A PRACTICAL APPLICATION OF THE TRANSLATIONAL ENERGY CRITERIA: EVALUATION OF BASEBALL AND SOFTBALL HEAD IMPACT INJURY POTENTIALS

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ABSTRACT

The development of the Unified Head Injury Theory (UHIT) has been under way at The Ohio State University for the last eight years. The new criteria have two major parts. The first deals with translational (rigid impact) head injuries which include skull fracture and brain contusion. The second part deals with rotational (induced brain motion) head injuries which include diffuse axonal injuries (DAI) and bridging vein tears.

The first criteria of the UHIT is called the Translational Energy Criteria (TEC) and is the subject of this paper. The TEC can estimate the severity of brain contusion (Equivalent Abbreviated Injury Scale, EAIS) and the occurrence of skull fracture (Probability of Skull Fracture, POSF). The TEC is based on the response of the Translational Head Injury Model (THIM). The THIM is a collection of one-dimensional, three-degrees-of-freedom, semi-definite lumped parameter models; each model consists of two masses, two dampers, and a spring. The THIM is derived from mechanical impedance experiments conducted on human cadaver heads, and the TEC was validated for use with the Hybrid III head with accident reconstruction data.

A series of 13 softballs of various construction, one baseball, and two ball helmets were evaluated with the TEC, the Severity Index (SI), and the Head Injury Criterion (HIC) at three impact speeds. The softball impacts were to the side of the head, while the baseball impacts were to both the front and side of the head. The helmeted head impacts were only to the side of the head and only with softballs.

The evaluation of the softball tests indicated that an impact squarely over the temple at ball speeds of approximately 17.9, 26.9, and 35.8 meter per second will result in an average EAIS of 2.8 , 4.2, and 5.8 respectively. The baseball study, conducted at the University of Michigan, indicated that under the same impact conditions as the softball study a baseball head impact will result in a slightly lower EAIS value. The baseball study very graphically demonstrates that a direct head impact, as opposed to a glancing blow to the head, is a rare event. The helmet study showed that for the helmets tested, very little benefit was realized for direct head impacts above 26.9 meter per second. The HIC and the SI were unable to distinguish the hardness of the softball at all speeds. Also, the HIC and the SI failed to give a realistic or meaningful evaluation of the severity of the impacts, ie the HIC of 6,000 has no real world injury severity reference as well as the HIC of 3,000. The TEC was able to distinguish the hardness of all the softball, and to evaluate the impacts continuously in terms of the Abbreviated Injury Scale (AIS).

INTRODUCTION

Head injuries traditionally have been broken down into two major injury categories: translational (rigid impact) or rotational (induced brain motion). In reality, the vast majority of head injuries are generated from both translational and rotational inputs. The type and severity of head injuries depend, in general, on the absolute magnitudes of the translational and rotational inputs. The injuries most commonly associated with a translational input are skull fracture and cortical contusion (coup and contrecoup), while the injuries associated with rotational inputs are bridging vein tears and diffuse axonal injuries (DAI). The criteria which tie the translational and rotational type injuries into one theory have been developed at The Ohio State University. The Unified Head Injury Theory is now being used to evaluate or reevaluate many of the head injury studies being conducted at the present time. These studies involve A- and B-pillars head impacts, bicycle helmets, windshield head impacts, airbags, children's playgrounds, and more. Head impacts with small projectiles, such as softballs or baseballs constitute one area of study in which the rotational input is very small in relation to the translational input.

Even though serious head injuries in baseball or softball are rare (10 to 12 a year with no helmet), an experimental study was undertaken to evaluate various softballs, using the Translational Energy Criteria (TEC), Severity Index (SI), and the Head Injury Criterion (HIC) as head injury predictors. The softballs studied were divided into three groups: two were based on the ball core material (kapok or cork) and one involved reduced injury softballs. The softballs were fired from a cannon at three velocities, 17.9, 26.9, and 35.8 meter per second, at the side of the head and through the center of gravity of a Hybrid III dummy head mounted on a Euro-Sid neck.

Two commonly sold softball/baseball helmets were evaluated using the same experimental procedure as outlined for the softball tests. The helmet evaluations were carried out using a softball with a kapok center.

A baseball head impact study conducted at the University of Michigan Transportation Research Institute (UMTRI) in 1984 was reanalyzed using the TEC. In this Michigan study less control was used in firing the baseballs against the Hybrid III head. This loss of control resulted in random impacts to the front and side of the dummy's head. The impact velocity for these tests was approximately 36.5 meters per second.

This study of lightweight, high velocity projectile head impacts offers a good opportunity to examine the TEC, the SI, and the HIC under the conditions of small head rotations and to study these criteria under impact conditions different from those for which they were derived.

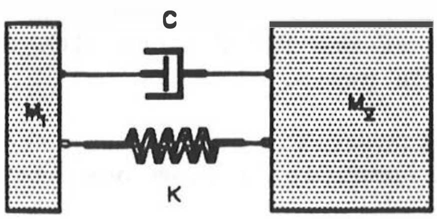
BACKGROUND

Mechanical lumped parameter models have been used frequently to predict head response under simulated impact conditions. In the early 1970's a number of these lumped parameter head injury models were developed. The first was developed by A. Slattenschek in 1979 [1] with the Vienna Institute Index (JIT), and was used to evaluate windshield head impacts. Next came the Effective Displacement Index (EDI) developed by J. Brinn in 1970 [2], which was basically a filter that allowed real time crash analysis of head injury potential.

Finally, the Revised Brain Model was prossed by W. Fan in 1971 [3]. This model and criteria separated head injuries into two parts: first, for short impact durations related to velocity, and secondly, for long impact durations related to deflection. Fan was one of the first to see the dependency of velocity and displacement in brain injuries. Each of these criteria, the SI in 1966 [4] and the HIC in 1971 [5], is all based on the Wayne State Tolerance Curve (WSTC) [6],[7],[8]. During this same period a one-dimensional, two degree-of-freedom lumped parameter model was introduced by R. Stalnaker [9],[10] to predict head impact responses.

This new model was composed of two masses connected by a spring and damper in parallel (Figure 1). The model parameters were determined by fitting the model driving point mechanical impedance response to the experimental driving point mechanical impedance response data obtained from cadaver tests conducted to the side of the head. A new head injury criterion, completely independent of the WSTC, was developed from the response of this new lumped parameter model. The Mean Strain Criterion (MSC) used model deflection divided by average head width as an injury predictor; for example, a mean strain of 0.0061 m/m was equivalent to the AIS of 3. However, the model response at the anti-resonance did not correlate well with the experimental response data.

The MSC lumped parameter model was modified in 1985 by R. Stalnaker [11]. This new model was the same as the old model but for a damper added in series with the spring (Figure 2). The addition of this damper resulted in the model response fitting the experimental data very well. In addition to the model upgrade, more impedance test data were added to the lateral or Left-Right (L-R) data base. More cadaver impedance tests were conducted in the Anterior-Posterior (A-P), Posterior-Anterior (P-A), and the Superior-Inferior (S-I) directions, and additional models were constructed. These directional head models were named the Translational Head Injury Model (THIM). The MSC, now renamed the New Mean Strain Criteria (NMSC) was upgraded using Strain and Strain Rate as the injury predictors. The NMSC was expanded to include injury predictions in five directions: L-R, R-L, A-P, P-A, and S-I. This was the first time a distinction was made between the NMSC (criteria) and the THIM Models.



M_1 (kg)	M_2 (kg)	C (N-sec/m)	K (N/m)
0.18	4.06	420.3	4553300

Figure 1: The Old MSC Model (Lateral)

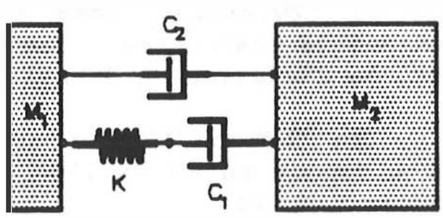


Figure 2: The New Translational Head Injury Model (THIM)

Although the NMSC correlated very well with the cadaver experimental data, a threshold value had to be placed on the strain rate so that strains would not accumulate for very low strain rates. Also, the scatter of the cadaver head injury data for impacts of different directions could lead to more than one injury predicting function, depending on how the curve fitting was accomplished. For these reasons in 1987 R. Stalnaker [12] introduced the Translational Energy Criteria (TEC). This new criteria utilized the THIM models and head impact test data obtained from subhuman primate studies carried out in the early 1970s [13]. All of these tests and the models were for the L-R direction. The impact data recorded were head injury information and the impact force. Because of the uniformity of test specimens, simplicity of the experimental procedure, and the large number of tests conducted, a complete parametric study could be made between the head injuries and the model response. The results of this study indicated:

1) The energy dissipated by the damper connecting the two masses best predicts brain injury.

2) The power stored in the spring best predicts skull fracture.

Before the TEC could be extended to human, the THIM had to be better defined. This was accomplished by V. Rojanavanich in three papers [14,15,16]. The first (1988) fixed all of the model constants through detailed parametric studies of the THIM Model, and the second (1989) studied the response of the TEC to variations of force and acceleration inputs. The third paper (1990) defined the model elements (mass, dampers, and spring) with respect to the head, (total head mass, skull stiffness, and brain damping). This paper also discussed the linear interpolation method used to generate THIM for any given head impact direction. With the THIM completely explained, the TEC for human and the Hybrid III may be defined.

The TEC for humans was determined by correlating the injury function obtained for the primates data to cadaver test data [17,18,19]. The injury data presented in these three publications were updated to 1985 AIS values in consultation with the original authors. This work is in preparation and will be published soon.

The TEC was formulated for use with the Hybrid III from accident reconstructions carried out by the National Highway Traffic Safety Administration (NHTSA) [20,21]. These reconstructions were of pedestrians and unbelted automobile passengers. The formulation of the TEC for use with the Hybrid III will be discussed in detail later in this paper.

The THIM and TEC for both humans and dummies have been completely documented in a report to NHTSA [22], and a TEC computer program has been written and documented [23].

At present, there is no widely accepted standard governing the use or evaluation of baseball/softball helmets. Different leagues have their own standards: professional baseball leagues require the use of helmets, professional softball leagues in general do not, and most high schools in the United State do require the use of helmets. The head injury criterion most often used to evaluate these helmets is the Gadd Severity Index (SI). As reported by V. Hodgson [24], the SI represents the probability of a serious head injury, that is, an SI of 1,500 indicates a 40% chance of a serious head injury. The severity of head injury is not known; it could be an AIS = 3, 4, 5, or 6. All of these AIS numbers are in the class of injuries referred to by the SI as "serious head injury."

Before the effectiveness of any helmet can be determined, the injury potential for the unhelmeted head must be obtained. Also, in the case of softballs more than one type of balls is being used due to the many different leagues of various skill levels. Therefore, the objectives of this study were to evaluate the maximum injury potential of three types of softballs and one type of baseballs. In addition, these results were used in the evaluation of two models of baseball/softball helmets. This study also evaluated the TEC in the real world accident conditions.

APPLICATION OF THE TEC TO HYBRID III

In 1986 a series of automobile occupant reconstructions were reported by R. Saul [21], and in 1988 a series of pedestrian reconstructions were reported by J. Kessler [20], both studies were conducted by NHTSA. When they were reviewed, 18 reconstructions were determined to be useful for relating the TEC to real life accident injuries. The criteria used to select the cases were:

1) The main injuries were to the head.

2) The head injuries were translational in nature.

3) The reconstruction was though to be good.

4) The entire accident file and reconstruction data were available.

The 18 cases chosen along with the injury information are summarized in Table 1.

The analogue tapes of the acceleration data from the accident reconstructions were obtained from NHTSA and were processed in the following manner:

1) The acceleration signal was filtered at Class 1000.

2) The acceleration signal was then filtered at Class 800.

3) The acceleration signal was then normalized with respect to the mass M2.

4) The acceleration signal was then zeroed.

The acceleration signal for reconstruction S39145 is shown in Figure 3, with the post processed signal shown in Figure 4. The processed acceleration signal A(t) is then used as the output acceleration of mass M2, and the input force F(t) on mass M1 necessary to generate the M2 acceleration is found. During this process the energy dissipated by damper C2 and the maximum power stored in spring K are recorded for each reconstruction.

Table 1: The Pedestrian/Occupant Reconstruction Cases

Test No.*	Case No.	Impact Direction	Highest 3-AIS	Skull Fracture
S10RRE-1	78-08-209	L-R	6,5,2	No
S39013-1	78-02-211	A-P	4,2.1	Yes
S39015-1	67-11-206	LR-AP**	5,5,1	Yes
S39056-1	79-08-219	L-R	5,1,1	No
S39090-1	82-03-201	L-R	2,1,0	No
S39109-1	19-05-220	A-P	1,1,0	No
S39135-1	87-08-215	P-A	2,1,0	No
S39145-1	81-08-206	LR-PA**	1,0,0	No
S73097-2	[redacted]-28-207	A-P	2,1,1	No
S73103-2	146-020484	A-P	3,3,2	No
S73108-2	133-111983	L-R	5,4,4	Yes
S86240-1	82-08-205	L-R	4,4,3	Yes
S86242-1	81-09-202	L-R	2,0,0	No
S86243-1	83-02-204	AP-SI**	1,0,0	No
S86245-1	81-08-207	A-P	2,1,1	No
S86252-1	83-02-201	L-R	4,2,0	No
S86254-1	82-07-202	AP-LR**	3,2,1	No
S101182-1	82-07-203	L-R	6,0,0	Yes

*1 = Data is from Kessler [20]
*2 = Data is from Saul [21]
** = Off-Axis Impact

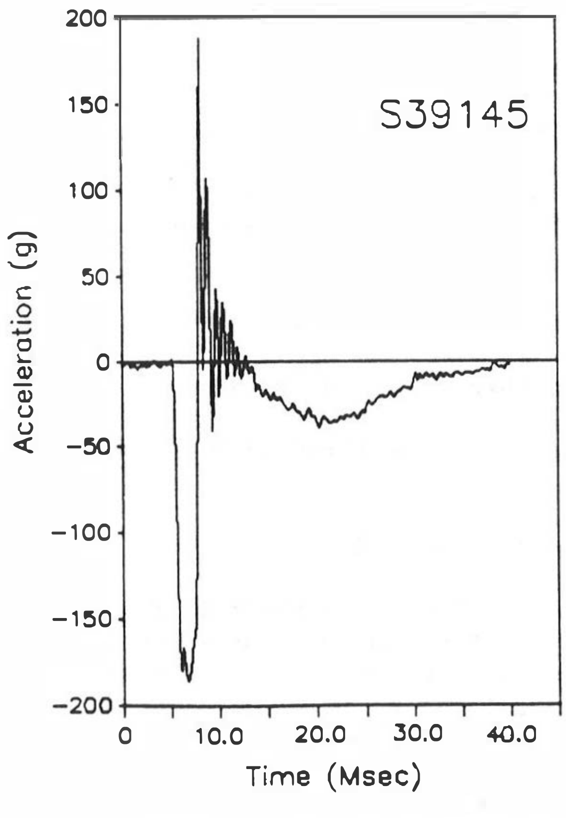


FIGURE 3: Dummy Head Acceleration

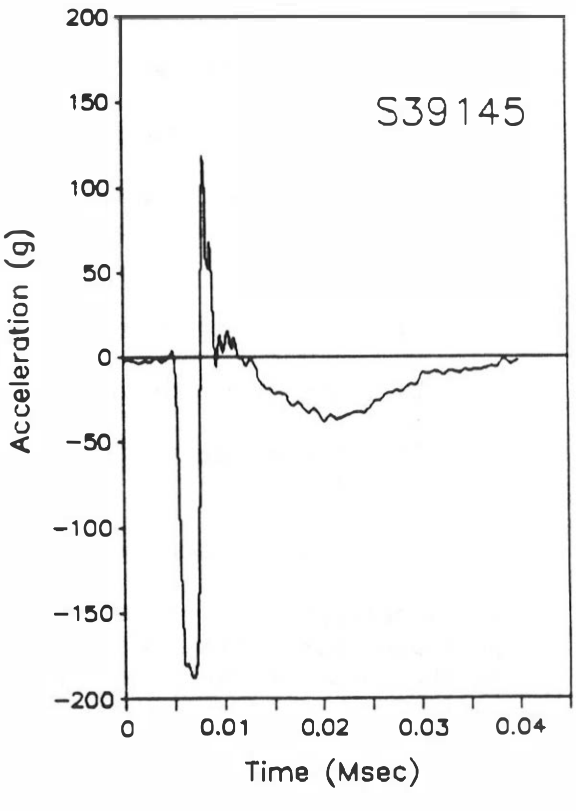


FIGURE 4: Model M2 Acceleration

M. Ulman (1986) reported a relationship between any three highest AIS injury numbers recorded for an accident victim and the probability of that victim dying [25]. Table 3 presents this 3-AIS and its relationship to the probability of death. A functional relationship between fractional AIS numbers and the Probability of Death (POD) was needed because the TEC function derived from the subhuman primate studies was in terms of AIS, not probability of death. This function was obtained by a linear regression fit (correlation coefficient of 0.992) using the method of least squares for the singular AIS codes, (1,0,0), (2,0,0), (3,0,0), (4,0,0), and (5,0,0), and the log of the corresponding probability of death numbers (Table 2). This function (Equation 1) is:

$$EAIS=1.85LOG_{10}(POD)+2.31$$

The fractional AIS numbers are redefined as Equivalent AIS, or EAIS. The EAIS = 0, and EAIS = 6 were, by definition, assigned probability of death values of 0% and 100% respectively. A graph of the function is shown in Figure 5.

The 3-AIS numbers for each accident victim listed in Table 1 were converted to EAIS numbers through Table 2 or Equation 1. The energy dissipated by damper C2 and the power stored in spring K were determined for each reconstructed accident. The results of the reconstruction are given in Table 3.

A linear regression fit using the method of least squares was carried out between the EAIS numbers and the energies dissipated by C2, found in Table 3. The function used for this regression analysis was of the same form obtained in the subhuman primate studies [13]. The results of the curve fit, shown in Figure 6, are given by Equation 2 (correlation coefficient of 0.973):

$$EAIS=4.14\sqrt{EC_2}$$

The skull fracture part of the TEC was determined by plotting the "No Skull Fractures" as a zero and the "Skull Fractures" as a one; then a normal probability distribution function was used to connect the no fractures to the fractures. The Skull Fracture Probability Function is given in Figure 7 for a Mean of 7,365 Watts and the Standard Deviation of 700 Watts.

The TEC for use with the Hybrid III dummy head is now defined by Equation 2 or Figure 7.

SOFTBALL STUDY

Method - The softball study consisted of 71 head impacts (37 low speed, 13 medium speed, 13 high speed, and 6 helmet cases) and was carried out in the Gurdjian-Lissner Biomechanics Lab at the Wayne State University, Detroit, Michigan. The test set-up consisted of a Hybrid III head mounted on a Euro-Sid neck. The neck was rigidly mounted to a seismic-mass with the right side of the head facing the National Operating Committee on Standards for Athletic Equipment (NOCSAE) Baseball Batter's Helmet air cannon. The head was instrumented with a tri-axial accelerometer at the center of gravity and an angular accelerometer mounted on the head back plate and aligned so as to measure the angular

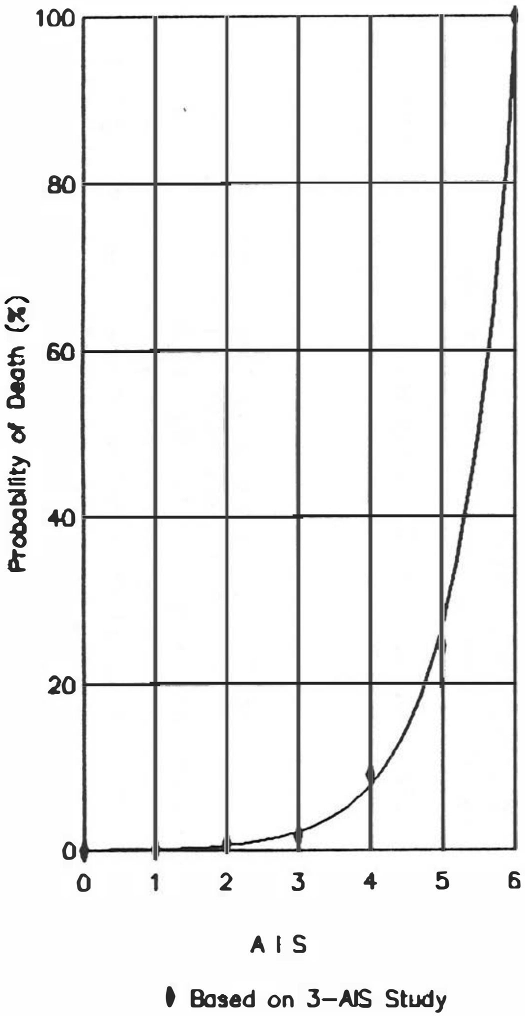


FIGURE 5: EQUIVALENT AIS FUNCTION

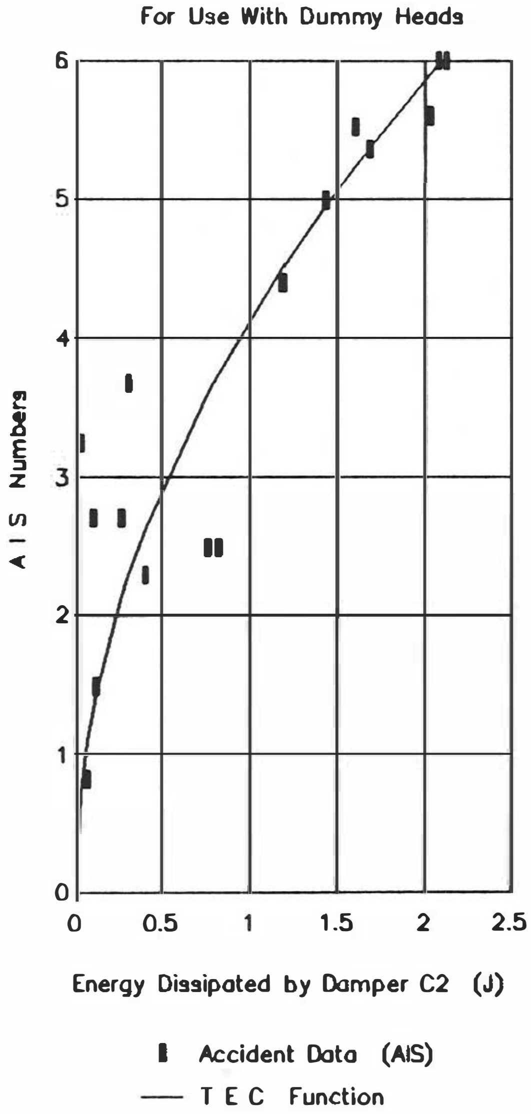


FIGURE 6: TRANSLATIONAL ENERGY CRITERIA: Brain Contusion

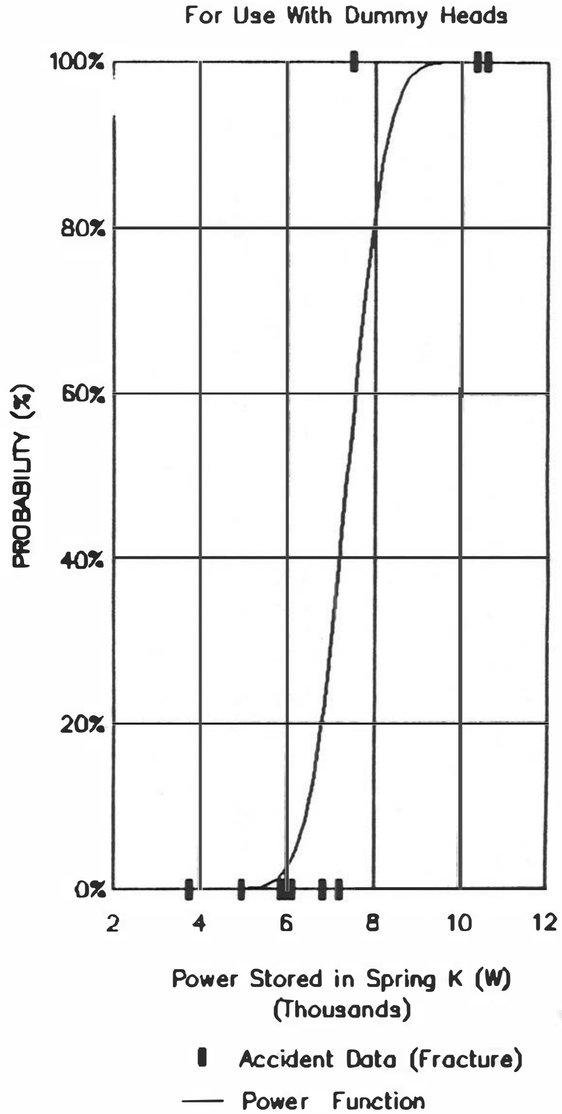


FIGURE 7: TRANSLATIONAL ENERGY CRITERIA: Skull Fracture

Table 2: 3-AIS Rankings and Mortality Rates Calculated from Logarithmic Regression

3-AIS Ranking	Mortality Rate (%)	3-AIS Ranking	Mortality Rate (%)
1 0 0	0.15	4 3 3	26.71
1 1 0	0.35	4 4 0	30.08
1 1 1	0.81	4 4 1	33.89
2 0 0	0.94	4 4 2	38.17
2 1 0	1.21	4 4 3	43.00
2 1 1	1.57	4 4 4	48.44
2 2 0	2.03	5 0 0	24.52
2 2 1	2.63	5 1 0	25.88
2 2 2	3.41	5 1 1	27.32
3 0 0	1.82	5 2 0	28.84
3 1 0	2.08	5 2 1	30.45
3 1 1	2.37	5 2 2	32.14
3 2 0	2.71	5 3 0	33.93
3 2 1	3.10	5 3 1	35.82
3 2 2	3.54	5 3 2	37.81
3 3 0	4.05	5 3 3	39.91
3 3 1	4.62	5 4 0	42.13
3 3 2	5.28	5 4 1	44.48
3 3 3	6.03	5 4 2	46.95
4 0 0	9.15	5 4 3	49.56
4 1 0	10.30	5 4 4	52.32
4 1 1	11.61	5 5 0	55.23
4 2 0	13.07	5 5 1	58.02
4 2 1	14.73	5 5 2	61.55
4 2 2	16.59	5 5 3	64.97
4 3 0	18.69	5 5 4	68.58
4 3 1	21.05	5 5 5	72.40
4 3 2	23.71	6 0 0	100.00

Table 3: The Results of the Pedestrian/Occupant Reconstructions

Test No.*	Probability of Death (%)	EC2 (J)	Fractional AIS	PK (W)	Skull Fracture
S10RRE-1	100.00%	2.080	6.00	5878	No
S39013-1	14.73%	0.211	4.50	4458	Yes
S39015-1	58.02%	2.029	5.60	22471	Yes
S39056-1	27.32%	1.433	5.00	7212	No
S39090-1	1.21%	0.763	2.49	6026	No
S39109-1	0.35%	0.120	1.50	1597	No
S39135-1	1.21%	0.821	2.49	4956	No
S39145-1	0.15%	1.906	0.82	10796	No
S73097-2	1.57%	0.266	2.70	3745	No
S73103-2	5.28%	0.306	3.68	6810	No
S73108-2	52.32%	1.600	5.52	10607	Yes
S86240-1	43.00%	1.684	5.36	10368	Yes
S86242-1	0.94%	0.405	2.29	854	No
S86243-1	0.15%	0.069	0.82	1258	No
S86245-1	1.57%	0.103	2.70	1050	No
S86252-1	13.07%	1.186	4.41	6107	No
S86254-1	3.10%	0.290	3.25	1440	No
S101182-1	100.00%	2.125	6.00	7517	Yes

*1 - Data is from Kessler [20]
*2 - Data is from Saul [21]

accelerations about the A-P axis. The point of impact was lined up approximately along the L-R axis. The X-, Y-, Z-linear acceleration, the X-angular acceleration, and the online Severity Index were recorded at the time of each impact.

The specifications for the 13 different softballs tested are given in Table 4. Each ball was tested at an average speed of 18.4 ± 0.4, 27.3 ± 0.3, and 36.4 ± 0.5 meters per second. Three head impacts per ball were carried out at 18.4 meter per second for each of the 13 ball types. Also, for ball types A, E, and H two different balls were tested.

TABLE 4: Softball Specifications

Label	Weight (gm)	Cover	Core	COR*
A	191.8	Synthetic	KAPOK	0.50
B	186.1	Leather	KAPOK	0.52
C	176.7	Synthetic	KAPOK	0.52
D	184.1	Synthetic	KAPOK	0.48
E	186.4	Leather	KAPOK	0.50
F	180.1	Leather	CORK	0.47
G	188.1	Leather	KAPOK	0.50
H	185.8	Leather	CORK	0.47
I	178.1	Leather	CORK	0.50
J	192.0	Synthetic	KAPOK	0.50
K	186.9	Synthetic	CORK	0.50
M	194.9	Leather	RIF	0.47
N	182.1	Leather	RIF	0.47

* = Coefficient of Restitution

Results - The results of the repeatability study based on peak acceleration showed that the tests were repeatable to within ± 2.5%. The results of the reproducibility study, again based on peak acceleration, were that softballs A, E, and H were each reproducible to within ± 5%. A typical resultant acceleration and the THIM response are shown in Figures 8 and 9. The summary of the results (the TEC, HIC, SI, angular acceleration, and probability of skull fracture) for each ball at each head impact speed is given in Table 5.

BASEBALL STUDY

Method - A study was conducted at The University of Michigan Transportation Research Institute (UMTRI) in 1984 for the Insurance Institute for Highway Safety. [26] In this study baseballs were propelled at the head of a Hybrid III dummy by a baseball pitching machine. Impacts were conducted to the front and side of the dummy's head at an average speed of 37.4 ± 0.9 and 37.6 ± 1.1 meter per second respectively. The dummy's head was instrumented with a tri-axial accelerometer package. Twenty-two head impacts were conducted, ten to the front and twelve to the side of the head. The TEC was determined by electronically hand digitizing the A-P, L-R, and S-I acceleration traces reported in the UMTRI report and processing the digitized data as reported above. The HICs were calculated from the digitized data and compared with the reported HICs as a check of the digitizing procedure.

TABLE 5: SUMMARY OF SOFTBALL PERFORMANCE

Label	Impact Speed (m/s)	EC2 (J)	EAIS*	PK (W)	Skull Fracture (%)	SI	HIC	Angular Acceleration (rad/sec/sec)
A	17.9	0.574	3.14	8593	96	265	153	601
A	26.9	1.159	4.46	19488	100	980	401	1804
A	35.8	2.350	6.00	38400	100	1403	885	8880
B	17.9	0.540	3.04	7908	78	298	146	688
B	26.9	1.103	4.35	17538	100	774	355	1338
B	35.8	2.007	5.87	33055	100	1198	737	5344
C	17.9	0.699	3.46	10480	100	383	188	735
C	26.9	1.471	5.02	23347	100	952	500	1870
C	35.8	2.634	6.00	42004	100	1350	1006	6513
D	17.9	0.557	3.09	8403	93	308	141	668
D	28.9	1.291	4.70	21233	100	881	405	1587
D	35.8	2.253	6.00	35793	100	1344	836	6513
E	17.9	0.479	2.87	7146	38	258	123	668
E	28.9	1.032	4.21	16154	100	738	335	1420
E	35.8	1.978	5.82	32020	100	1221	745	5010
F	17.9	0.394	2.60	5688	1	220	107	688
F	26.9	1.012	4.18	16021	100	709	327	1086
F	35.8	1.929	5.75	33444	100	1132	718	4509
G	17.9	0.550	3.07	8247	90	322	140	668
G	26.9	1.307	4.73	21584	100	906	416	1578
G	35.8	2.282	6.00	34775	100	1318	821	5344
H	17.9	0.394	2.80	5711	1	252	103	935
H	26.9	0.999	4.14	15724	100	693	318	1169
H	35.8	1.956	5.79	35710	100	1213	808	5177
I	17.9	0.383	2.56	5454	1	199	100	488
I	28.9	0.961	4.06	14094	100	825	308	1253
I	35.8	1.803	5.56	28779	100	1101	657	3006
J	17.9	0.517	2.98	7655	34	297	135	601
J	26.9	1.187	4.51	19001	100	894	397	1753
J	35.8	2.239	6.00	38574	100	1272	859	4843
K	17.9	0.379	2.55	5232	1	228	112	601
K	26.9	0.959	4.05	14201	100	683	331	1837
K	35.8	1.827	5.80	27497	100	1194	717	5177
M	17.9	0.214	1.92	2741	0	132	78	534
M	26.9	0.558	3.09	7445	46	417	218	1753
M	35.8	1.572	5.19	22085	100	1123	614	3507
N	17.9	0.322	2.35	4381	0	177	99	735
N	26.9	0.777	3.85	10780	100	508	272	1336
N	35.8	1.800	5.24	24024	100	990	833	3674

* - Equivalent AIS Number (Fractional Scale)

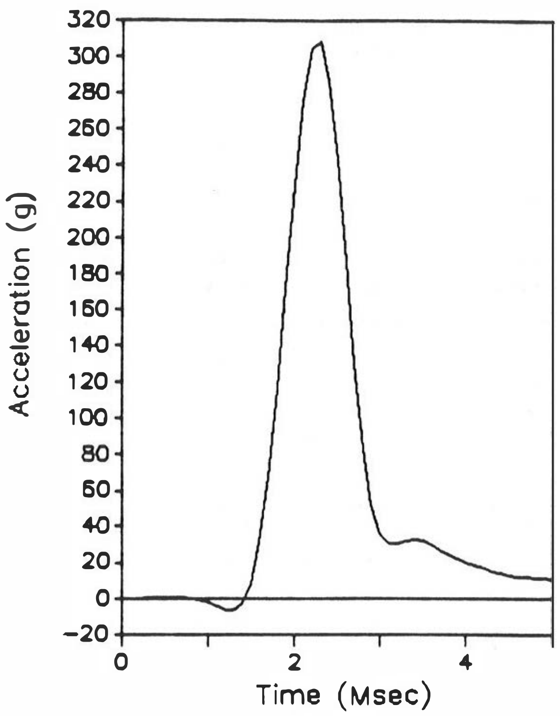


FIGURE 8: Resultant Acceleration
Ball A

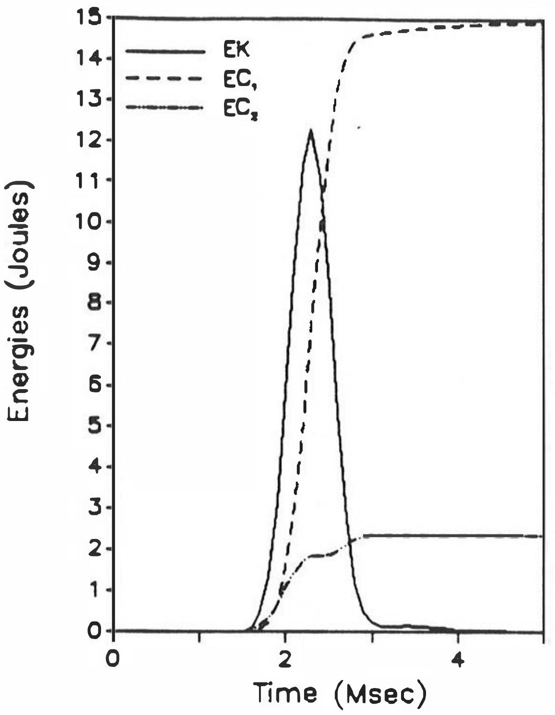


FIGURE 9: Spring and Damper Energies
Ball A

<u>Results</u> - The results of this study are illustrated in Table 6. There were no significant differences found between the digitized and reported HICs. Therefore, the HICs shown in Table 6 are the ones reported by UMTRI.

HELMET STUDY

<u>Method</u> - Six baseball/softball helmets were evaluated, three at 35.8 meters per second and three at 26.9 meters per second. They were of good quality and were purchased at a nationally known sporting goods store. The helmets were placed on the Hybrid III head and the tests conducted in the same manner as the softball evaluations. The same softball from the G group was used for all helmet impacts. A new helmet was used for each impact. All impacts were to the side of the head.

<u>Results</u> - Table 7 presents the results for the helmet study. The TEC, HIC, SI, angular acceleration, and probability of skull fracture are shown for each test, along with the average for each speed. The helmets were not damaged in any of the impacts.

DISCUSSION

<u>Softball Study</u> - The air cannon at Wayne State University offered good control and repeatability. The softballs used can be divided into three categories: long range, medium range, and short range. Each category is designed for the league in which the ball is used. Softballs A, B, C, D, E, G, and J are all in the long range category, while balls F, H, I, and K are medium range. Balls M and N are designed for use primarily by the handicapped or small

TABLE 6: RESULTS OF TEC AND HIC ANALYSES OF BASEBALL HEAD IMPACTS

Test No. (Frontal)	EC_2 (J)	EAIS[+]	PK (W)	% Skull Fracture	HIC
84BF23	0.374	3.05	12653	100	471
84BF24	1.057	4.31	33734	100	1659
84BF25	0.419	3.17	14330	100	553
84BF26	0.271	2.74	8806	98	336
84BF28	0.784	3.90	28055	100	1156
84BF29	0.468	3.28	15183	100	589
84BF30	0.347	2.97	11230	100	391
84BF31	0.751	3.84	22299	100	896
84BF32	0.915	4.11	30560	100	1341
84BF33	0.698	3.75	22334	100	927
Average A-P	0.608	3.51	19918		832
Stand. Dev.	0.268	0.54	8738		443
Test No. (Lateral)	**EC_2 (J)**	**EAIS[+]**	**PK (W)**	**% Skull Fracture**	**HIC**
84BS34	1.234	4.54	19678	100	320
84BS35	2.879	6.00	47384	100	962
84BS36	0.912	4.10	15357	100	297
84BS37	1.838	5.18	29166	100	587
84BS40	2.687	5.88	43771	100	922
84BS41	0.167[*]	2.33	3361	0	422
84BS42	1.933	5.27	30972	100	654
84BS43	1.392	4.72	22943	100	434
84BS44	0.629	3.62	10206	100	169
84BS45	2.273	5.56	36581	100	755
84BS46	2.293	5.58	37156	100	755
84BS47	1.089	4.35	18080	100	328
Average L-R	1.611	4.76	26221		550
Stand. Dev.	0.843	1.06	13588		249

* - Original Test Signals indicate larger A-P component
\+ - Equivalent AIS Number (Fractional Scale)
Average Frontal Impact Speed is 37.4 $\pm$ 0.9 m/sec
Average Lateral Impact Speed is 37.6 $\pm$ 1.1 m/sec

TABLE 7: SUMMARY OF HELMET IMPACTS WITH SOFTBALL "G"

Label	Impact Speed (m/s)	EC2 (J)	EAIS*	PK (W)	Skull Fracture (%)	SI	HIC	Angular Acceleration (rad/sec/sec)
HA1	35.8	1.864	5.65	27103	100	931	616	2004
HA2	35.8	1.808	5.57	26594	100	894	585	1670
HA3	35.8	1.993	5.84	29539	100	-	610	1670
Average	35.8	1.888	5.69	27745	100	913	604	1781
HC1	26.9	0.995	4.13	13476	100	489	340	534
HC2	26.9	1.010	4.16	13665	100	504	324	631
HC3	26.9	0.989	4.12	12937	100	482	331	498
Average	26.9	0.998	4.14	13359	100	491	332	554

children. The range of the ball, in some complex way, is related to the hardness of the ball. A meaningful head injury criterion should be able to sort out the hardness of each softball. The TEC, SI, and HIC for each impact speed have been sorted in terms of injury potential, from the highest to the lowest. The results of this sorting are shown in Table 8, where ranking goes from one to thirteen. If indeed the long range balls A, B, C, D, E, G, and J, are the hardest, then they should be found in the first seven rows of the table. Likewise, the medium range balls should be in the next four rows. Finally, the short range balls should be in the last two rows. The TEC and SI placed every ball in the appropriate category, while the HIC was wrong ten times. Bar graphs showing the injury ranking for the TEC, HIC, and SI are given in Figures 10, 11, and 12, respectively.

TABLE 8: COMPARISON OF TEC, HIC AND SI ANALYSES

	17.9 m/sec			26.8 m/sec			35.8 m/sec		
Rank	TEC	SI	HIC	TEC	SI	HIC	TEC	SI	HIC
1	C	C	C	C	A	C	C	A	C
2	A	G	A	G	C	G	A	C	A
3	D	D	B	D	G	D	G	D	J
4	G	B	D	J	J	A	D	G	D
5	B	J	G	A	D	J	J	J	G
6	J	A	J	B	B	B	B	E	H
7	E	E	E	E	E	E	E	H	E
8	F	H	K	F	F	K	H	B	B
9	H	K	F	H	H	F	F	K	F
10	I	F	H	I	K	H	K	F	K
11	K	I	I	K	I	I	I	M	I
12	N	N	N	N	N	N	N	I	N
13	M	M	M	M	M	M	M	N	M

[Ruled lines are printed below rank 7 and below rank 11.]

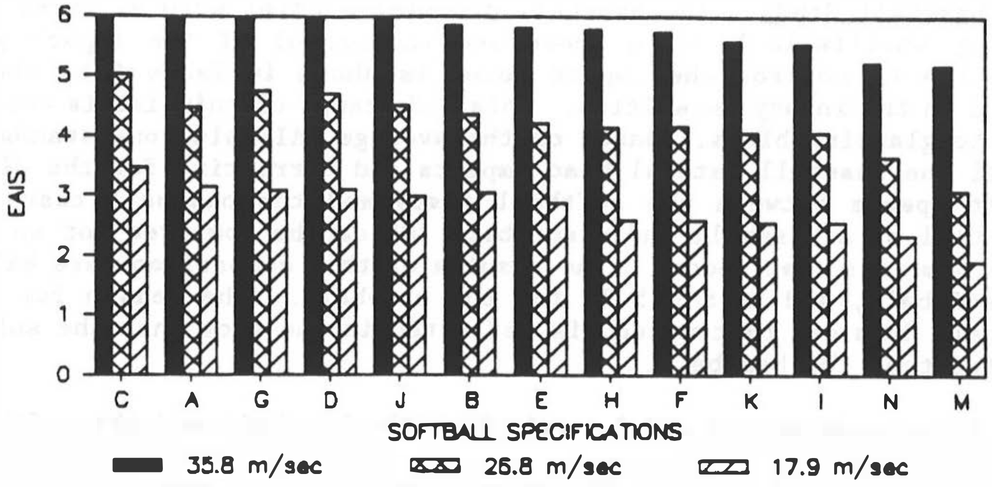


FIGURE 10: Results of TEC Analysis for Softball Head Impact

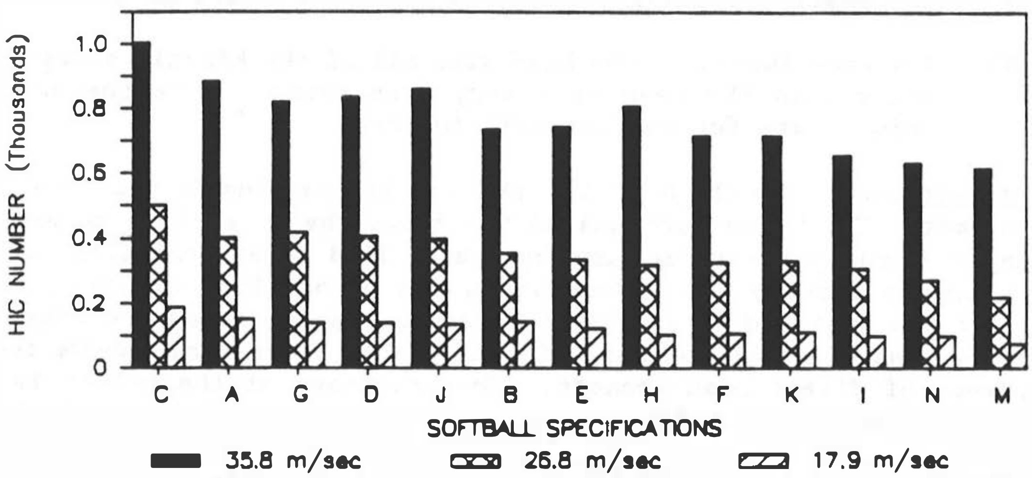


FIGURE 11: Results of HIC Analysis for Softball Head Impact

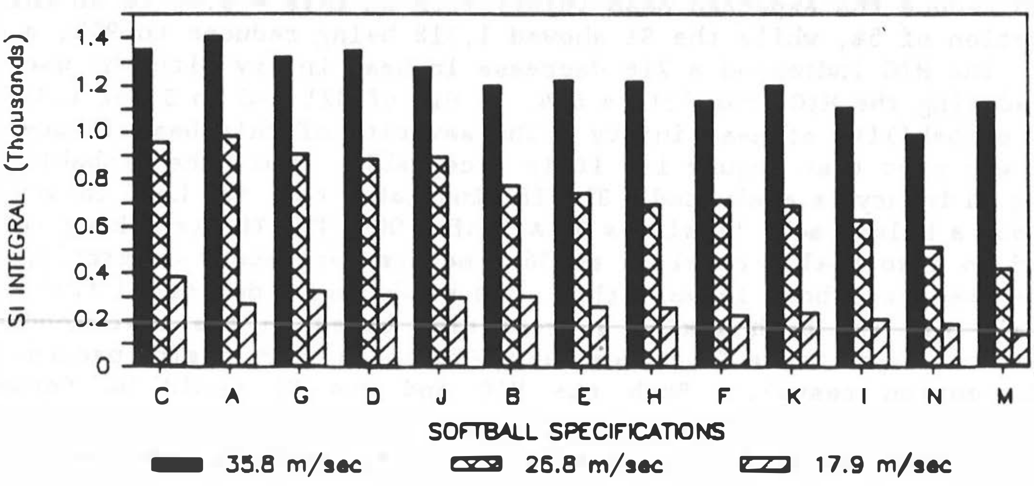


FIGURE 12: Results of SI Analysis for Softball Head Impact

Baseball Study - The baseball pitching machine used at UMTRI was found to be very unreliable both in speed and in control of the impact point. This inability to control the impact point is shown in Table 6 by the very large spread in the injury severities. This wide range of injuries is due for the most part to glancing blows. Based on the average EAIS plus one standard deviation of all the baseball lateral head impacts and correcting for the differences in impact speeds between the softball tests and the baseball tests, the injury potential of a baseball and a softball "G" can be compared for an impact speed of 36.4 meters per second. The results of this comparison were EAIS = 6.00 for the softball, and EAIS = 5.24 for the baseball. The reason for this, if the baseball data can be trusted, is reflected in the fact that the softball is 25% heavier than the baseball.

Three main points can be made from the baseball and the softball studies:

1) In these studies the impacts are squarely over the temple, with all the impact energies going directly into the head.

2) In general, the softball is not thrown as fast as the baseball.

3) A direct impact to the head with all of the kinetic energy of the ball going into the head is a very rare event. Note the scatter of the injury data for the baseball impacts.

Helmet study - In the helmet study very little benefit was seen from the use of a helmet. The helmet attenuated the impact by 5% at 36.4 meters per second (making the injury treatable) and by 12% at 27.3 meters per second. At the two impact speeds studied, no reduction in the probability of skull fracture was seen. At the 36.4 and 27.3 meters per second impact speeds, the helmet padding of 1.5 cm. was bottomed out early in the event. This again shows the very rare occurrence of direct head impacts. The advantage of the helmet is not in its ability to attenuate the impact but in its ability to deflect the ball.

The TEC - The TEC is the first head injury criteria to give an insight into the full range of head injury severities in all directions from rigid impacts. Using the TEC to evaluate the baseball/softball helmets showed that the helmet would reduce the expected head injury from an EAIS = 6.00 to an EAIS = 5.69, a reduction of 5%, while the SI showed 1,318 being reduced to 913, a decrease of 31%. The HIC indicated a 21% decrease in head injury with the use of a helmet by reducing the HIC from 821 to 604. A HIC of 821 and an SI of 1,318 both imply some probability of head injury. The severity of this head injury is unknown, but, whatever that injury is, it is acceptable. Only the probability of there being an injury is evaluated. The TEC indicated that the head injury in question without a helmet most likely is an AIS of 6.00. The TEC is making its prediction based on a softball traveling at 36.4 meters per second contacting the temple, where the skull bone is very thin, and producing a depressed fracture. The SI and the HIC are both making a prediction based on the test conditions which formed the Wayne State Tolerance Curve (forehead; A-P; rigid, padded, and induced brain motion tests). Both the HIC and the SI would be formulated much differently if only the rigid impact part of the WSTC were used. The TEC for use with the Hybrid III in any direction is now ready for general use for impact resulting in translational types of injuries.

CONCLUSIONS

1) The Translational Energy Criteria for use with the Hybrid III is completed.

2) The Translational Energy Criteria was found to be more useful than the HIC or the SI in evaluating the softballs, the baseball, and the helmets.

3) A softball head impact was found to be slightly more severe than a baseball impact at the same speed.

4) A softball or a baseball direct head impact can result in a serious head injury at impact speeds over 17.9 meters per second.

5) A baseball/softball helmet offers little benefit for impacts over 26.9 meters per second.

6) The HIC indicated that all but four impacts were acceptable, and the SI indicated that all impacts were acceptable.

7) Severe head injuries from baseball and softball impacts are rare but do occur. The use of a helmet can reduce this occurrence by deflecting the ball more easily.

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