Skid Tests on a Select Group of Bicycle Helmets to Determine Their Head-Neck Protective Characteristics

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Abstract

A select group of bicycle helmets, representative of hard shell, micro-shell and noshell with either rubber straps or nylon cover models, were subjected to skid-type impacts to smooth and rough concrete inclined at five angles from 30 to 60 degrees. Impact occurred in the range of 6.5-8.5 mph (10.4-13.7 km/hr), the upper limit of which was dictated by risk of damage to the neck transducer in the modified Hybrid III dummy. Two dummy body orientations at impact, both symmetrical to the sagittal plane, were investigated.

Test results predict that hard and micro-shell helmets provide about equal protection from cervical spine injury. The hard and micro-shell helmets tended to slide rather than hang up on impact with concrete. This sliding tendency was the mechanism that reduced the potential for neck injury. Nylon covers on the no-shell helmets were helpful under some conditions in allowing sliding to occur as the cover was stripped off the helmet by friction with the concrete.

Under the test conditions, head injury risks from the standpoint of linear accelerations, were negligible in all cases. Rotational head motion did not approach dangerous levels of combined angular acceleration and angular velocity.

Because of rebounding onto the rubber dummy face after sliding impacts, several methods were used to save the face from abrasive contact with the concrete. A polycarbonate faceguard attached to a micro shell helmet not only saved the dummy face from being abraded, but reduced head-neck injury index measurements. It also assisted in keeping the helmet in place.

Results of this series of tests (and similar previous tests of the unhelmeted dummy), predict that any helmet similar to those used in these tests will protect the brain and neck much better than wearing no helmet.

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Skid Tests on a Select Group of Bicycle Helmets to Determine Their Head-Neck Protective Characteristics

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1.Introduction

This study is an extension of a series of abbreviated skid tests conducted previously [Reference 1 at end]. The object of the current study was to investigate more thoroughly the relative risk of head, face and neck injury in bicycle helmets with various outer surfaces. Tests were conducted with a modified, full-sized Hybrid III Dummy instrumented with head-neck transducers. The dummy, while wearing one of six different bicycle helmets, was driven into one of two different textured slabs of concrete set at varying oblique angles (see Figure 1). The effect when a large component of tangential loading occurred was evaluated.

The variables investigated were:

SHELL: hard, micro or none

SURFACE: smooth concrete, rough concrete

SLAB ANGLES: 30 degrees-60 degrees; 7.5 degree increments

SPEED-mph(km/hr): 6.5-8.5 (10.4-13.7)

BODY ORIENTATION: 2

Micro-shell helmets were not available on dealers' shelves in the Detroit metropolitan area at the time of the previous skid tests. These helmets are molded expanded polystyrene (eps) or expanded polypropylene (epp) no-shell helmets covered with a very thin shell composed of thermoplastic material such as polycarbonate. This thermoplastic material is heated in thin sheets and vacuum formed onto the eps or epp liner in typically 0.015 in - 0.018 in (0.38mm - 0.46mm) thicknesses for the purpose of conspicuity, slippery exterior surface, some extra penetration resistance and structural integrity, with only a small increase in weight.

Hard shell helmets are typically eps molded liners covered by an injection molded shell made of a variety of thermoplastic substances, such as high density polyethylene, which vary in thickness between 0.062 in - 0.080 in (1.6 mm - 2.0 mm). This type of helmet construction is designed to make the molded liner relatively more impenetrable to sharp objects, more likely to hold together during a collision and to skid on impact surfaces. Typically, the no-shell, micro-shell, and hard shell helmet weights would be on the order of 0.42 lb, 0.56 lb, and 0.73-0.89 lb (1.9 N, 2.5 N, and 3.2 - 4.0 N), respectively.

11.Test Procedures

Instrumentation for these tests included a linear triaxial accelerometer mounted at the dummy head center of gravity; an accelerometer in the head to measure angular accelerations about an axis perpendicular to the mid-sagittal plane; and also a transducer to measure shear force, axial force and flexion-extension bending at the head-neck interface. A force transducer was mounted under the slab to measure the shear and perpendicular components of impact force. Figure 1 shows

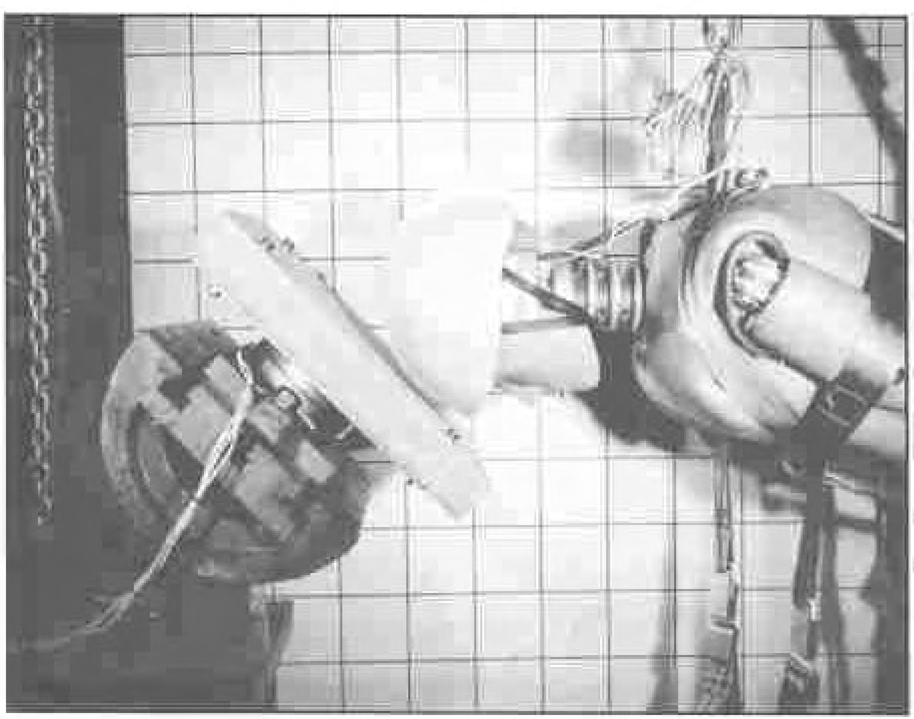

Figure 1: Bicycle helmet skid test setup with no-shell helmet mounted on the Hybrid III dummy in position to contact a smooth concrete slab attached to a force transducer. The dummy was driven horizontally at the slab, which was set at various angles between 30 and 60 degrees.

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the dummy in an orientation with the neck at 0 degrees and trunk at +17 degrees to the horizontal, about to strike the slab inclined at 45 degrees. The dummy had been reduced in weight to 130 lb (578 N) by removal of arms and legs.

In this phase of testing a rough surface was added (see Figure 2), and only five helmet models, representative of hard shell, micro-shell and no-shell helmets with expanded polystyrene (eps) liners currently available on the market, were tested. Limited tests of a unique no-shell helmet with rubber straps, provided by the Bicycle Helmet Safety Institute, were also conducted. The six helmets used in this phase of testing were:

- Zephyr: no-shell eps with rubber straps on exterior surface
- LT-1100: no-shell eps with nylon cover
- LT-900: eps with micro-shell
- LT-950: nylon net impregnated eps with rnicro shell
- Troxel Comp Sx: eps with ABS hard shell
- Troxel Coronado: eps with polypropylene hard shell

These helmets are pictured in Figure 3. Several tests were also conducted with a faceguard attached to the LT-950 micro-shell helmet, as displayed in Figure 4.

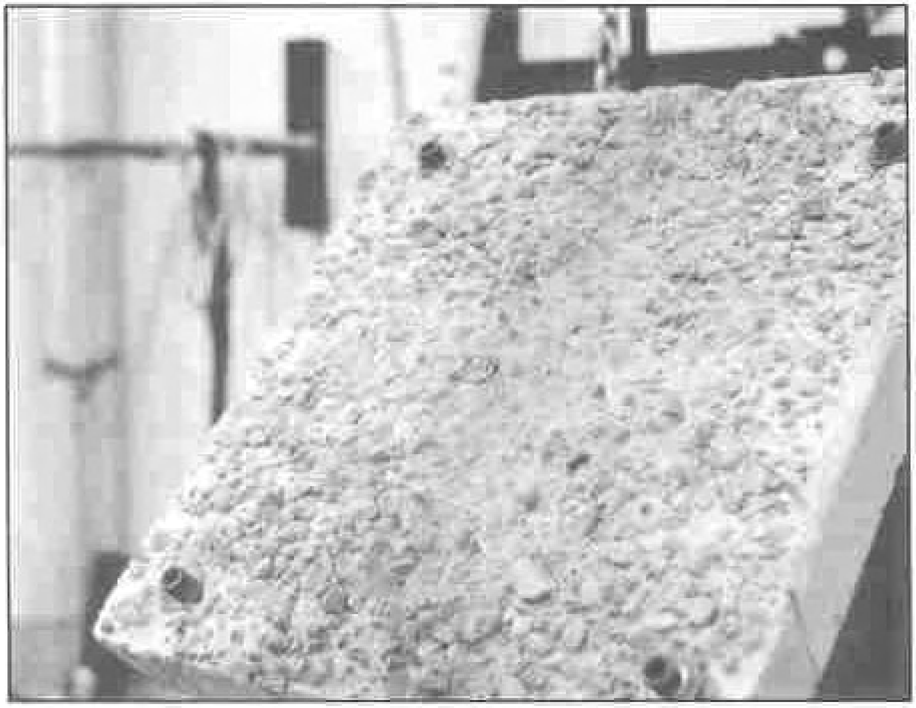

Figure 2: Rough concrete slab with small pebbles embedded into the surface (see penny for size comparison to pebbles).

Figure 3. The six types of bicycle helmets used in this series of tests include left to right: In the top row no-shell with attached external rubber straps; hard shell; micro-shell. Bottom row: no-shell with removable nylon cover, hard shell with increased occipital coverage; micro-shell with embedded liner net.

Figure 4. Micro-shell helmet with polycarbonate faceguard attached.

The order of tests and the test conditions are as presented in Table 1, columns 1-7. Nomenclature for the measurements, given in the tables as peak values, is as follows:

- **velocity** - average velocity through 1.00 in (25.40 mm) spaced infra-red light beams across the path of the dummy within 1 in (25 mm) of impact. Units: mph= 1.609 km/hr.
- **My** - bending moment measured about a transverse (y) axis at the head-neck junction of the Hybrid III dummy. Units: ft-lb= 1.356 N-m (Newton meter).
- **force** - lb=4.448 N (this conversion is also used for weight, which is the force necessary to restrain a body against free fall due to force of gravity).
- **dur** - duration of impact as measured in milli-sec (ms) on the bending moment oscillogram.
- **Fz** - axial force measured in the neck of the dummy.
- **Fx** - shear force applied to the neck of the dummy in the anterior-posterior direction (or visa versa).
- **Lz** - perpendicular force component applied to the concrete slab by impact of the dummy.
- **Lx** - parallel to the slab surface force component.
- **r** - angular accelerations measured about a transverse axis (y) in the dummy head. Units: radians/s/s.
- **Aap** - linear acceleration measured in the anterior-posterior (ap) direction in the dummy head. Units: G (acceleration due to force of gravity; at sea level G = 32.2 ft/s/s (9.8 m/s/s)).

- **Asi -** linear acceleration measured in the superior-inferior (si) direction in the dummy head.
- **Severity Index** (SI)[Footnote a below] - computed on the resultant head acceleration Ar of Aap and Asi.

[a] $$\textit{Severity Index } (SI)^2 = \int_0^T A^{2,5}\, di,$$

where T is effective impact duration.
A is instantaneous acceleration (G).
dt is time increment of integration.

Because of the limited space for the large amount of data given in some of the tables, data in all of the tables have been given only in U.S. units, instead of both U.S. and SI (International System) units as in the text, where the above conversion factors have been used.

Conduct of a typical test was as follows. After calibrating the ten measurement channels given in the nomenclature, the surface was selected as either the smooth concrete slab, judged to be typical of concrete roadways, or concrete with small pebbles--on the order of 1/4 in (6 mm) diameter--impregnated in the surface, representative of a rough, leached road surface. The surface was clamped at the desired angle between 30 degrees and 60 degrees, in 7.5 degree increments. The modified Hybrid III dummy was oriented in one of two angles of attack with the neck set in its maximum extended position. The most used body orientation was with the cervical spine horizontal, in which case the thoracic spine was at + 17 degrees to the horizontal. In the second orientation, the cervical spine was -15 degrees and the thoracic spine +2 degrees to the horizontal (see Figure 5).

The dummy was suspended from above and held in alignment below by seat belts attached to aluminum guide bars mounted on rollers, which ran in parallel overhead and floor tracks set in a vertical plane. A helmet was fastened snugly on the 7 1/8 sized dummy head, after fixing the slab inclination and body orientation

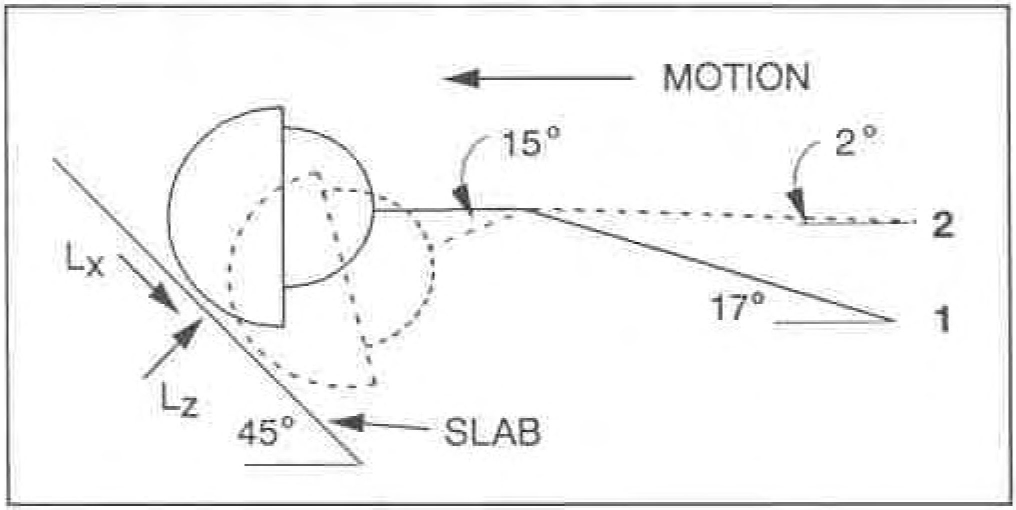

Figure 5. Dummy body orientations 1 and 2 at impact with a concrete slab at 45 degrees.

Table 1
Conditions and Peak Values of All Tests

Test	Helmet Type	surf	Angle slab deg	Angle neck deg	Angle body deg	Vel mph	M_y ft-lb	dur ms	F_z lb	F_x lb	L_z lb	L_x lb	α-up r/s/s	α-dn r/s/s	A_{sp} G	A_{si} G	SI	Ar G	Remarks
1	Zephyr-1; no-shell rub cov	smth conc	45	0	17	6.7	121	175	795	185	945	478	2410	1471	20	21	23	44	Grabs and rebounds
2	Adura 1100-1; no-shell nyl cov	"	"	"	"	6.3	87	42	815	165	910	280	2160	2257	34	21	59	49	Cover slips off; skids
3	LT 900-1; micro-shell	"	"	"	"	6.4	98	34	690	250	795	255	1786	2445	24	15	20	30	Skids
4	Coronado-2; hard shell	"	"	"	"	6.5	91	36	720	265	840	268	2678	2719	27	16	50	60	Skids
5	Adura 1100-1; no-shell wo/ cov	"	"	"	"	6.4	120	44	910	160	1000	323	2785	2548	26	25	44	45	No net; Skids
6	Adura 1100-3; no-shell nyl cov	"	"	"	"	6.3	129	164	765	180	845	510	2357	1317	18	18	20	27	No net. Grabs and rebounds
7	Comp sx-3; hard shell	"	"	"	"	6.2	109	44	665	185	755	215	1607	2514	19	12	16	28	Skids
8	LT 950-1; micro-shell & net	"	"	"	"	6.5	87	37	660	210	765	240	2143	2411	21	13	25	33	Skids
9	Zephyr-1; no-shell rub cov	rough conc	"	"	"	6.2	126	151	770	220	880	518	2160	1436	18	16	18	32	Only Zephyr available
10	Adura 1100-4; no-shell nyl cov	"	"	"	"	6.4	113	166	705	190	885	520	2803	1009	17	17	17	28	Grabs and rebounds
11	LT 900-3; micro-shell	"	"	"	"	6.3	130	166	730	210	775	478	1718	718	19	16	28	48	Grabs and rebounds
12	Coronado-3; hard shell	"	"	"	"	6.5	133	57	745	235	780	333	1857	1518	23	18	26	31	Skids
13	Comp SX-4; hard shell	"	"	"	"	6.1	117	181	650	220	770	370	1732	1026	16	12	15	28	Grabs and rebounds
14	LT 950-2; micro-shell & net	"	"	"	"	5.8	100	166	635	175	780	413	1393	735	11	12	4	15	Helmet on backwards
15	Coronado-3; hard shell	"	"	"	"	6.2	121	49	735	215	775	295	2446	2090	29	-	29	38	Skids
16	LT 950-2; micro-shell & net	"	"	"	"	6.3	113	54	680	205	790	345	1786	1173	15	15	13	22	Skids
17	Zephyr-1; no-shell rub cov	rough conc	30	"	"	6.2	112	154	585	190	635	410	1178	992	13	9	3	14	Grabs and rebounds
18	LT 900-4; micro-shell	"	"	"	"	6.3	109	49	475	220	520	308	1453	1327	11	10	9	22	Skids
19	Adura 1100-4; no-shell nyl cov	"	"	"	"	6.3	107	174	545	195	595	365	-	-	15	13	7	17	Grabs and rebounds;
20	Adura 1100-4; no-shell nyl cov	"	"	"	"	6.3	113	174	580	210	633	473	1603	1163	16	17	8	21	Grabs and rebounds
21	Coronado-2; hard shell	"	"	"	"	6.2	75	34	310	205	458	165	1071	2001	19	6	9	24	Skids
22	Comp SX-4; hard shell	"	"	"	"	6.4			140	310	428	225	3107	1214	13	7	10	19	Questionable; may be end
23	Comp SX-4; hard shell	"	"	"	"	6.4	54	29	305	150	428	175	714	2052	20	6	10	23	Skids
24	Pro Action-2 w pc mask	"	"	"	"	6.5	45	29	335	150	475	175	714	1881	25	16	15	26	Helmet & mask skid
25	Zephyr-1; no-shell rub cov	"	37.5	"	"	6.3	107	161	615	200	753	468	2071	1317	22	17	14	26	Grabs and rebounds
26	Adura 1100 6; no-shell nyl cov	"	"	"	"	6.4	110	167	625	175	725	470	1946	941	-	-	10	20	Grabs and rebounds
27	LT 900-6; micro-shell	"	"	"	"	6.3	110	64	545	205	650	280	1786	2873	17	10	14	32	Skids
28	Coronado-2; hard shell	"	"	"	"	6.3	90	34	510	220	630	208	1788	2702	23	13	4	37	Skids
29	Adura 1100-6; no-shell nyl cov	"	"	"	"	6.2	109	184	590	170	675	403	1714	1060	20	10	13	22	Grabs and rebounds
30	Comp SX-4; hard shell	"	"	"	"	6.2	83	32	525	220	640	220	1607	2770	24	16	19	27	Skids
31	LT 950-1; micro-shell & net	"	"	"	"	6.3	104	47	550	195	655	248	1964	2548	21	19	13	24	Skids
32	Zephyr-1; no-shell rub cov	"	52.5	"	"	6.5	137	129	960	205	1108	575	1964	906	28	24	57	56	Grabs and rebounds
33	Adura 1100-6; no-shell nyl cov	"	"	"	"	6.5	120	141	850	170	1048	478	2071	1094	24	21	33	34	Grabs and rebounds
34	LT 900-6; micro-shell	"	"	"	"	6.7	132	144	775	200	993	410	1910	1005	21	20	27	33	Grabs and rebounds
35	Coronado-4; hard shell	"	"	"	"	6.6	135	59	940	210	1118	363	1914	1748	30	27	56	43	Skids
36	Comp SX-5; hard shell	"	"	"	"	6.6	115	67	695	205	908	270	1532	1454	20	14	22	30	Skids
37	LT 950-3; micro-shell & net	"	"	"	"	6.6	115	62	815	190	990	345	1678	1625	20	15	20	25	Skids
38	Adura 1100-5; no-shell nyl cov	"	60	"	"	6.5	124	129	1210	150	1188	505	1257	568	30	24	58	59	Grabs and rebounds

Table 1(cont.)

Test	Helmet Type	surf	Angle slab deg	Angle neck deg	Angle body deg	Vel mph	M_y ft-lb	dur ms	F_z lb	F_x lb	L_z lb	L_x lb	α-up r/s/s	α-dn r/s/s	Aap G	Aai G	SI	Ar G	Remarks
39	LT 900-6; micro-shell	*	*	*	*	6.6	128	131	1230	150	1225	528	1203	701	26	26	58	45	Grabs and rebounds
40	Coronado-4; hard shell	*	*	*	*	6.4	136	129	1125	200	1128	448	1589	804	24	25	71	60	Grabs and rebounds
41	LT 950-5; micro-shell & net	*	*	*	*	6.6	123	131	1170	135	1163	495	1786	884	23	19	36	34	Grabs and rebounds
42	Comp SX-5; hard shell	*	*	*	*	6.5	135	124	925	180	1100	343	1246	858	22	17	27	39	Grabs and rebounds
43	Comp SX-6; hard shell	smth conc	*	*	*	7.3	152	87	1090	200	1350	353	2196	2052	24	21	42	35	Grabs and skids
44	Adura 1100-7; no-shell nyl cov	*	*	*	*	7.3	140	131	1245	170	1475	440	1839	2565	22	29	53	39	Grabs and rebounds
45	LT 900-7; micro-shell	*	*	*	*	7.3	133	62	1245	175	1500	330	1578	2565	25	32	59	47	Grabs and skids
46	Coronado-5; hard shell	*	*	*	*	7.3	143	59	1245	190	1488	363	1482	2702	20	26	47	41	Grabs and skids
47	LT 950-7; micro-shell & net	*	*	*	*	7.4	125	59	1315	150	1553	358	1539	2661	25	29	62	56	Grabs and skids
48	Comp SX-7; hard shell	*	30	*	*	8.3	119	29	360	150	250	125	714	2428	28	9	31	38	Skids
49	Adura 1100-7; no-shell nyl cov	*	*	*	*	7.9	63	32	105	150	535	150	714	1744	22	5	20	37	Skids
50	LT 900-7; micro-shell	*	*	*	*	8.4	45	24	385	150	600	175	536	1922	31	5	34	32	Skids
51	Coronado-6; hard shell	*	*	*	*	8.4	55	32	390	150	605	150	357	2052	32	10	27	32	Skids
52	LT 950-7; micro-shell & net	*	*	*	*	8.6	65	29	370	150	618	150	1250	2514	26	10	25	30	Skids
53	Comp SX-7; hard shell	*	45	-15	2	6.4	116	156	795	170	998	218	2285	1026	11	16	12	26	Grabs and rebounds
54	Adura 1100-7; no-shell nyl cov	*	*	*	*	6.1	98	144	960	145	1140	363	2053	1985	13	19	15	25	Grabs and rebounds
55	LT 900-6; micro-shell	*	*	*	*	6.4	102	97	865	155	1055	258	1286	1265	5	12	3	28	Skids
56	Coronado-6; hard shell	*	*	*	*	6.4	112	74	925	160	1113	265	1546	1754	12	16	14	22	Skids
57	LT 950-8; micro-shell & net	*	*	*	*	6.3	103	79	930	155	1123	260	1357	1847	10	16	14	29	Skids
58	Comp SX-7; hard shell	*	37.5	*	*	6.6	92	38	550	195	753	200	1643	2531	20	11	19	26	Skids
59	Adura 1100-8; no-shell nyl cov	*	*	0	17	6.7	92	57	600	205	783	225	1643	2531	21	16	17	24	Skids
60	LT 900-6; micro-shell	*	*	*	*	6.7	66	37	450	220	630	150	1250	2018	19	7	18	30	Skids
61	Coronado-6; hard shell	*	*	*	*	6.7	76	34	520	230	748	170	1786	2702	25	11	29	40	Skids
62	LT 950-8; micro-shell & net	*	*	*	*	6.7	78	37	510	205	743	173	1714	2565	23	10	21	27	Skids
63	Comp SX-7; hard shell	*	30	*	*	6.6	50	29	315	150	508	150	536	2018	22	7	13	22	Skids
64	Adura 1100-8; no-shell nyl cov	*	*	*	*	6.8	61	42	365	170	520	143	857	1984	20	6	11	20	Skids and strips
65	LT 900-6; micro-shell	*	*	*	*	6.5	25	27	235	100	408	100	357	1026	20	5	11	19	Skids
66	Coronado-6; hard shell	*	*	*	*	6.4	49	27	315	195	490	150	714	2257	26	7	15	24	Skids
67	LT 950-8; micro-shell & net	*	*	*	*	6.5	44	32	285	150	463	125	714	1710	21	5	11	21	Skids
68	LT 950-6; micro-shell &	*	*	*	*	6.6	41	29	260	190	423	145	357	1471	22	7	12	32	Skids
69	LT 950-6; micro-shell &	*	37.5	*	*	6.5	67	34	495	150	728	160	1250	2223	25	10	25	32	Skids
70	LT 950-6; micro-shell &	*	45	*	*	6.5	77	37	680	200	933	175	857	2086	27	15	37	39	Skids

of the dummy. Attached to the upper bar was a tension spring which was pulled back by a winch to a selected position pre-determined to produce a velocity of near either 6.5 or 8.5 mph (10.4 or 13.7 km/hr) [Footnote a below].

> *Footnote a: In these types of tests, during which large tangential forces can act on the head when hang-up with the concrete occurs, the neck load transducer controls how extreme the environment can be allowed to become before forces and/or bending moments approach damage levels in the dummy. For these surfaces, angles and some helmets, damage levels to the dummy head-neck transducers were approached in this relatively low velocity range.*

A quick release was actuated and the spring pulled the dummy to a point in close proximity to the slab, after which it was allowed to free wheel through a velocity-measuring, infra-red timing gate into forehead impact with the inclined concrete slab. Impact occurred in the range of 2.5 in (64 mm) to 6 in (152 mm) above the front rim of the helmet. If the helmet did not grab the concrete and rebound, the head of the dummy was free to slide up the length of the 15 in (380 mm) slab, shortly after which rubber bumpers on the tracks stopped the guide bars and subsequent tension on the suspension belts stopped the dummy.

III. Results

Peak Values of All Tests. Oscillograms of all tests were obtained. Peak values along with impulse duration, taken from the time the bending moment channel My left zero amplitude until return, were extracted electronically from the oscilloscope. They are tabulated in Table 1 along with conditions for each test. Figures a-d in the appendix illustrate the oscillograms for 6.5 mph (10.4 km/hr) impact to the smooth concrete slab inclined at 45 degrees for the rubber strap covered no-shell, nylon covered no-shell, micro-shell and hard shell helmets, respectively.

To clarify the effects of the various conditions on neck loads and head accelerations, data were extracted from Table 1 and reassembled into Tables 2-8. Linear head accelerations (Aap, Asi, Ar) and Severity Indices (SI), indicators of potential for brain injury, were extremely low under these test conditions and consequently were not extracted from Table 1. It should be pointed out that they do not become significant under these types of skid impact simulations unless a helmet is not worn as demonstrated in the earlier study.

Effect of Neck-Body Orientation, for near 6.5 mph (10.4 km/hr) impacts to smooth concrete inclined at 45 degrees (see Table 2 for data). When the helmet on the dummy head strikes the smooth concrete slab as depicted in the Figure 5, the impulsive force acting on the helmet can be broken into two components--one perpendicular to the slab

(Lz), and a component parallel to the surface (Lx). Assuming that the concrete was perfectly smooth, the maximum force of friction which could be developed is a μLz, where μ is the coefficient of sliding friction on the smooth concrete slab. This was determined experimentally from the tangent of the concrete ramp angle at which helmet sliding commences due to the force of gravity component along the ramp.

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Values of μ were found as follows:

Helmet type	μ
Hard shell	0.24
Micro shell	0.22
No-shell	0.70 (0.17 when sliding on its nylon cover)

With this information and the slab force component measurements, Lz and Lx, it is possible to obtain a better understanding of why the helmets skid or hang up on the smooth concrete slab. This information also helps clarify why, when the dummy's body orientation is switched from 1 to 2, the head and neck injury measurements change in the manner shown in Table 2.

The dummy strikes the slab more perpendicularly in body orientation 2 than 1. This causes the following changes, regardless of helmet type tested:

1. The perpendicular force component acting on the slab, Lz, increases and consequently μLz also increases.

2. Neck injury parameters My, Fz, and their duration all increase.

3. Head injury parameter *alpha*, decreases.

4. Parallel force component Lx, remains about the same for hard shell and micro-shell helmets, but increases in the no-shell helmet.

Because the concrete is not perfectly smooth, surface roughness is a factor in all three types of helmets, as was evident by the scratch marks on the helmet exteriors after all skid tests. It is for this reason that the parallel force component, Lx, measured on the force cell under the slab, is greater than the maximum friction force which could be developed if perfectly smooth surfaces of the same materials were impressed against each other.

In the case of the no-shell helmet, body orientation 1, the concrete surface penetrated into and hung onto the nylon cover and eps on the front, causing a momentary hang-up, forcing the neck into flexion. Because the nylon cover was not glued to the eps liner, the liner slid in the cover. The cover was caught on the concrete, pulling it off the rear of the liner. This provided a runway with less friction, allowing the head to skid and bounce, as is evident from the Lx oscillogram

Table 2. Effect of neck-body orientation at 6.5 m.p.h., smooth concrete at 45°.

Test	Orientation	Helmet Type	My ftlb	dur ms	Fz lb	α-up r/s/s	α-dn r/s/s	L_z	μL_z	L_x	Remarks
2	1	Adura 1100-1; no shell nyl cov	87	42	815	2160	2257	910	155	280	Cover slips off; skids
54	2	Adura 1100-7; no shell nyl cov	98	144	960	2053	1385	1140	800	363	Grabs and rebounds
8	1	LT 950-1; micro shell & net	87	37	660	2143	2411	765	166	240	Skids
57	2	LT 950-8; micro shell & net	103	79	930	1357	1847	1123	250	260	Skids
4	1	Coronado-2; hard shell	91	36	720	2678	2719	840	200	268	Skids
56	2	Coronado-6; hard shell	112	74	925	1546	1754	1113	267	265	Skids

trace in Figure b. The friction component dropped from 280 lb (1250 N) to sporadic amounts generally less than the 155 lb (690 N), calculated as maximum from using the eps-nylon coefficient of friction. During the skidding and bouncing phase of motion, the torque acting on the head, due to friction, was overcome by the internal torque in the dummy resisting flexion and the neck straightened to its equilibrium position.

In body orientation 2, the perpendicular force component acting on the no-shell helmet was 25 percent higher than for orientation 1. This provided enough friction and gripping to prevent skidding and stripping of the cover, causing a rolling motion of the head. This forced the neck to remain in flexion until all the kinetic energy of the dummy (less the energy dissipated by friction and deformation) was absorbed, after which the dummy rebounded straight back from the slab horizontally.

Both the hard shell and micro-shell helmets, in body orientation 1, hung up momentarily and forced the dummy into neck flexion, followed by release into a straight neck. During tests of hard and micro-shell helmets with body orientation 2, there was an increase in perpendicular force components by 33% and 47%, respectively, over orientation 1. This phenomena doubled the time during which the neck compression-flexion was sustained, but still reached only about the half the 144 ms duration of the no-shell helmet. This situation occurred because there was not enough gripping action of the concrete on these slippery shells to develop much higher than the theoretical maximum, μLz, below which skidding would occur. Consequently, as the dummy kinetic energy was dissipated in time, the Lx force resisting skidding more quickly fell below the skid force level in the hard and micro-shell than for the no-shell helmet. In orientation 2, the no-shell helmet could have developed 800 lb (3560 N) to prevent skidding, compared to only 250-267 lb (1110-1190 N) for the slippery shells.

Angular accelerations were greater in body orientation 1 than in body orientation 2, which was more perpendicular to the slab. This was because leverage of the forces acting on the head to cause it to rotate, and their rate of application and release, decreases as the impact center moves toward the top of the helmet. In none of the six tests listed in Table 2, or any test listed in Table 1, was the 4500 r/s/s tolerance level and other criteria for parasagittal bridging vein rupture approached [Reference 3 at end].

Nylon v Rubber Covered No-Shell Helmet, for 6.5 mph (10.4 km/hr), smooth concrete inclined at 45 degrees. The data in Table 3 show that whatever function exterior coverings serve, such as to provide higher visibility or strength, they should also be slippery to minimize the risk of injury. For these test conditions, the nylon slip-on cover slips off when contact with the concrete slab occurs and allows the helmet to skid on the nylon, preventing the long duration neck loading which occurs on impact in the case of the rubber strapped helmet model. This same pattern of grabbing the concrete was observed with the rubber strapped no-shell helmet in each test condition in which it was evaluated. Because there was only one rubber strapped helmet available, it was tested six times. However, the data shown in this table are results from its first use. In most cases, the other helmets were tested only once or twice.

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Table 3. Nylon covered v rubber strapped no-shell helmets, 6.5 mph, 45°, smooth concrete.

Test	Helmet Type	M_y ft-lb	dur ms	F_z lb	α-up r/s/s	α-dn r/s/s	Remarks
1	Zephyr-1; no-shell rub cov	121	175	795	2410	1471	Grabs and rebounds
2	Adura 1100-1; no-shell nyl cov	87	42	815	2160	2257	Cover slips off; skids

Effect of Slab Angle, for 6.5 mph (10.4mph km/hr) impacts to a rough surface. Data in Table 4 show that the no-shell helmet gripped the surface at any angle, resulting in long duration neck loading, which did not occur in the hard shell or micro-shell helmets until the concrete slab was at 60 degrees. For the smooth surface concrete impacts in the no-shell helmet, the nylon cover tended to slip off and eliminate the long duration neck loading. However, the pebbles in the rough surface penetrated through the nylon cover into the eps to prevent slippage, thereby resulting in high, long duration neck loading.

Effect of Faceguard on Micro-Shell Helmet Performance. During the course of previously conducted skid tests [Reference 1 at end], the expensive silicon rubber face of the dummy became abraded from bumping and scraping against the concrete slab subsequent to the initial impact. During those tests it was demonstrated how a clear polycarbonate hockey-type faceguard could be attached to the shell of a hard shell bicycle helmet to eliminate facial rubber damage to the dummy. In this series, tests were conducted to show a faceguard could also be attached to the micro-shell helmet by means of straps anchored to both the shell and 'T' nuts embedded in the nylon net impregnated molded eps liner; that the faceguard could take some significant impacts and scraping but not be torn off the helmet or allow the helmet to rotate on the head; and that a faceguard would protect the dummy's face from abrasion.

In tests during which the dummy face contacted the slab after the initial impact, besides abrading the face the friction caused a rapid change in rotational direction in the head (angular acceleration) and forced the orientation of the neck from extension to flexion. These secondary rotational changes due to facial impact were completely eliminated by the faceguard (compare oscillograms of the third trace from the bottom in Figures c and e, appended). Also, the initial head angular accelerations and the force and bending measurements between head and neck were reduced. The reduction in critical head-neck injury peak measurement on the dummy are tabulated in Table 5 for three comparative impacts of the dummy head wearing a micro-shell helmet with impregnated nylon net, with and without a faceguard.

Many of the retention straps in current use are uncomfortable, complicated for children to adjust properly, and do not maintain the helmet in place, particularly when acted upon by tangential force components. This is at least in part because bicycle helmets are not complete coverage helmets. A chin bearing rear hook-

Table 4. Effect of slab angle, 6.5 mph, rough surface.

Test	Helmet Type	Angle deg	M_y ft-lb	dur ms	F_z lb	α-up r/s/s	α-dn r/s/s	Remarks
20	Adura 1100-4; no-shell nyl cov	30	113	174	580	1803	1163	Grabs and rebounds
10	Adura 1100-4; no-shell nyl cov	45	113	166	705	2303	1009	Grabs and rebounds
38	Adura 1100-5; no-shell nyl cov	60	124	129	1210	1257	568	Grabs and rebounds
18	LT 900-4; micro-shell	30	109	49	475	1453	1327	Skids
16	LT 950-2; micro-shell & net	45	113	54	680	1786	1173	Skids
41	LT 950-5; micro-shell & net	60	123	131	1170	1786	684	Grabs and rebounds
21	Coronado-2; hard shell	30	75	34	310	1071	2001	Skids
12	Coronado-3; hard shell	45	133	57	745	1857	1518	Skids
40	Coronado-4; hard shell	60	136	129	1125	1589	804	Grabs and rebounds

Table 5. Effects of faceguard on micro-shell helmet (30°, 37.5°, 45°), 6.5 mph, smooth concrete.

Test	Helmet Type	Faceguard	Angle deg	M_y ft-lb	dur ms	F_z lb	α-up r/s/s	α-dn r/s/s	Remarks
67	LT 950-8; micro-shell & net	N	30	44	32	285	714	1710	Skids
68	LT 950-8; micro-shell & pcgrd	Y	*	41	29	250	357	1471	Skids
62	LT 950-8; micro-shell & net	N	37.5	78	37	510	1714	2565	Skids
69	LT 950-8; micro-shell & pcgrd	Y	*	67	34	495	1250	2223	Skids
8	LT 950-1; micro-shell & net	N	45	87	37	660	2143	2411	Skids
70	LT 950-8; micro-shell & pcgrd	Y	*	77	37	680	857	2086	Skids

up faceguard keeps the helmet in place during impact and makes the helmet more stable during riding. If a bike rider is going to wear a helmet, the faceguard can complete the protective equipment by reducing the risk of: 1) facial injury by abrading plastic instead of facial soft tissue and bone; 2) neck injury by reducing the facial-pavement friction and subsequent twisting, bending, and compression [Footnote a below]; and 3) brain injury by reducing sudden rotational movements during facial impact, and lowering linear head accelerations by absorbing energy by deformation in the event impact occurs on the guard. Figure 4 illustrates the polycarbonate faceguard mounted on the micro-shell helmet at the conclusion of these tests.

Footnote a: The latter can occur in the cervical spine due to body inertia loading, somewhat analogous to the loads on the fifth wheel in a jack knifing semi-trailer.

Effect of Velocity Increase on Head-Neck Loads, for smooth concrete at 30 degrees. Data given in Table 6 reveal a general pattern of increased neck loading (My, Fz) with velocity change over the relatively small range of 6.5-8.5 mph (10.4-13.7 km/hr) when hitting the smooth pavement at 30 degrees. This impact attitude produced relatively erratic friction conditions of skidding and skipping along the concrete in all four helmets, at both speeds. This behavior caused erratic angular acceleration changes without a pattern related to velocity, but prevented sustained high neck injury criteria. Past experience indicates that as the speed of impact increases, kinetic energy increases as the speed squared and the potential for injury escalates, especially as the surface angle increases. In a few preliminary trials these effects were found to hold, but it was not possible to increase speeds much above the 6.5 mph (10.4 km/hr) level at higher concrete slab angles without risking damage to the very expensive transducers which resist the head-neck loads in this dummy attitude.

Effect of Surface Roughness at 6.5 mph (10.4 km/hr), smooth v rough concrete, impact at 30 and 45 degree slab angles. It was found that for either of these two angles or surface roughness, the micro-shell and hard shell helmets skid, whereas the cover slips off the no-shell helmet and allows it to slide on its cover only in the

Table 6. Effect of velocity (6.7, 8.4 mph), smooth concrete, 30°.

Test	Helmet Type	Vel - mph	M_y ft-lb	dur ms	F_z lb	α-up r/s/s	α-dn r/s/s	Remarks
64	Adura 1100-8; no-shell nyl cov	6.8	61	42	365	857	1984	Skids and strips
49	Adura 1100-7; no-shell nyl cov	7.9	63	32	135	714	1744	Skids
67	LT 950-8; micro-shell & net	6.5	44	32	285	714	1710	Skids
52	LT 950-7; micro-shell & net	8.6	65	29	370	1250	2514	Skids
66	Coronado-6; hard shell	6.4	49	27	315	714	2257	Skids
51	Coronado-6; hard shell	8.4	55	32	390	357	2052	Skids
63	Comp SX-7; hard shell	6.6	50	29	315	536	2018	Skids
48	Comp SX-7; hard shell	8.3	119	29	360	714	2428	Skids

case of the smooth concrete at 30 and 45 degrees. Referring to Table 7, all three helmet types show significantly higher neck bending when impacting the rough concrete as compared to the smooth, but the no-shell helmet rough concrete condition produced much longer high intensity neck loading than the others. The head angular accelerations did not show a pattern related to surface roughness at either angle.

Effects of Slab Angle (30, 37.5, 45 degrees) for smooth concrete impacts at 6.5 mph (10.4 km/hr). For smooth concrete impacts at any of these angles, all three types of helmets skidded. The no-shell helmet skidded on its own nylon cover which was stripped off by the friction between head and pavement. Data obtained for these effects are listed in Table 8. Stripping of the nylon cover was not always a reliable occurrence on the smooth concrete, eg. test 6, Table 1, and did not occur in the case of the rough surface. The pattern for all three types of helmets is a tendency for neck loads and head accelerations to gradually increase as the slab angle increases.

Comparisons of Angle at Which The Three Types of Helmets Gripped the Smooth and Rough Concrete Slabs on Impact at 6.5 mph (10.4 km/hr). The data presented in Table 9 illustrates the angle at which gripping occurred due to impact of the dummy head in body orientation 1 (thorax angle + 17 degrees, neck angle 0 degrees to horizontal), wearing any of the three types of helmets, with rough and smooth concrete at five different slab angles between 30 and 60 degrees. The no-shell helmet with rubber straps gripped the concrete at any angle from 30 degrees and higher, whereas the no-shell helmet with the nylon cover went up to 45 degrees on the smooth concrete before gripping, mainly due to nylon cover release. While not consistent, the nylon cover slipped off and prevented neck load buildup more often than not (see Figure f, appended, for a comparison of no-shell and hard shell oscillograms, equivalent conditions). Rough concrete caused the no-shell helmet to grip at any angle. The micro shell and hard shell helmets performed about equally in beginning to grip at 60 degrees on smooth concrete and 45 degrees for the rough surface. Figure g, appended, shows a comparison of micro-shell and hard shell helmet performances for 6.5 (10.4 km/hr) impact to the smooth concrete slab inclined at 45 degrees.

IV. Conclusions

1. For large tangential component loading of a helmet, which is often likely to occur when a fall from even a slow moving bicycle onto the pavement occurs, hard shell and micro-shell helmets are predicted to be the safest of the four types of helmet outer surfaces tested.

2. No-shell helmets with slip-over nylon (or similar material) covers are predicted to be the next most safe helmets in event of a skid-type fall onto a concrete surface. On smooth pavement, the covers are likely to be stripped off and allow skidding to occur, alleviating sustained loading of head and neck.

Table 7. Effect of surface roughness at 6.5 mph, smooth (S) vs. rough (R) concrete at 30°and 45° slab angles.

Test	Helmet Type	surf	Angle slab deg	M_y ft-lb	dur ms	F_z lb	α-up r/s/s	α-dn r/s/s	Remarks
64	Adura 1100-8; no-shell nyl cov	S	30	61	42	365	857	1984	Skids and strips
20	Adura 1100-4; no-shell nyl cov	R	"	113	174	580	1803	1163	Grabs and rebounds
67	LT 950-8; micro-shell & net	S	"	44	32	285	714	1710	Skids
18	LT 900-4; micro-shell	R	"	109	49	475	1453	1327	Skids
66	Coronado-6; hard shell	S	"	49	27	315	714	2257	Skids
15	Coronado-3; hard shell	R	"	121	49	735	2446	2890	Skids
2	Adura 1100-1; no-shell nyl cov	S	45	87	42	615	2160	2257	Cover slips off; skids
10	Adura 1100-4; no-shell nyl cov	R	"	113	166	705	2303	1009	Grabs and rebounds
8	LT 950-1; micro-shell & net	S	"	87	37	660	2143	2411	Skids
16	LT 950-2; micro-shell & net	R	"	113	54	680	1786	1173	Skids
4	Coronado-2; hard shell	S	"	91	36	720	2678	2719	Skids
12	Coronado-3; hard shell	R	"	133	57	745	1857	1518	Skids

Table 8. Effects of slab angle (30°, 37.5°, 45°), 6.5 mph, smooth concrete.

Tes	Helmet Type	Angle slab deg	M_y ft-lb	dur ms	F_z lb	α-up r/s/s	α-dn r/s/s	Remarks
64	Adura 1100-8; no-shell nyl cov	30	61	42	365	857	1984	Skids and strips
59	Adura 1100-6; no-shell nyl cov	37.5	92	57	600	1643	2531	Skids
2	Adura 1100-1; no-shell nyl cov	45	87	42	615	2160	2257	Cover slips off; skids
67	LT 950-8; micro-shell & net	30	44	32	285	714	1710	Skids
62	LT 950-8; micro-shell & net	37.5	78	37	510	1714	2565	Skids
8	LT 950-1; micro-shell & net	45	87	37	660	2143	2411	Skids
66	Coronado-6; hard shell	30	49	27	315	714	2257	Skids
61	Coronado-6; hard shell	37.5	76	34	520	1786	2702	Skids
4	Coronado-2; hard shell	45	91	36	720	2678	2719	Skids

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Table 9. Comparisons of angle at which the three types of helmets gripped the smooth and rough concrete slabs on impact at 6.5 mph.

Helmet	Angle - degrees					Surface
	30	37.5	45	52.5	60	
No-shell	■[1]		■[2]			Smooth
No-shell	■					Rough
Micro-shell					■[3]	Smooth
Micro-shell			■			Rough
Hard Shell					■	Smooth
Hard Shell			■[4]		■	Rough

1. Rubber strip covered.
2. Cover pulled off.
3. Micro-shell with net liner skidded until 60 degrees.
4. Rough surface erratic, i.e.: sometimes pebbles come loose and act as ball bearings to promote skid. Comp SX helmet gripped at 45 degrees, but skidded at 52.5 degrees.

3. Rubber strap covered, no-shell helmets similar to that tested are predicted to be the most hazardous of the four helmet types in a skid-type accident. This prediction is based

on the hanging-up-on-concrete characteristics displayed in these tests.

4. A face shield attached to either a hard or micro-shell helmet is predicted to be the safest equipment for head, neck and face, in the event of a skid-type fall onto the front of the head or face.

5. Results predict that any type of bicycle helmet similar to those used in the helmet drop tests conducted previously [Reference 1 at the end], or in these skid tests, is much more likely to minimize or prevent serious head or neck injury than wearing no helmet, regardless of what kind of head impact occurs in a bicycle crash.

V. Recommendations

1. Bicycle helmets should be covered with either a micro-shell or hard shell to reduce the risk of injury due to 'hang-up' with the pavement in a crash.

2. Helmets for children should provide more head coverage and a simpler retention system to improve stability.

3. Helmets for children should be equipped with a chin-bearing faceguard for maximum protection of face, head, and neck.

4. Helmet manufacturers should conduct research to devise an appropriate bicycle helmet faceguard for youth and offer it in their line of protective products.

VI. Comment

1. Parents should set an example by always wearing a helmet while riding a bicycle and insist upon their children always wearing a helmet while riding.

VII. References

1. Hodgson, V.R.: Impact, Skid, and Retention Tests on a Representative Group of Bicycle Helmets to Determine Their Head-Neck Protective Characteristics. Michigan Department of Public Health, Lansing, Michigan, February 1990.

2. Gadd, C.W.: Use of a Weighted - Impulse Criterion for Estimating Injury Hazard; Proceedings of the Tenth Stapp Car Crash Conference, Society of Automotive Engineers, Two Pennsylvania Plaza, New York, NY, 1966.

3. Lowenhielm, P.: Tolerance Level for Bridging Vein Disruption Calculated With a Mathematical Model; Journal of Bioengineering, Vol. 2 pp 501-507, 1978, Pergamon Press, Ltd.

Appendix

Figure a. Rubber strap covered no-shell helmet; 6.5 mph impact to smooth slab @ 45 degrees. Characterized by high friction gripping and skipping along slab (see Lz, Lx), prolonged bending moment (My) and axial force (Fz), near injury threshold, lasting approx. 175 ms, as head rolls up slab driven by the body and rebounds. Relatively moderate angular acceleration and very low linear acceleration (Aap Asi).

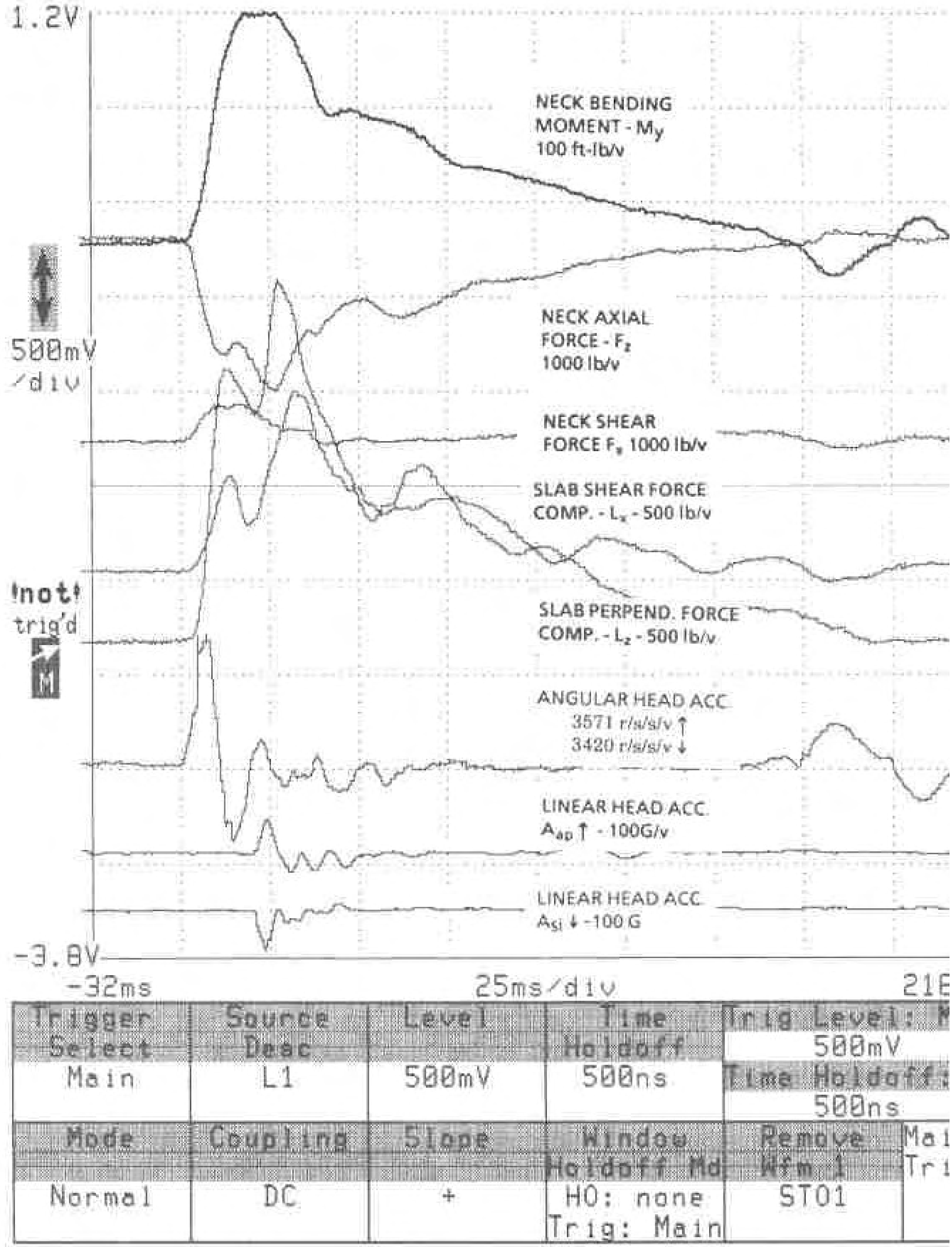

1.2V
500mV
/div
!not!
trig'd
M
-3.8V
NECK BENDING
MOMENT - M_y
100 ft-lb/v
NECK AXIAL
FORCE - F_z
1000 lb/v
NECK SHEAR
FORCE F_x 1000 lb/v
SLAB SHEAR FORCE
COMP. - L_x - 500 lb/v
SLAB PERPEND. FORCE
COMP. - L_z - 500 lb/v
ANGULAR HEAD ACC
3571 r/s/s/v ↑
3420 r/s/s/v ↓
LINEAR HEAD ACC
A_{ap} ↑ - 100G/v
LINEAR HEAD ACC
A_{si} ↓ -100 G
-32ms
25ms/div
Trigger Select
Main
Source Desc
L1
Level
500mV
Time Holdoff
500ns
Trig Level:
500mV
Time Holdoff:
500ns
Mode
Normal
Coupling
DC
Slope
+
Window Holdoff Md
H0: none
Trig: Main
Remove Wfm 1
ST01

Figure b. Nylon covered no-shell helmet; 6.5 mph impact to smooth slab @ 45 degrees. Characterized by initial gripping and then sliding after about 40 ms, as the nylon cover slips off the helmet, so that neck bending (My) and axial force (Fz) are relieved before reaching injury threshold, Moderate angular acceleration and low linear acceleration (Aap,Asi).

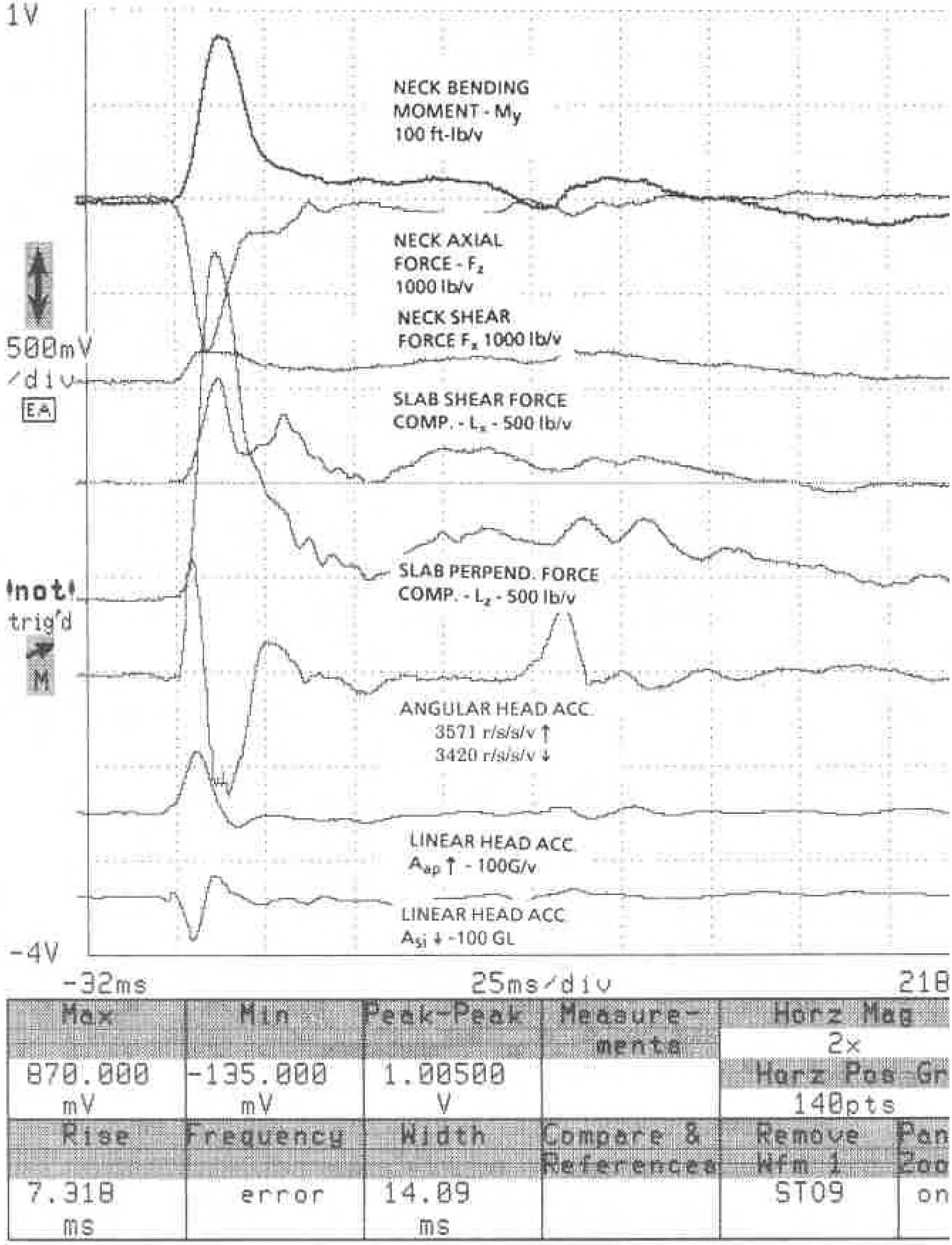
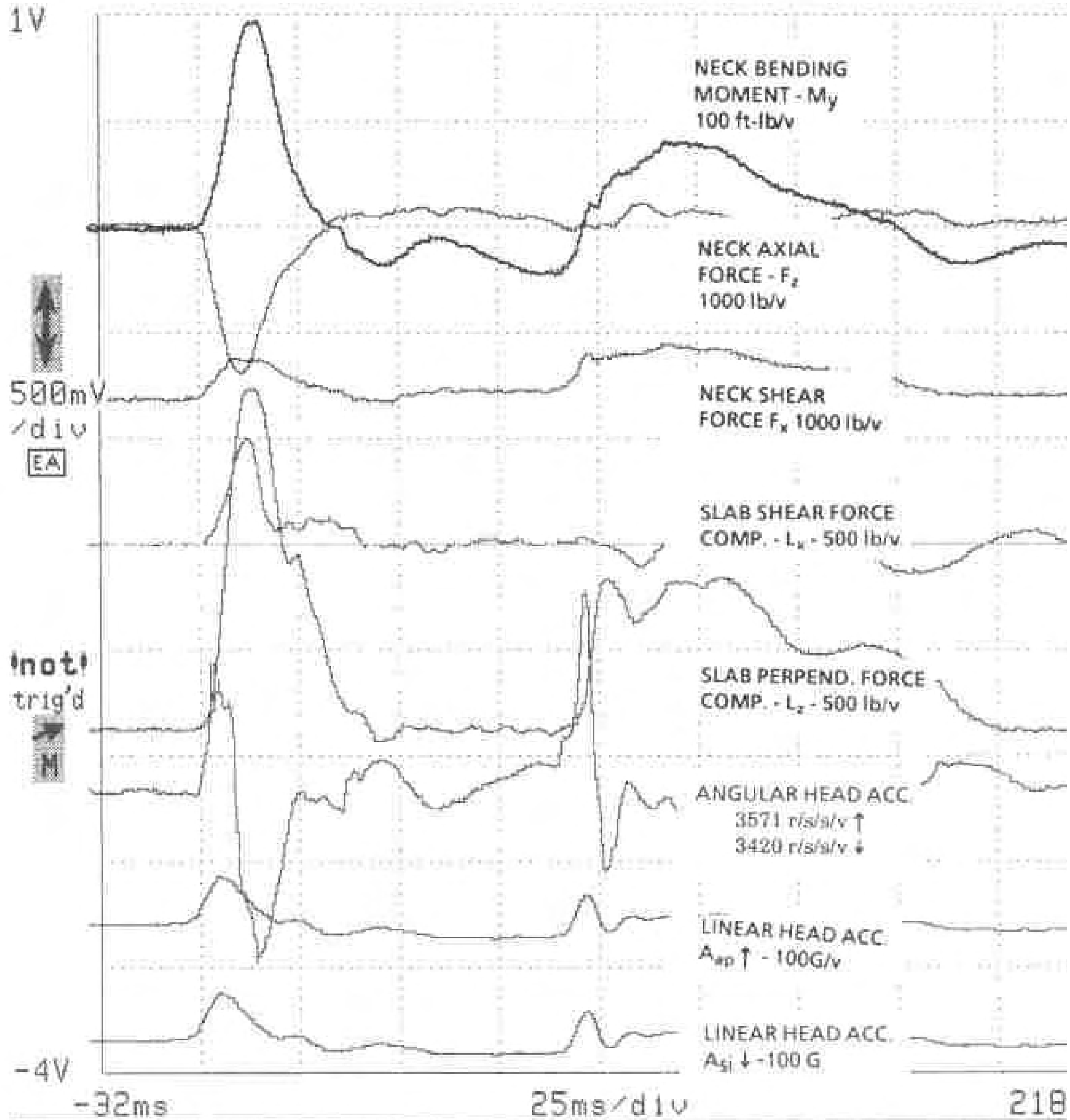
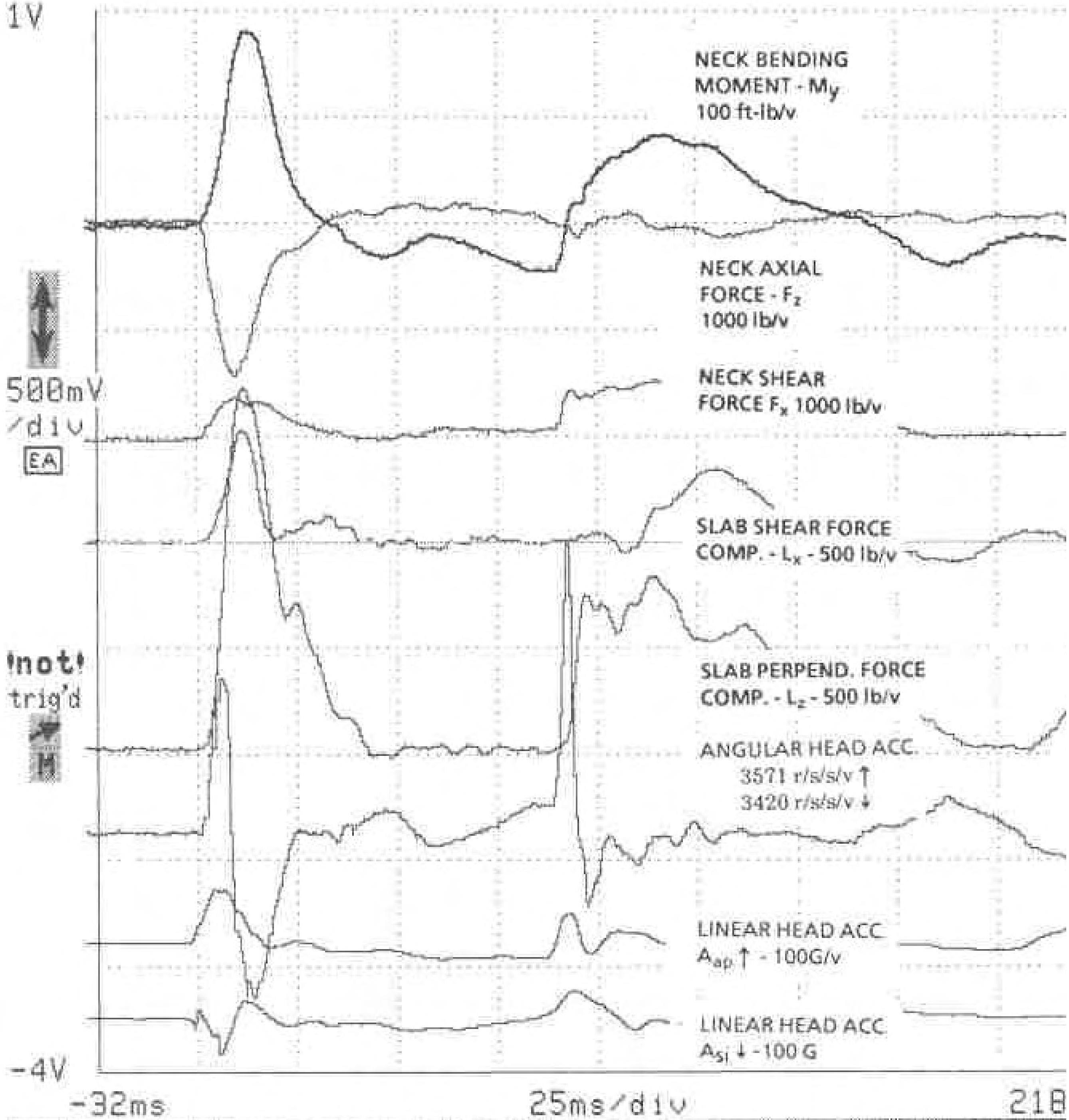

1V
NECK BENDING MOMENT - M_y 100 ft-lb/v
NECK AXIAL FORCE - F_z 1000 lb/v
NECK SHEAR FORCE F_x 1000 lb/v
500mV /div
EA
SLAB SHEAR FORCE COMP. - L_x - 500 lb/v
SLAB PERPEND. FORCE COMP. - L_z - 500 lb/v
!not! trig'd
M
ANGULAR HEAD ACC 3571 r/s/s/v ↑ 3420 r/s/s/v ↓
LINEAR HEAD ACC A_{ap} ↑ - 100G/v
LINEAR HEAD ACC A_{si} ↓ -100 GL
-4V
-32ms
25ms/div
218
Max
870.000 mV
Min
-135.000 mV
Peak-Peak
1.00500 V
Measure-ments
Horz Mag
2x
Horz Pos Gr
140pts
Rise
7.318 ms
Frequency
error
Width
14.09 ms
Compare & References
Remove Wfm 1
ST09
Pan Zoo
on

Figure c. Micro-shell helmet; 6.5 mph impact to smooth slab @ 45 degrees. Characterized by initial flexion (My) and Axial Force (Fz) followed by release and landing on face, causing abrupt flexural bending, which in turn causes higher than initial angular acceleration spike. Low linear acceleration (Aap, Asi)



Max	Min	Peak-Peak	Measure-ments	Horz Mag 2x	
975.000 mV	-225.000 mV	1.20000 V		Horz Pos Gr 140pts	
Rise	Frequency	Width	Compare & References	Remove Wfm 1	Pan Zoo
8.220 ms	error	13.91 ms		ST017	on

Figure d. Hard shell helmet; 6.5 mph impact to smooth slab @ 45 degrees. Almost identical to micro-shell helmet performance (see Figure c)



Max	Min	Peak-Peak	Measure-ments	Horz Mag	
				2x	
910.000 mV	-220.000 mV	1.13000 V		Horz Pos Gr	
				140pts	
Rise	Frequency	Width	Compare & References	Remove Wfm 1	Pan Zoo
7.178 ms	error	12.99 ms		ST025	on

Figure e. Micro-shell helmet with polycarbonate facemask; 6.5 mph impact to smooth slab @ 45 degrees. In comparison to Figure c, micro-shell w.o. guard, the principal difference is the lack of a high secondary angular acceleration which coincides with the abrupt change in flexural bending moment in Figure c, corresponding to when the face of the dummy hit the concrete on the first bounce after impact.

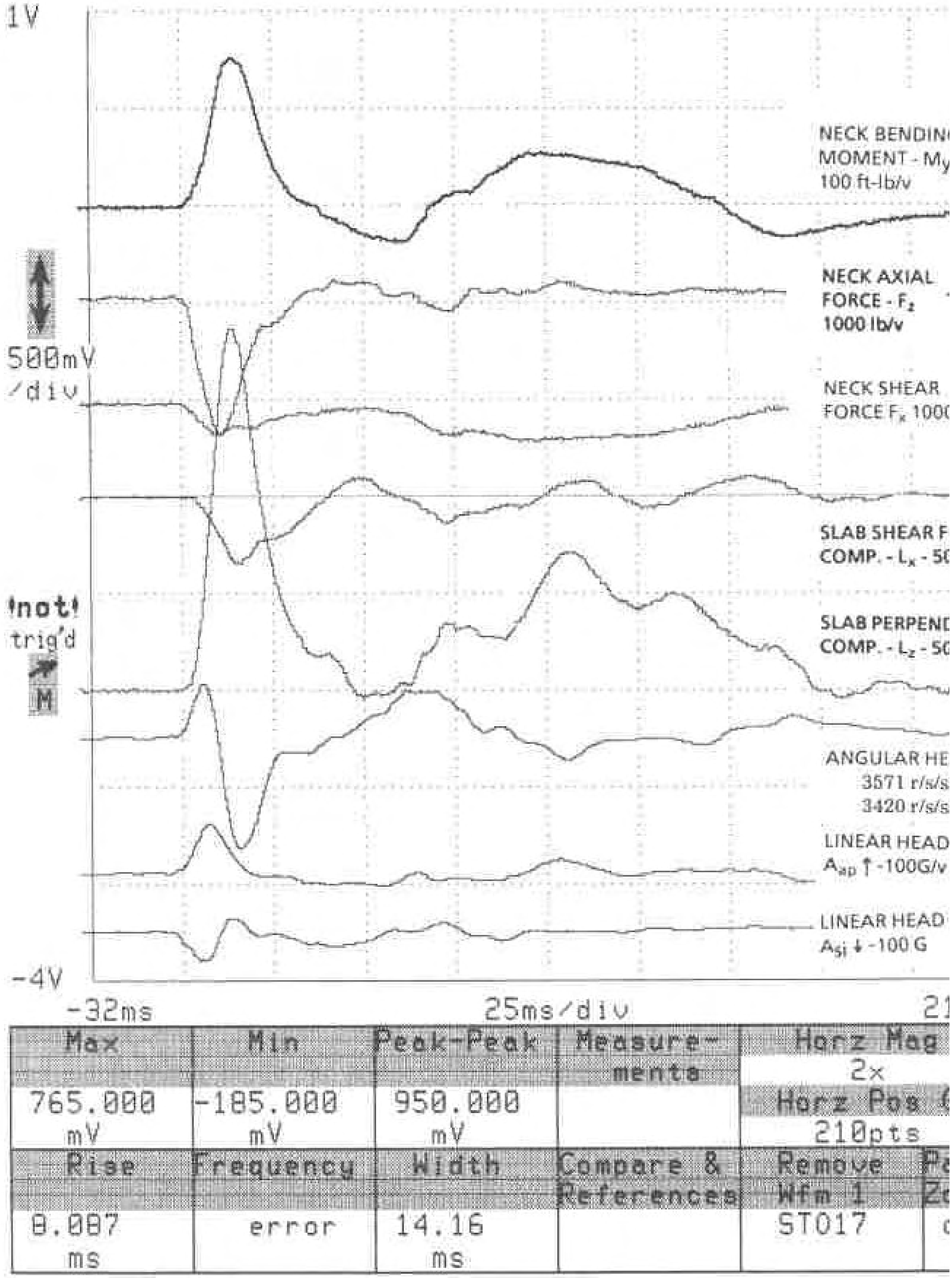
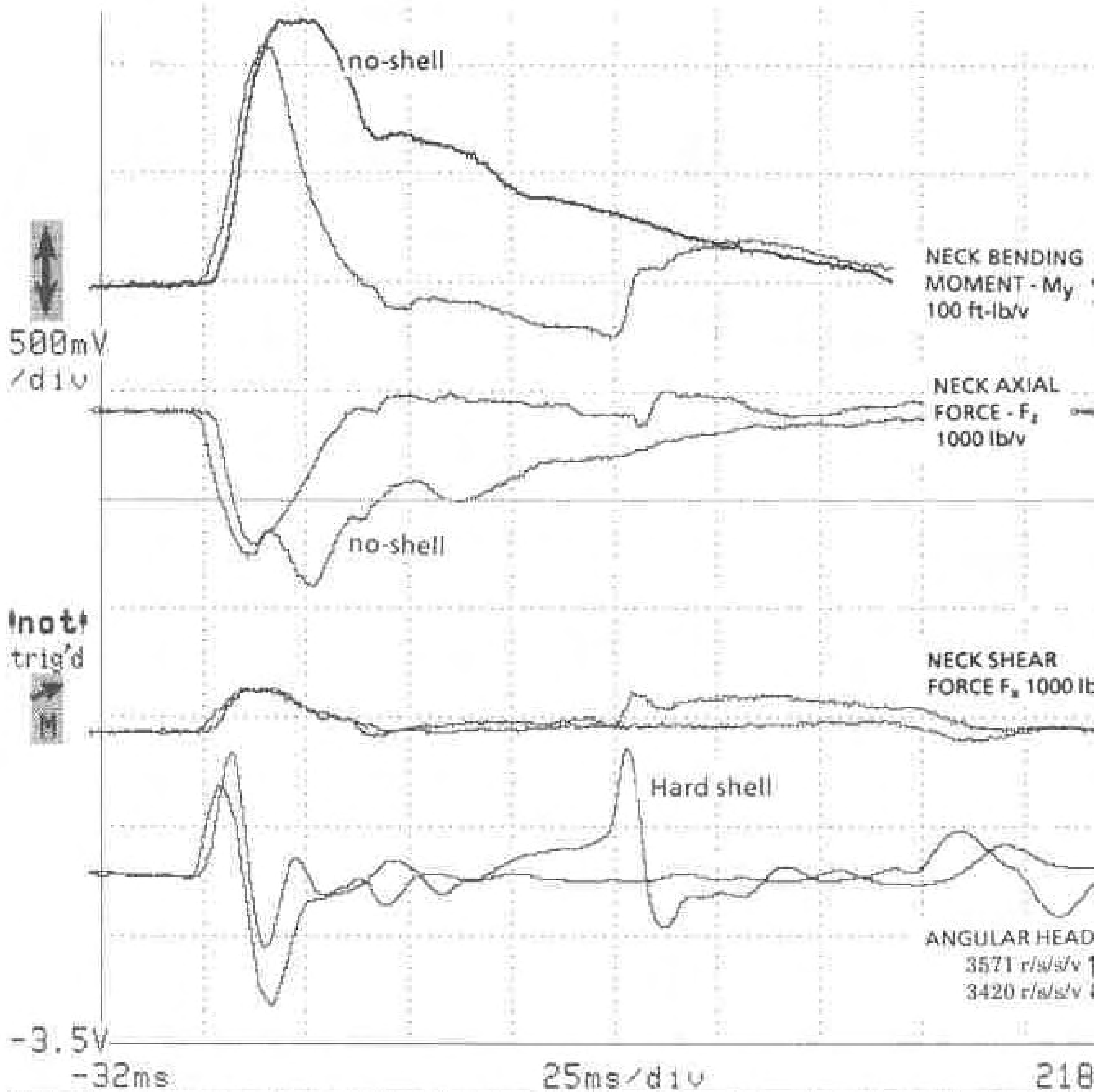
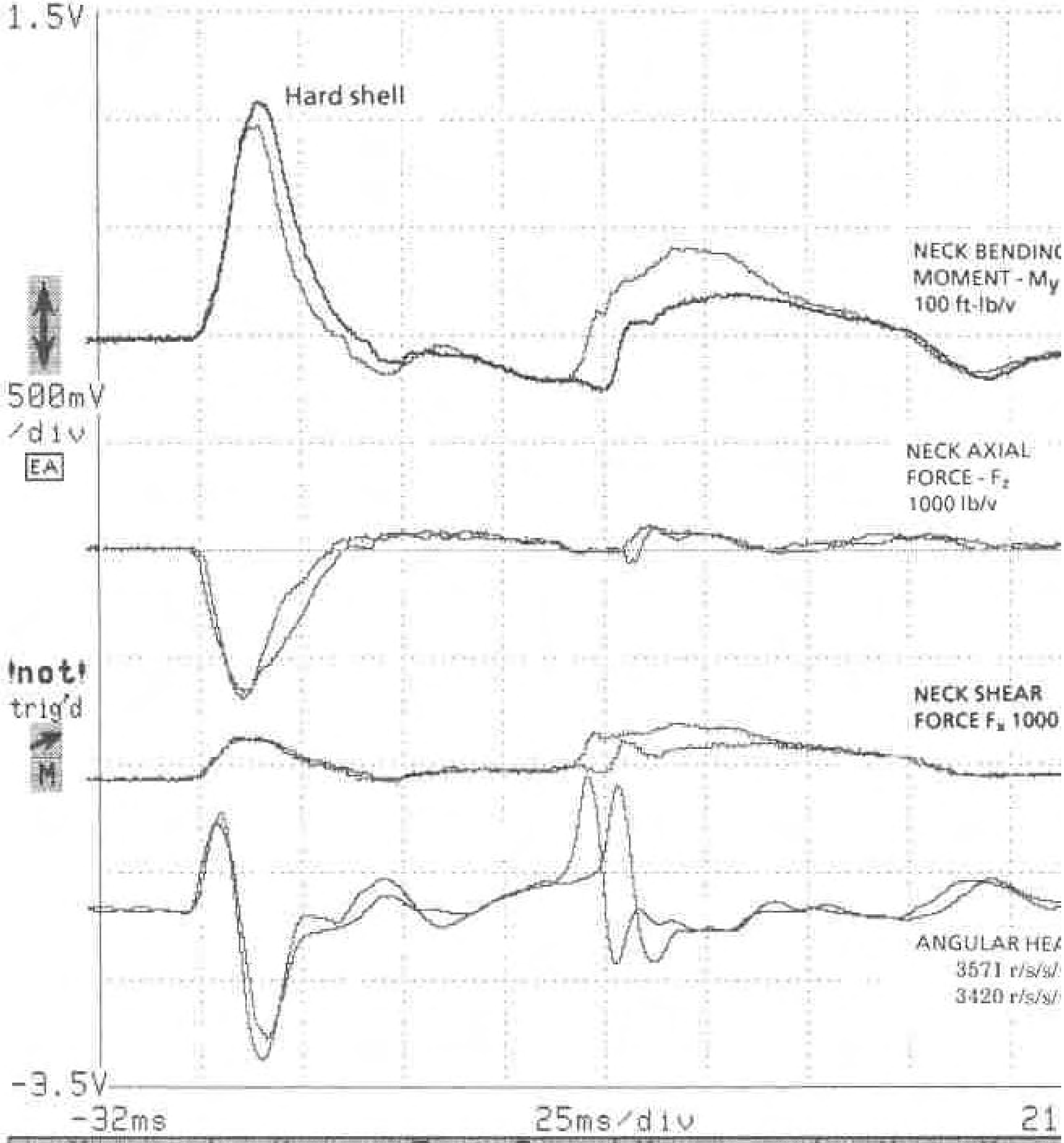

1V
NECK BENDIN
MOMENT - M_y
100 ft-lb/v
NECK AXIAL
FORCE - F_z
1000 lb/v
500mV
/div
NECK SHEAR
FORCE F_x 100
SLAB SHEAR F
COMP. - L_x - 5
'not'
trig'd
M
SLAB PERPEND
COMP. - L_z - 5
ANGULAR HE
3571 r/s/s
3420 r/s/s
LINEAR HEAD
A_{ap} ↑ -100G/v
LINEAR HEAD
A_{si} ↓ -100 G
-4V
-32ms
25ms/div
21
Max
Min
Peak-Peak
Measure-
ments
Horz Mag
2x
765.000
mV
-185.000
mV
950.000
mV
Horz Pos
210pts
Rise
Frequency
Width
Compare &
References
Remove
Wfm 1
8.087
ms
error
14.16
ms
ST017

Figure f. No-shell vs hard shell helmet; 6.5 mph impacts to smooth slab @ 45 degrees. The principal difference in the dummy head-neck transducer measurements shows up as a much more prolonged bending (My) and axial compression force (Fz) neck loading, when the no-shell helmet gripped the concrete and rebounded, whereas the hard shell helmet bounced off the concrete and landed on the face, causing a secondary angular head acceleration because of momentary gripping of the concrete by the face before skidding.



Max	Min	Peak-Peak	Measure-ments	Horz Mag	
1.21000 V	-180.000 mV	1.39000 V		2x / Horz Pos Gr / 140pts	
Rise	Frequency	Width	Compare & References	Remove Wfm 1	Pan Zoo
10.31 ms	error	54.79 ms		ST01	on

Figure g. Micro-shell vs hard shell helmet; 6.5 mph impacts to smooth slab @ 45 degrees. The instrumentation signatures of the two types of helmets were similar for smooth concrete impact cases, but with some variation for rough concrete impacts, which produced the least consistent results of the two surfaces.



Max	Min	Peak-Peak	Measure-ments	Horz Mag	
1.09000 V	-255.000 mV	1.34500 V		2x	
				Horz Pos G	
				140pts	
Rise	Frequency	Width	Compare & References	Remove Wfm 5	Pa Zo
10.07 ms	error	16.60 ms		ST049	o

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(end of study)

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