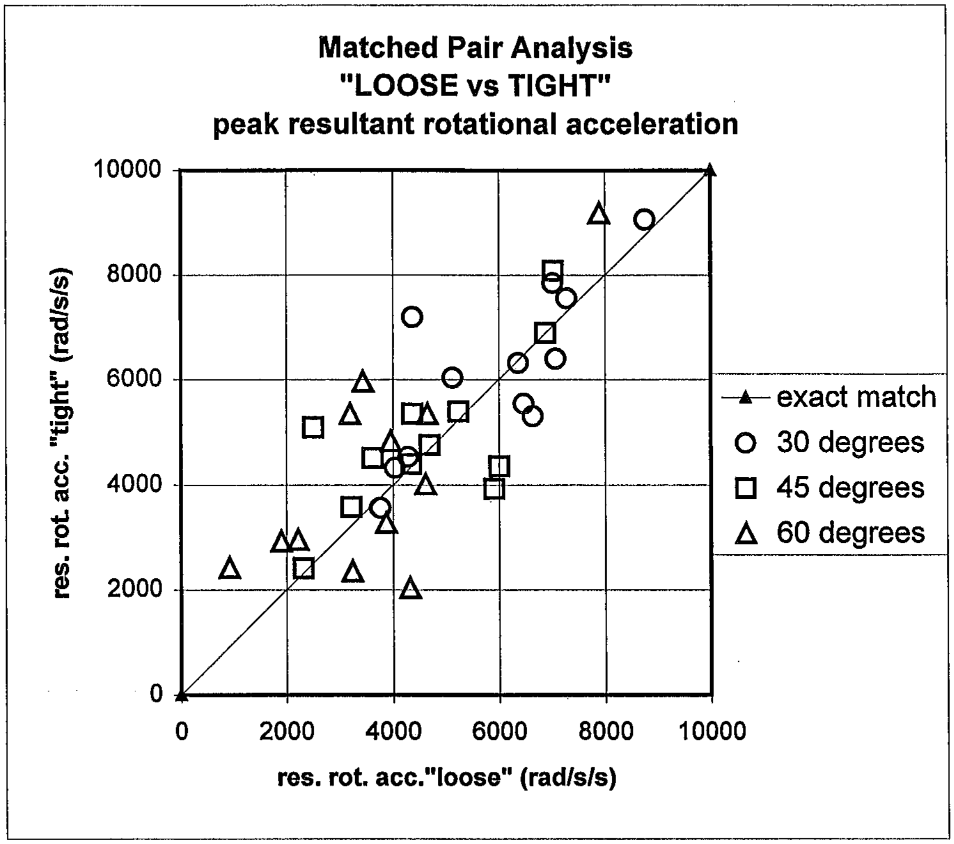

Figure 5-2: Loose vs. tight, rotational acceleration, isolating anvil angle.

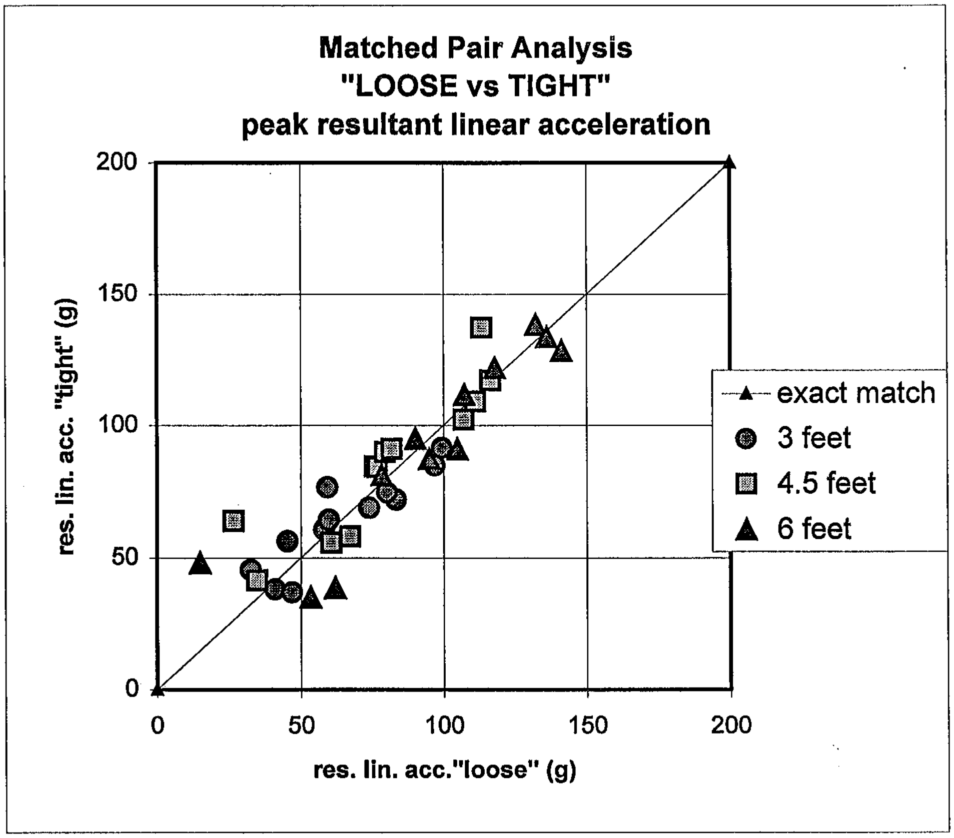

Figure 5-3: Loose vs. tight, linear acceleration, isolating drop height.

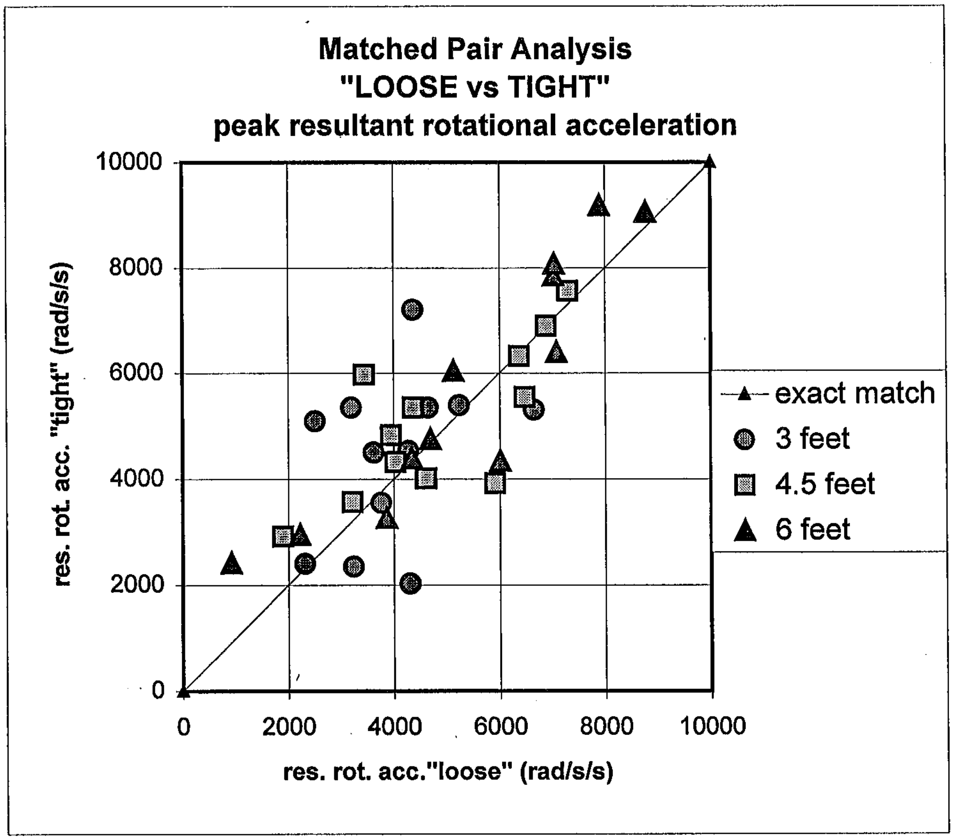

Figure 5-4: Loose vs. tight, rotational acceleration, isolating drop height.

Referencing Figure 5-1 and Figure 5-3, which compare linear accelerations, it is apparent that the tight and loose conditions result in mostly the same peak-G levels.

Referencing Figure 5-2 and Figure 5-4, which compare rotational accelerations, there is far less correlation between the loose and tight conditions. There is, nevertheless, as much scatter above the "exact match" line, where the tight condition experiences higher rotational accelerations, as there is below this line, where loose condition experiences higher rotational accelerations.

Based on these observations, we conclude that in the current tests, the effect of chinstrap tightness has no dominant effect on the headform acceleration responses.

5.2 Anvil Angle

With regard to linear acceleration, Figure 5-1 illustrates that the shallower the angle, the higher the acceleration. This is not surprising, since the helmet tends to glance off the steeper angles, transmitting less shock to the headform.

With regard to rotational accelerations, Figure 5-2 tends to demonstrate that shallower angles result in higher rotational accelerations as well, although this tendency is less pronounced. Presumably, this occurs for similar reasons as the linear accelerations, where there is more sliding action along the anvil at steeper angles, rather than grabbing.

The fact that there are anvil angle trends visible in these charts that combine several test parameters, it would indicate that the anvil angle has a dominant effect on peak acceleration levels.

5.3 Drop Height

Figure 4-2, 4-3 and 4-4 show the general trend for increasing drop heights to produce increasing levels of linear and rotational acceleration for individual tests. However, there are some interesting exceptions to this trend, especially in Figure 4-4 where the front and side locations show a sharp drop in peak accelerations at increased drop heights. In these cases, the higher speed, coupled with the steeper angle, caused the helmet to slide across the anvil, rather than interact with it.

However, when all configurations are combined, shown in Figure 5-3 and Figure 5-4, drop height does not appear to dominate the overall peak acceleration levels.

5.4 Impact Location

In the current test series, especially impact to the rear results in high rotational accelerations. The impacts to the rear of the helmet at 6 feet resulted in rotational accelerations ranging from about 7000 to about 9200 rad/s^2, irrespective of the anvil angle. Even tests conducted at 4.5 feet at the rear of the helmet resulted in peak rotational accelerations ranging from about 6900 to 7600 rad/s^2. The only other tests showing similar levels of peak rotational acceleration are the tests on the left and right at 30 degrees at 6 feet, giving peak rotational accelerations in the range from about 6400 to 7800 rad/s^2. This supports current belief that the rotational acceleration response in helmet testing is very sensitive to the combination of anvil shape and orientation, helmet shape and headform orientation.

5.5 Linear vs. Rotational Acceleration

There has often been discussion within the helmet community regarding the relationship between linear and rotational head accelerations. Figure 5-1 shows the relationship between peak linear and peak rotational accelerations for all the impacts conducted in this current study.

Additionally, a linear regression line has been fitted through the data, indicating an R^2 value of only 0.4209 (where an ideal set of data that fall on a line would have an R^2 = 1.0000). This shows that for this current study, there is poor correlation between linear and rotational acceleration.

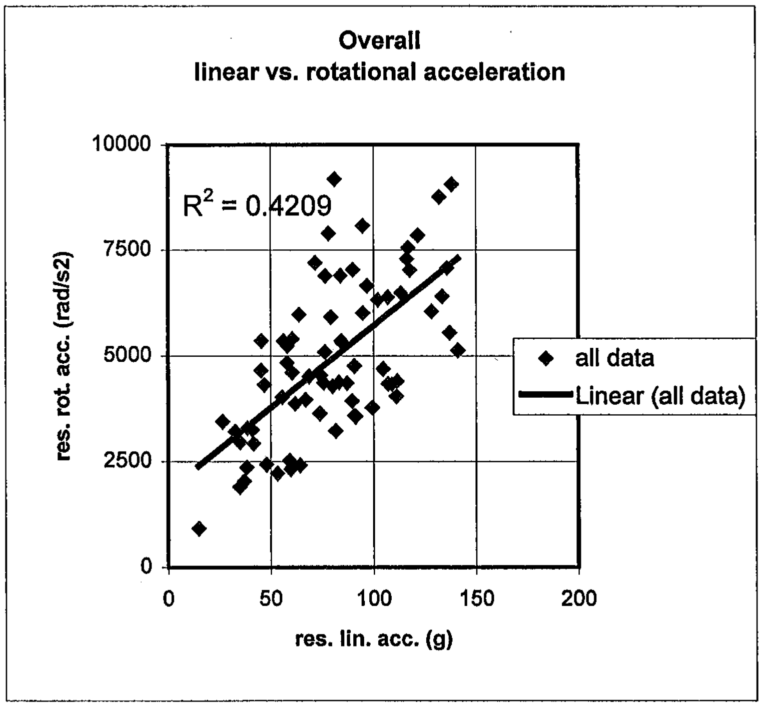

Figure 5-1: Linear vs. rotational acceleration.

6. *SUMMARY AND CONCLUSIONS*

1. Seventy-two impact tests were conducted on identical bicycle helmets using a modified Hybrid III headform capable of measuring tri-axial linear and rotational accelerations. Test parameters included the anvil angle, drop height, impact site and chinstrap tightness.

2. In the current test series, chinstrap tightness was not found to have a significant effect on the resulting peak linear or angular accelerations.

3. The anvil angle was found to have a significant effect on the resulting peak linear and angular accelerations. Shallower anvil angles resulted in higher peak accelerations, but this effect was more dominant for linear accelerations than for rotational accelerations.

4. Within a given set of parameters, increased drop heights were found to cause higher levels of linear and rotational acceleration, except in cases where steep anvil angles caused poor interaction with the helmet. However, the drop height was not found to be as dominant factor as the anvil angle in influencing peak accelerations.

5. The helmet currently tested showed highest rotational acceleration responses at the rear. Because of the helmet's specific design, this suggests and corresponds to current belief, that the combination of helmet shape, anvil shape and contact conditions have a dominant effect on the rotational acceleration responses in helmet testing.

6. The scatter observed for peak rotational acceleration responses indicates that the test method could require further repeatability improvements. This scatter, however, also indicates the high sensitivity of the rotational acceleration responses obtained in helmet testing to variations in the test parameters. This sensitivity seems to be intrinsic to assessing headform rotational acceleration responses.

7. Major items not addressed in this study are possible tolerance limits (performance criteria) for rotational accelerations in bicycle helmet testing and effects of design parameters (e.g. fit, shell type, deformation characteristics of the liner). The current study, however, shows that rotational acceleration responses in bicycle helmet testing do provide additional helmet performance information and the role of some test parameters has been identified.

APPENDIX A: DATA TRACES