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Final Report

Analysis of Hybrid III Lower Leg Instrumentation and An Associated Injury Criterion

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16. Abstract

This report describes a series of static and dynamic tests which were conducted on the Hybrid III lower leg instrumentation. The tests were conducted to determine the accuracy of the lower leg instrumentation measurements, the ability to calculate a maximum bending moment, and the feasibility of conducting a single impact lower leg calibration.

An analysis of the bending moment distribution in the lower leg for several different load conditions showed that a proposed maximum calculated bending moment equation did not accurately predict the maximum bending moment for loadings possible in automotive crash environments. Lower leg measurements of Y-moments and X-shears were found to be accurate and repeatable for the static conditions. Measurements by the knee clevis force transducers, however, were neither accurate nor repeatable. The accuracy of Z-force and X-moment measurements was not assessed in this testing, however, neither exhibited intolerable sensitivity to cross axis loads. The feasibility of a dynamic lower leg calibration procedure was demonstrated, although response corridors were not established.

The Hybrid III instrumented lower leg is shown to be effective in the measurement of X-shear at the ankle and Y-moments both in the ankle and upper tibia, although a method to determine maximum bending moment does not currently exist.

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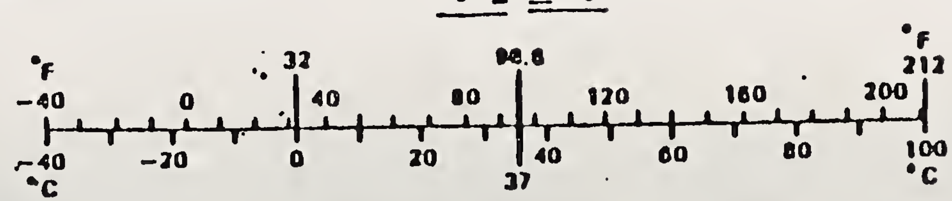
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	metric ton	t
		VOLUME		
tsp	teaspoons	5	milliliters	mL
Tbsp	tablespoons	15	milliliters	mL
in^3	cubic inches	16	milliliters	mL
fl oz	fluid ounces	30	milliliters	mL
c	cups	0.24	liters	L
pt	pints	0.47	liters	L
qt	quarts	0.95	liters	L
gal	gallons	3.8	liters	L
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	5/9 (after subtracting 32)	degrees Celsius	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10 000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	metric ton (1000 kg)	1.1	short tons	
		VOLUME		
mL	milliliters	0.03	fluid ounces	fl oz
mL	milliliters	0.06	cubic inches	in^3
L	liters	2.1	pints	pt
L	liters	1.06	quarts	qt
L	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5 (then add 32)	degrees Fahrenheit	°F



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Department of Transportation
National Highway Traffic Safety Administration

TECHNICAL SUMMARY

Report Title: Analysis of Hybrid III Lower Leg Instrumentation and Associated Injury Criteria	Date: April 1992
Report Author(s): Saul, Roger A. and Zuby, David S.	

NHTSA Docket Number 74-14; Notice 39 proposed using the Hybrid III dummy and a number of new injury criteria for testing done in accordance with MVSS 208. The new injury criteria included requirements for measurements made by lower leg instrumentation. When the final rule (Notice 45) was issued, the lower leg injury criteria were not included, but the rule did announce that a Supplemental Notice of Proposed Rulemaking would be issued to include requirements for those Hybrid III measurements.

The proposed lower leg injury criterion published in Notice 39 was based on a combined moment/compression load ratio. Subsequent to issuing Notice 45, a maximum calculated bending moment criterion was developed which was thought to have a stronger biomechanical basis. Some concerns had been expressed, however, that the criterion was over-simplified and that the assumptions from which it was derived were too specific to be applicable to all possible load configurations.

The approach taken in the project was to first analytically evaluate the proposed maximum calculated bending moment criterion. Following this, the Hybrid III lower leg was subjected to both static and dynamic tests. The static tests were conducted to ensure that the lower leg instrumentation measured loads accurately, to compare the calculated maximum moment with the actual maximum, and to explore alternative criteria. The dynamic tests were conducted to evaluate the feasibility of conducting a single impact lower leg calibration test.

The analysis of the bending moment distribution in the lower leg for several different load conditions showed that the proposed maximum calculated bending moment equation did not accurately predict the maximum bending moment for loadings possible in automotive crash environments. Also, the current configuration of the Hybrid III lower leg instrumentation does not allow the accurate determination of an unknown bending moment distribution and therefore, a prediction of the maximum moment.

Lower leg measurements of Y-moments and X-shears were accurate and repeatable for quasi-static conditions. Measurements by the knee clevis force transducers were neither accurate nor repeatable. It appears that these force transducers are susceptible to large errors when the applied load is not strictly along their sensitive axes. For this reason, measurements from the knee clevis sensors would be of little value in the crash test environment. The accuracy of Z-force and X-moment measurements was not assessed in this testing. However, neither the Z-force sensor nor the X-moment sensor exhibited intolerable sensitivity to cross axis loads.

The feasibility of a dynamic lower leg calibration procedure was demonstrated. Response corridors were not established, however.

The Hybrid III instrumented lower leg appears to be an effective tool for the measurement of X-shear forces at the ankle and Y-moments both in the ankle and upper tibia. Currently, however, a method to assess lower leg fracture injuries based upon a maximum calculated bending moment from these measurements does not exist.

1.0 INTRODUCTION

NHTSA Docket Number 74-14; Notice 39 proposed using the Hybrid III dummy and a number of new injury criteria for testing done in accordance with MVSS 208. The new injury criteria included requirements for measurements made by the lower leg instrumentation. When the final rule (Notice 45) was issued, the lower leg injury criteria were not included, but the rule did announce that a Supplemental Notice of Proposed Rulemaking would be issued to include requirements for those Hybrid III measurements.

The proposed lower leg injury criterion published in Notice 39 which was based on a combined moment/compression load ratio [1][1] is shown below:

$$M/M_c + P/P_c \leq 1$$

where	M	:	measured bending moment
	M_c	:	critical bending moment
	P	:	measured axial load
	P_c	:	critical axial load

An analysis of this criterion found that the expression might not be of the proper form. The expression implies that moment and axial compression are additive in propagating tibia fracture. However, since the failure mechanism for tibia bending is presumed to be tensile, it was concluded that axial compression coexisting with moment should inhibit fractures. A "maximum calculated bending moment" criterion was proposed as an alternative to the Notice 39 criterion, because it was believed to have a stronger biomechanical basis [2]. More recently, however, the alternative criterion was criticized because the expression used to define the

[1]Numbers in brackets represent references at the end of this report.

maximum bending moment may have been over-simplified and that the assumptions on which it was based were too specific to be applicable to all possible load configurations.

This project was initiated to evaluate the Hybrid III leg instrumentation and "maximum calculated bending moment" injury criterion. This report describes the effort and presents the results of the work.

2.0 APPROACH

The proposed "maximum calculated bending moment" criterion was evaluated using the principles of engineering mechanics for statically determinate structures [3,4,5]. Additionally, the Hybrid III lower leg was subjected to both static and dynamic tests. It had been assumed that the lower leg instrumentation was capable of accurately measuring the forces and moments at the sensor locations. When the results of a first quasi-static test series suggested that measurements from four instrumented lower legs were inaccurate and inconsistent, additional tests were conducted in an attempt to obtain more accurate lower leg measurements. This test series incorporated test fixture and test procedure improvements and investigated the effects of several lower leg geometry and design features on the accuracy of measurements. It was ultimately discovered that the accuracy of lower leg measurements of quasi-static loads was extremely sensitive to the rigidity of the test fixture's base. Once a test set-up was designed that produced measurements which appeared to be accurate, tests were conducted to assess the repeatability and reproducibility of the measurements made by the lower leg under both static and dynamic conditions. The dynamic tests were also used to assess the feasibility of a dynamic calibration procedure for lower leg response.

Sign Convention

Prior to initiating evaluations of the "maximum calculated bending moment" criterion and the Hybrid III lower leg instrumentation, it was necessary to choose a lower leg sign convention. The measurements from the lower leg instrumentation are numerous and easily misinterpreted, since there had not been a standardization of sign convention or wiring configuration. Although the Denton drawing package specifies a wiring configuration for the lower leg, those at VRTC were not consistent. Prior to conducting testing all lower leg assemblies at VRTC were corrected to agree with the Denton specification [6].

The sign convention was chosen to agree with that used to derive the calculated maximum moment equation. This convention assumes that if the tibia is bent concave toward the anterior, moments of the same sign (positive) are acting at both the upper and lower sensors (Figure 1). Note that the coordinate sign convention which coincides with this protocol is positive x-axis forward, positive y-axis to the left, and positive z-axis downward. The convention for shear and bending moment at a given point of a beam is taken from statics, and is said to be positive when internal forces and couples acting on each portion of the beam are directed as shown in Figure 2 [5,7,8]. The free-body diagram of Figure 2 represents the loading conditions shown in Figure 1. This is the sign convention adopted for this investigation.

3.0 ANALYSIS OF THE "MAXIMUM CALCULATED BENDING MOMENT" CRITERION

Prior to conducting static testing with the lower leg instrumentation, an analysis of the "maximum calculated bending moment" criterion's applicability was conducted. The "maximum calculated bending moment" criterion specified that the maximum bending moment in the lower leg should be calculated with the following equation:

$$M = \frac{M_{uy} * M_{ly} * d}{(C * M_u + a * M_l)}$$

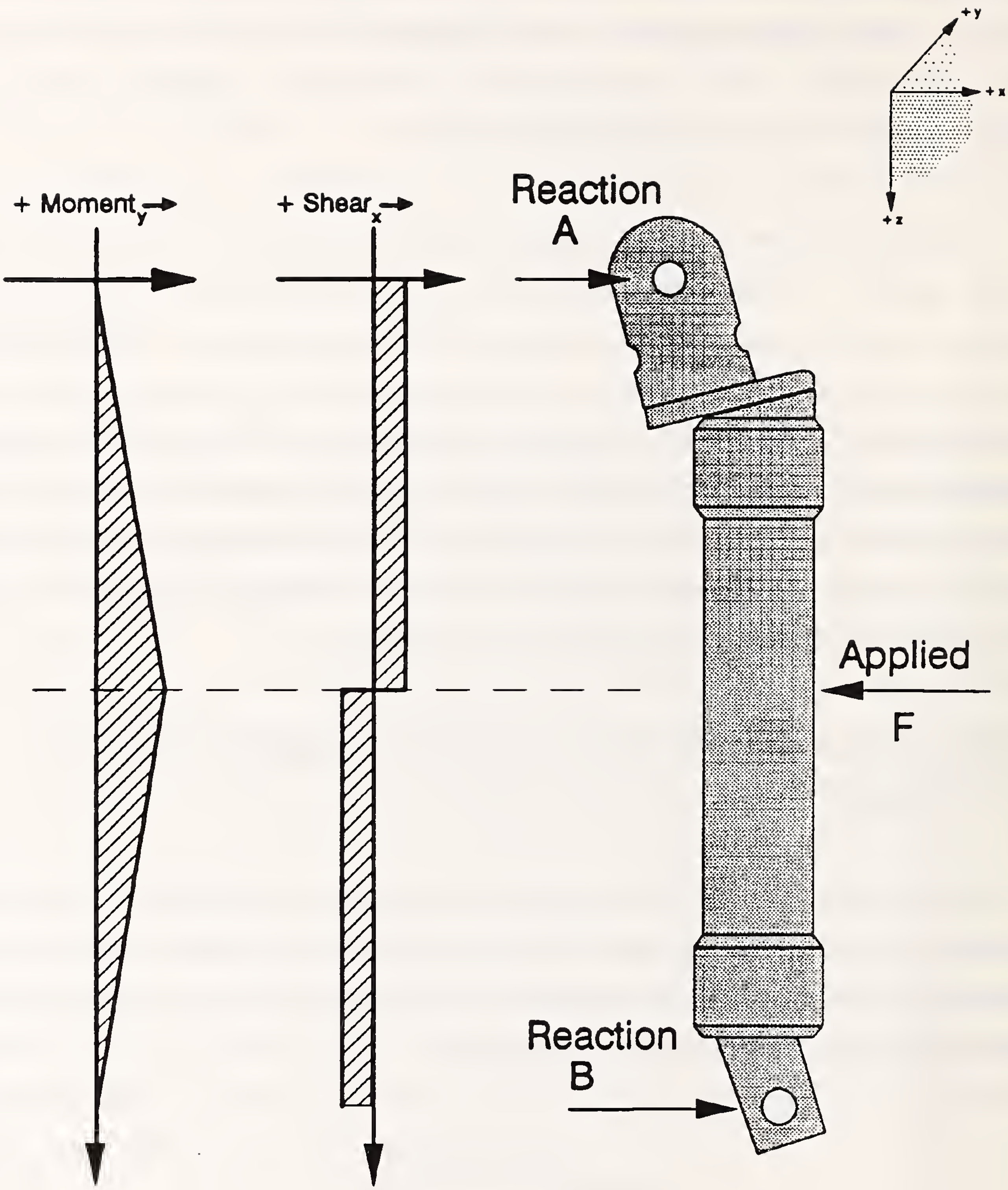


FIGURE 1 -- Sign Convention for Internal Shear and Bending Moments in the Lower Leg

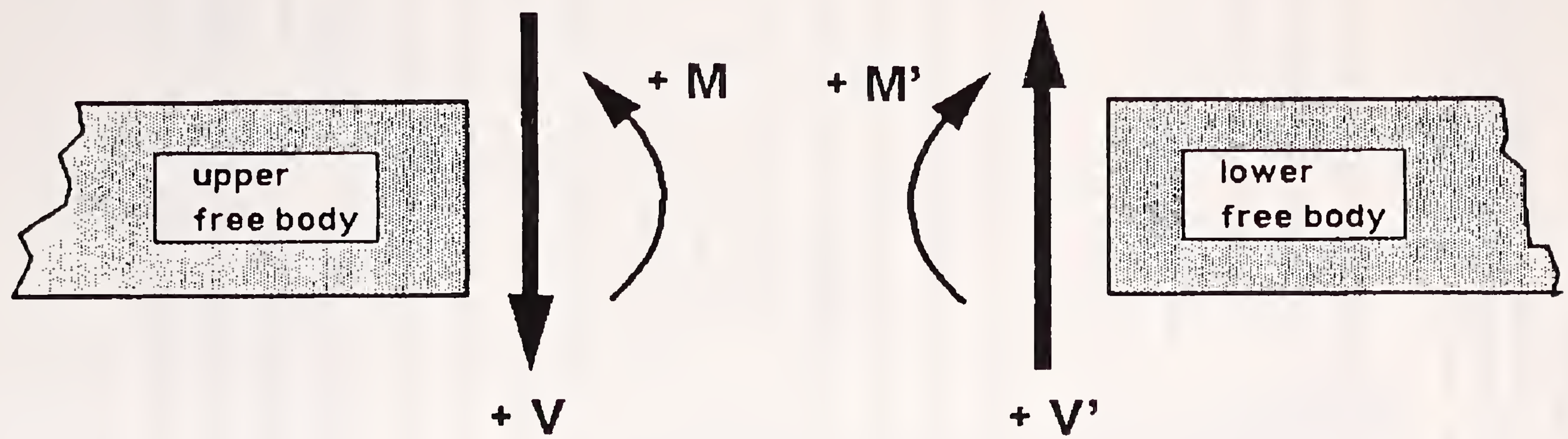


FIGURE 2 -- Definition of Positive Internal Shear and Bending Moments

where,

M_{uy} is the upper tibia moment measurement (Figure 3),
M_{ly} is the lower tibia moment measurement,
d is the distance between the ankle and knee pivot points (409 mm),
c is the distance between the lower sensor and the ankle pivot (76 mm), and
a is the distance between the upper sensor and the knee pivot (96 mm).

This equation was derived based on the assumption that the lower leg is a simply supported beam, and that the maximum moment occurs between the upper and lower moment sensors due to the application of a single point load. The geometry of the lower leg, however, is more complicated than a simply supported beam, and the loads which produce the measured moments can be more complex than a single point application.

Maintaining the assumption that the lower leg can be modelled as a simply supported beam, the maximum moment was calculated for several loading conditions which do not satisfy the other assumptions of the "maximum calculated bending moment equation's" derivation. The results are summarized in Table 1, and show that the maximum bending moment predicted with the "maximum calculated bending moment equation" ranges from 59% greater than to 7% less than the actual maximum moment for the loading conditions shown. The loadings shown in Table 1 represent relatively simple statically determinate cases. It would not be unusual for crash environment induced loadings to be significantly more complex. High-speed films from crash and sled tests, for example, have shown that the dummy's knee sometimes becomes wedged in the deformed knee bolster. This may result in a cantilever or, possibly, statically indeterminate load configuration. Larger discrepancies between the actual moment and that predicted by the "maximum calculated bending moment equation" are possible for these more complex configurations. The results of this analysis suggest that the "maximum calculated bending moment equation" is not sufficient for the crash test environment because the assumptions from which it was derived are not general enough to accommodate the loadings which might be experienced by the lower leg.

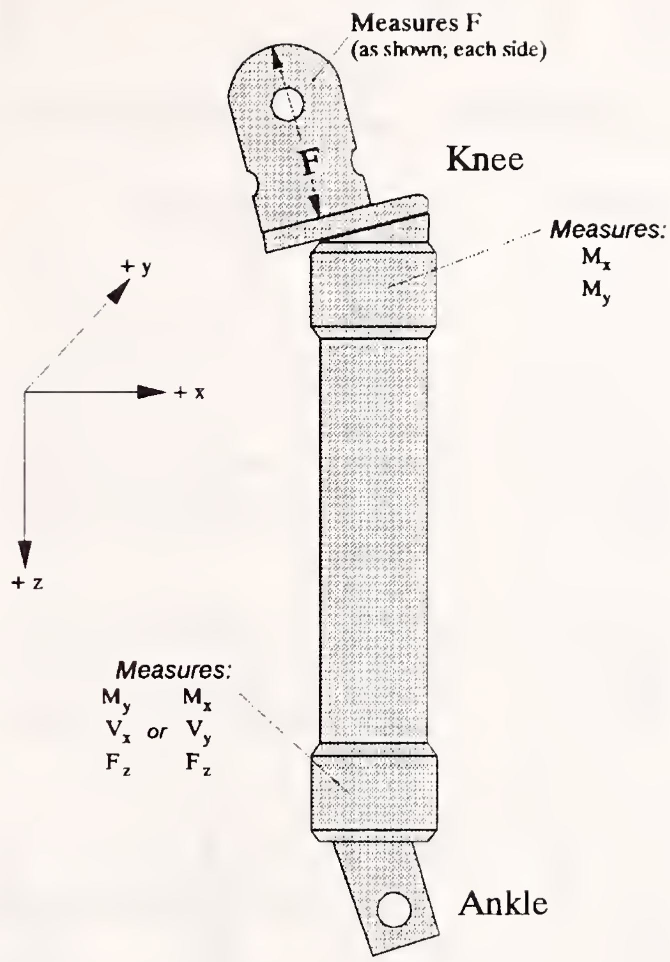
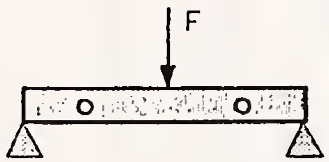
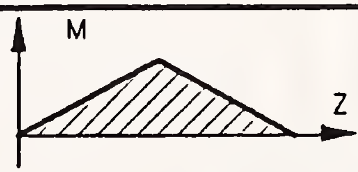
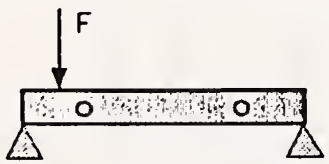
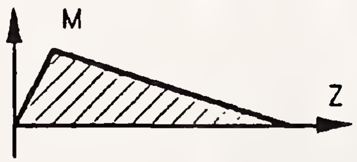
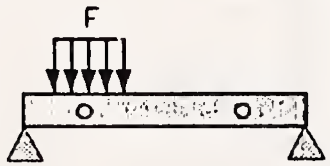
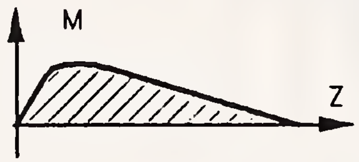
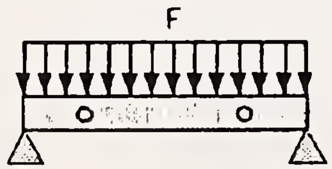
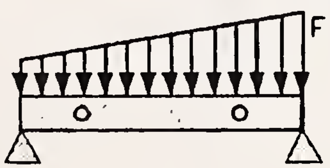
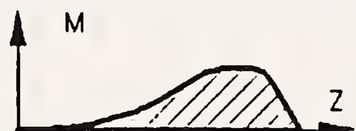


FIGURE 3 -- Force and Moment Measurement Capabilities of the Instrumented Hybrid III Lower Leg

NOTE: M_x and M_y are moments in the Y-Z and X-Z planes, respectively.

TABLE 1 -- Comparison of Actual Maximum Moment and Proposed "Calculated Maximum Moment" for Several Simple Loads

Load Diagram	Moment Diagram	M_u	M_l	$\frac{M_u * M_l * d}{(c\, M_u) + (a\, M_l)}$	M_{max} *	Diff
		.048 F	0.37 F	.102 F	.102 F	0 %
		.054 F	.013 F	.056 F	.059 F	− 5 %
		.064 F	.023 F	.087 F	.077 F	+13 %
		.037 F	.029 F	.081 F	.051 F	+59 %
		■ $2.8*10^{-4}$ F	■ $8*10^{-4}$ F	$9*10^{-4}$ F	■ .001 F	− 7 %

*Predicted from static mechanics ■Based on ≈ 1200 N/m slope o Denotes sensor location

4.0 STATIC TESTS

Three instrumented Hybrid III lower legs (Table 2) were subjected to a series of static tests to assess the repeatability and reproducibility of measurements made by the lower leg instrumentation.

TABLE 2 -- Instrumented Lower Leg - Transducer Configuration

LEG #	Transducer	Model#	S/N#
01	Tibia transducer	1583	03
	Ankle transducer	1584	040
	Knee Clevis - Transducer	1587	043
02	Tibia transducer	1583	040
	Ankle transducer	1584	034
	Knee Clevis - Transducer	1587	037
03	Tibia transducer	1583	039
	Ankle transducer	1584	033
	Knee Clevis - Transducer	1587	036

4.1. Repeatability and Reproducibility Tests

4.1.1. Procedure

Each of the three instrumented Hybrid III lower legs was subjected to two different static load conditions. The first was a point load applied at a point 44 mm above the ankle pivot, the second was also a point load and was applied at a point midway between the leg's two sensors. The loads were applied with an Instron testing device. The ends of the lower leg were supported on ball bearing surfaces that could only provide reaction forces perpendicular to the lower leg shaft. Figure 4 shows the Hybrid III lower leg set-up for a static test. Each of the legs was subjected to three trials for each load configuration.

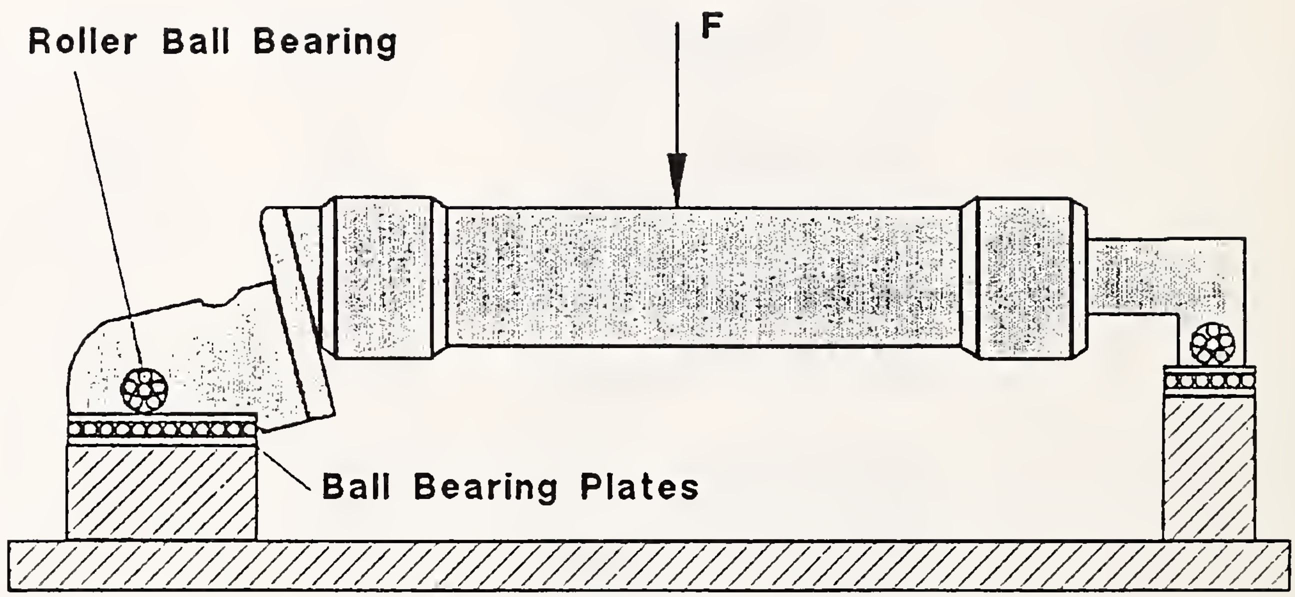


FIGURE 4 -- Quasi-static Test Set-up

The signals produced by the lower leg instrumentation in these tests were collected and digitized by a TransEra MDAS 7002 data acquisition system. Ten samples, taken over a one second interval, were collected from each channel in each test from both the loaded and unloaded lower leg assembly. Samples taken before the load was applied were a measure of each transducer's zero load offset and were used to remove bias from the data collected from the loaded assembly. Conditioning of the transducer signals was handled by Metraplex 340B electrical resistance strain gage (bridge) circuitry.

4.1.2. Results

The results of this testing are shown in Tables 3 and 4. The reported measurements are the averages of ten data points taken over one second under a constant load. The difference between calculated applied and measured Y-moment and X-shear loads for the end-loaded tests were between 1% and 5% of the applied loads, with the exception of the ankle shear loads measured in leg #2. The mid-shaft loaded tests provided slightly better accuracy, as all Y-moment and X-shear measurements displayed less than a 5% difference from the calculated applied loads. The measured Y-moments and X-shear displayed very little scatter. A high degree of repeatability was indicated by coefficients of variation for Y-moments and X-shear of less than 1% (Tables 5 and 6). Although reproducibility was not rigorously assessed, similar average measured loads for all three lower leg assemblies suggests generally good reproducibility.

Measurements of the knee clevis forces were not accurate. The indicated forces were between 35% less than and 170% greater than the applied load. Additionally, both clevis transducers did not indicate the same force, as they should have. Typically the left clevis indicated forces that were between 1.3 and 3 times greater than those indicated by the right. These measurements were somewhat repeatable, with coefficients of variation ranging between 2% and 10%. The knee clevis force measurements also did not appear to be reproducible. The upper (tibia) X-moment sensor provided accurate measurements. Load moments were not applied about the X-axis and the sensors did not indicate any such loads. The Z-force

TABLE 3 -- Quasi-static Load Data - Point Load 44 mm From Ankle Pivot

Test#	Leg#	Load Force (N)	Knee Clevis Force Right (N)	Knee Clevis Force Left (N)	Tibia X-Moment (Nm)	Tibia Y-Moment (Nm)	Ankle Y-Moment (Nm)	Ankle X-Shear (N)	Ankle Z-Force (N)
14	3	8060	83	192	1	87	297	900	76
15	3	8049	75	182	0	ND.	296	914	57
16	3	8067	90	185	0	ND.	296	911	86
Average Measured:		8059	83	187	0	87	296	908	73
Calculated Applied:			126	126	0	84	291	873	0
17	2	8047	77	238	0	88	300	1022	193
18	2	8041	77	248	0	88	298	1011	173
19	2	8045	91	238	0	88	298	1005	158
Average Measured:		8044	81	241	0	88	299	1013	175
Calculated Applied:			126	126	0	84	290	871	0
20	1	8095	ND.	77	0	86	296	921	185
21	1	8004	ND.	84	0	86	295	910	170
22	1	8006	ND.	84	0	87	297	910	150
Average Measured:		8035		82	0	87	296	913	168
Calculated Applied:			125	125	0	84	290	870	0

ND. - No Data because of channel malfunction.

TABLE 4 -- Quasi-static Load Data - Point Load at the Mid-shaft

Test#	Leg#	Load Force (N)	Knee Clevis Force Right (N)	Knee Clevis Force Left (N)	Tibia X-Moment (Nm)	Tibia Y-Moment (Nm)	Ankle Y-Moment (Nm)	Ankle X-Shear (N)	Ankle Z-Force (N)
23	1	4913	ND.	305	0	221	201	-2673	135
24	1	4913	ND.	344	- 1	221	200	-2698	125
25	1	4911	ND.	340	0	221	200	-2662	130
Average Measured:		4912		330	0	221	201	-2678	130
Calculated Applied:			168	168	0	225	196	-2578	0
26	2	4904	363	465	- 1	230	196	-2507	153
27	2	4937	345	451	- 3	230	195	-2498	163
28	2	4939	349	444	- 4	231	195	-2496	148
Average Measured:		4927	352	454	- 3	230	195	-2500	155
Calculated Applied:			168	168	0	226	197	-2586	0
29	3	4928	355	406	1	225	197	-2678	- 5
30	3	4926	355	406	1	225	197	-2678	0
31	3	4926	359	413	1	225	197	-2675	- 5
Average Measured:		4927	356	408	1	225	197	-2677	- 3
Calculated Applied:			168	168	0	226	197	-2586	0

ND. - No Data because of channel malfunction

TABLE 5 -- Quasi-static Repeatability Point Load 44 mm From Ankle Pivot

Leg#	Knee Clevis Force Right (C.V.)	Knee Clevis Force Left (C.V.)	Tibia X-Moment (C.V.)	Tibia Y-Moment (C.V.)	Ankle Y-Moment (C.V.)	Ankle X-Shear (C.V.)	Ankle Z-Force (C.V.)
1	Ud.	5%	Ud.	0%	0%	1%	11%
2	10%	2%	Ud.	0%	0%	1%	10%
3	8%	3%	25%	Ud.	0%	1%	21%

Ud. - Undefined.

TABLE 6 -- Quasi-static Repeatability Point Load at the Mid-Shaft

Leg#	Knee Clevis Force Right (C.V.)	Knee Clevis Force Left (C.V.)	Tibia X-Moment (C.V.)	Tibia Y-Moment (C.V.)	Ankle Y-Moment (C.V.)	Ankle X-Shear (C.V.)	Ankle Z-Force (C.V.)
1	Ud.	6%	Ud.	0%	0%	1%	4%
2	3%	2%	30%	0%	0%	0%	5%
3	1%	1%	0%	0%	0%	0%	Ud.

Ud. - Undefined.

transducer indicated loads that averaged approximately 2% full scale, though such loads were not applied.

4.2 Discussion of Quasi-static Results

The results of the repeatability and reproducibility testing suggested that the Hybrid III instrumented lower legs are capable of measuring applied Y-moment and X-shear loads reasonably accurately. These results also showed that the legs behaved in a generally reproducible manner, while each leg also produced repeatable responses to the quasi-static loads.

While the accuracy of the X-moment and Z-force sensors was not evaluated, the results of these tests demonstrate that the sensors for measuring these loads are not particularly sensitive to cross-axis loads. The knee-clevis force transducer, on the other hand, did not produce accurate indications in any of the quasi-static tests described here. Since this testing indicated that the knee clevis transducer does not measure accurately, no attempt was made to refine the "maximum calculated bending moment equation" or derive an alternative. The knee clevis transducer was the only sensor that could have provided non-redundant information to determine the leg's moment distribution.

Without additional information to determine the leg's moment distribution, a criterion based on the "maximum calculated tibia bending moment equation" does not appear to be feasible.

5.0 DYNAMIC (CALIBRATION-TYPE) TESTS

5.1 Purpose

Eleven impacts to three Hybrid III instrumented lower legs were conducted to assess the feasibility of a dynamic calibration procedure and provide data for the specification of preliminary calibration response corridors.

5.2 Procedure

The lower legs were mounted to the knee calibration fixture as shown in Figure 5. The shaft of the lower leg was aligned perpendicular to the laboratory floor. This perpendicular orientation was maintained by an open, clevis-like stop located at the ankle. The standard four-wire Hybrid III knee calibration pendulum was adapted to provide a point contact as shown in Figure 6. It's adapted mass measured 7.7 kg and it was directed to impact the lower leg at the point midway between the upper and lower sensors. The impact velocity was 2.91 ± 0.014 m/s.

The pendulum carried an accelerometer to measure its longitudinal acceleration. Force and moment data were collected from each of the lower leg's sensors. All data were collected through the data acquisition system, in place at the Transportation Research Center's Dummy Calibration Lab. Prior to digitization at a rate of 8000 sample/sec, the data was passed through an analog, low-pass filter with a cut-off frequency of 1650 Hz. Impact velocity of the pendulum was measured by a light trap system.

The first three (Test #1-3) impacts were to leg #1. These were performed in immediate succession. A brief interrogation of the pendulum acceleration data revealed that Tests #2 and #3 had significantly higher peak accelerations than Test #1. The cause of this difference was judged to result from the weakening of the foam filled tibia covering. Consistency of the pendulum's peak impact acceleration was maintained in Tests #4-6, with leg #2, by first performing a warm-up impact to the leg. Tests #7-9, with leg #3, were also preceded by a warm-up impact. Tests #8 and #9, however, resulted in unusually high pendulum accelerations. A loose seating between the ankle and the ankle stop was the suspected cause of these higher accelerations. Tests #10 and #11 were performed as above after checking this interface.

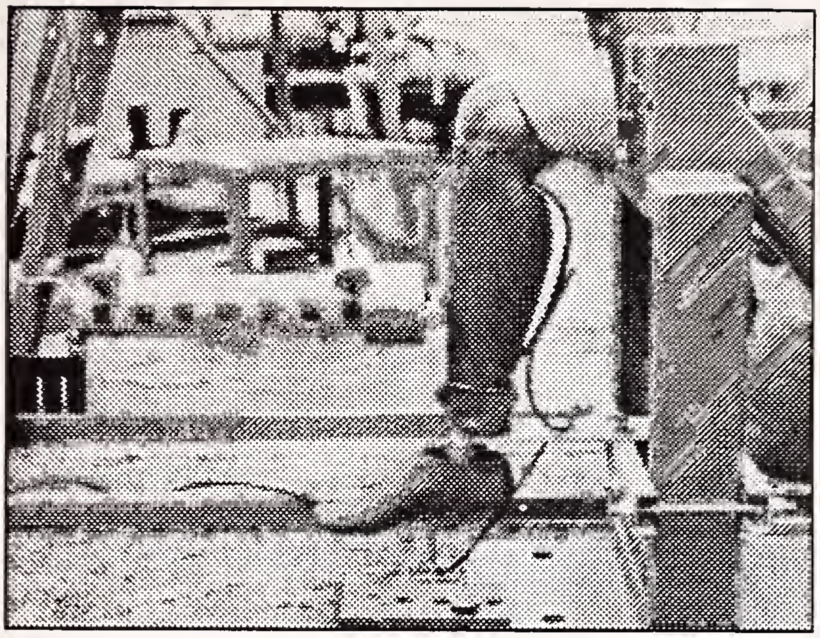


FIGURE 5 -- Lower Leg Dynamic Test Set-up

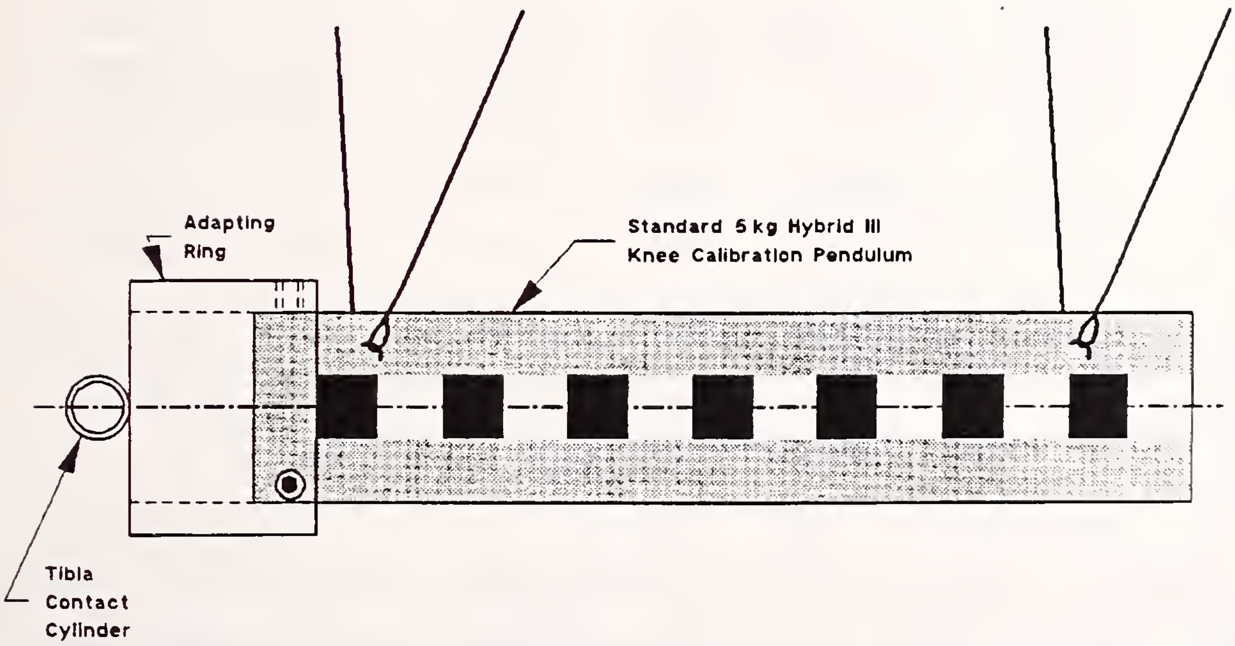


FIGURE 6 -- Adaptation of Knee Pendulum for Dynamic Lower Leg Tests

5.3 Results and Discussion

Complete data for these tests can be found in the Appendix. The data found in the Appendix are shown without additional digital filtering. Likewise, the reported peak values in this discussion are also "unprocessed". The coefficients of variation for the input force (pendulum impact force), as well as the outputs (Y-moments and X-shears) suggest adequate repeatability for a potential calibration procedure (Table 7). Tests #1-3 produced a coefficient of variation slightly higher than the other tests because these were conducted without a warm-up impact. As in the quasi-static tests, the knee clevis measurements do not display the same level of repeatability as the Y-moment and X-shear measurements.

TABLE 7 -- Dynamic Repeatability

Leg#	Pend. Impact Force (C.V.)	Knee Clevis Force Right (C.V.)	Knee Clevis Force Left (C.V.)	Tibia Y-Moment (C.V.)	Ankle Y-Moment (C.V.)	Ankle X-Shear (C.V.)	Ankle Z-Force (C.V.)
1	12%	26%	13%	6%	5%	6%	18%
2	2%	30%	15%	4%	4%	2%	14%
3	3%	Ud.	Ud.	4%	3%	1%	Ud.

Ud. - Undefined.

Furthermore, the clevis force measurements display the same inaccuracy as observed in quasi-static testing. A comparison of calculated applied and measured forces is shown in Table 8. The applied loads in this table were calculated from the pendulum's peak acceleration (m*a). Measurements from the Y-moment and X-shear sensors averaged 10% difference from the calculated applied loads. These differences ranged between 1% and 22%. Figure 7 illustrates that the differences between measured and calculated applied loads are smaller for larger input (impact) forces. This suggests that if a calibration were adopted based on the tests described here, a greater input force should be used.

TABLE 8 -- Comparison of Measured and Applied Loads

TEST NO.	LEG NO.		Peak Pend. Accel. (G)	Peak Pend. Force (N)	Peak Right Knee Force (N)	Peak Left Knee Force (N)	Peak Tibia Y-Moment (Nm)	Peak Ankle X-Force (N)	Peak Ankle Y-Moment (Nm)	Peak Ankle Z-Force (N)
01	1	measured	* 78	5886	-601	856	278	-4098	-172	418
		calculated			182	182	247	-3349	-153	0
		%difference			-430	369	12	22	12	---
02	1	measured	96	7259	-1003	1078	306	-4478	-187	* 592
		calculated			225	225	305	-4131	-189	0
		%difference			-546	379	0	8	-1	---
03	1	measured	98	7410	-983	1067	309	-4547	-190	* 576
		calculated			230	230	311	-4216	193	0
		%difference			-528	364	-1	8	-1	---
04	2	measured	80	6044	262	282	205	-3177	128	* 590
		calculated			187	187	254	-3439	157	0
		%difference			40	51	-19	-8	-19	---
05	2	measured	79	5924	405	350	223	-3237	138	***
		calculated			184	184	249	-3371	154	0
		%difference			120	90	-10	-4	-11	---
06	2	measured	81	6127	***	***	215	-3292	133	723
		calculated			190	190	257	-3486	159	0
		%difference			-100	-100	-16	-6	-17	---
07	3	measured	81	6097	419	238	232	-3720	150	***
		calculated			189	189	256	-3469	159	0
		%difference			122	26	-9	7	-5	---
08	3	measured	86	6474	***	***	215	-3644	147	791
		calculated			201	201	272	-3684	168	0
		%difference			-100	-100	-21	-1	-13	---
09	3	measured	85	6376	***	***	226	-3675	141	***
		calculated			198	198	268	-3628	166	0
		%difference			-100	-100	-16	1	-15	---
10	3	measured	82	6158	***	***	211	-3616	137	774
		calculated			191	191	259	-3504	160	0
		%difference			-100	-100	-19	3	-14	---
11	3	measured	84	6361	***	***	214	-3592	143	789
		calculated			197	197	267	-3620	165	0
		%difference			-100	-100	-20	-1	-14	---

* - Peak of pulse read from plot, spikes ignored.

*** - Approx. = 0 at impact, min. and max. out of sequence with impact.

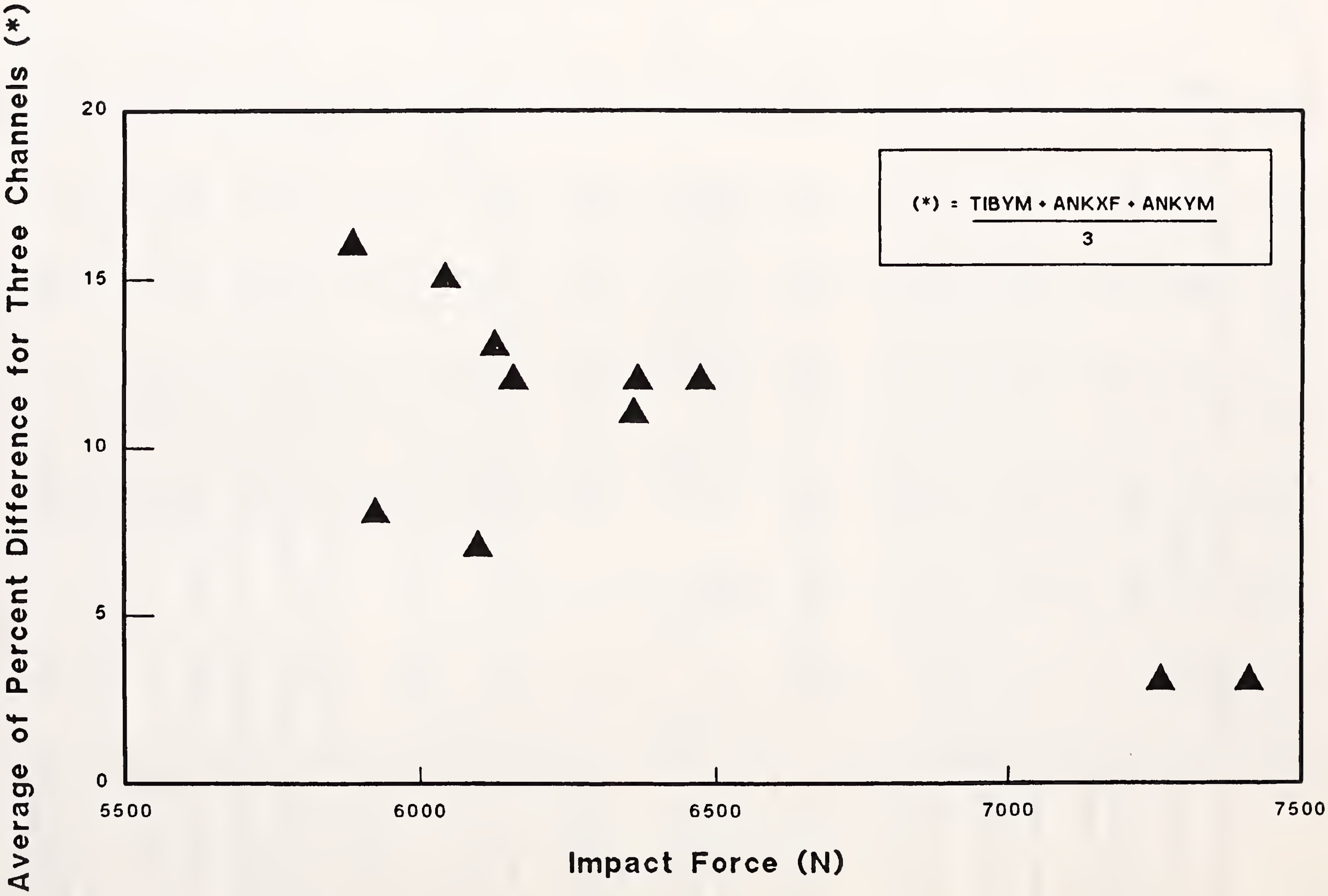


FIGURE 7 -- Accuracy of Lower Leg Dynamic Measurements

Preliminary response corridors were not developed from these tests because of the inconsistencies of Tests #1-3 and differences between measured and calculated applied loads. The results of this testing do, however, affirm the feasibility of a single impact calibration procedure for X-shear and Y-moment measurements. The test results also indicate the following two points for possible consideration in the refinement of a single impact calibration procedure for the Hybrid III lower leg:

1. Impact Force - Preliminary dynamic tests suggest that a higher impact force, will result in better agreement between measured and calculated loads. This might be accomplished in a revised procedure either by increasing impact velocity or pendulum mass.

2. Time Interval - It appears that response corridors should be developed from tests which are performed no less than 20 minutes apart, allowing the skin covering to recover. Although a small number of consecutive tests following a warm-up impact appeared to produce a repeatable result, continuous consecutive testing may result in degradation of the skin response.

6.0 DISCUSSION AND CONCLUSIONS

An analysis of the bending moment distribution in the lower leg for several different load conditions showed that the "maximum calculated bending moment equation" did not accurately predict the maximum bending moment for loading conditions possible in crashes. Also, the current configuration of the Hybrid III lower leg instrumentation does not allow the accurate determination of an unknown bending moment distribution and therefore, a prediction of the maximum moment.

Lower leg measurements of Y-moments and X-shears were accurate and repeatable for quasi-static conditions. Measurements by the knee clevis force transducers were neither accurate nor repeatable. For this reason, measurements from the knee clevis sensors would be of little value in the crash test environment. The accuracy of Z-force and X-moment measurements was not assessed in this testing. However, neither the Z-force sensor or the X-moment sensor exhibited intolerable sensitivity to cross axis loads.

The feasibility of a dynamic lower leg calibration procedure was demonstrated. Response corridors were not established, however.

The Hybrid III instrumented lower leg appears to be an effective tool for the measurement of X-shear forces at the ankle and Y-moments both in the ankle and upper tibia. Currently, however, a method to assess lower leg fracture injuries from these measurements does not exist.

7.0 REFERENCES

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8. NHTSA Data Tape Reference Guide, Appendix E; August 1985.

APPENDIX -- Dynamic Lower Leg Test Data

Mnemonics Key

PENXG	Pendulum longitudinal acceleration
TIBYM	Tibia (upper) Y-moment
ANKXF	Ankle (lower) X-shear
ANKYM	Ankle (lower) Y-moment

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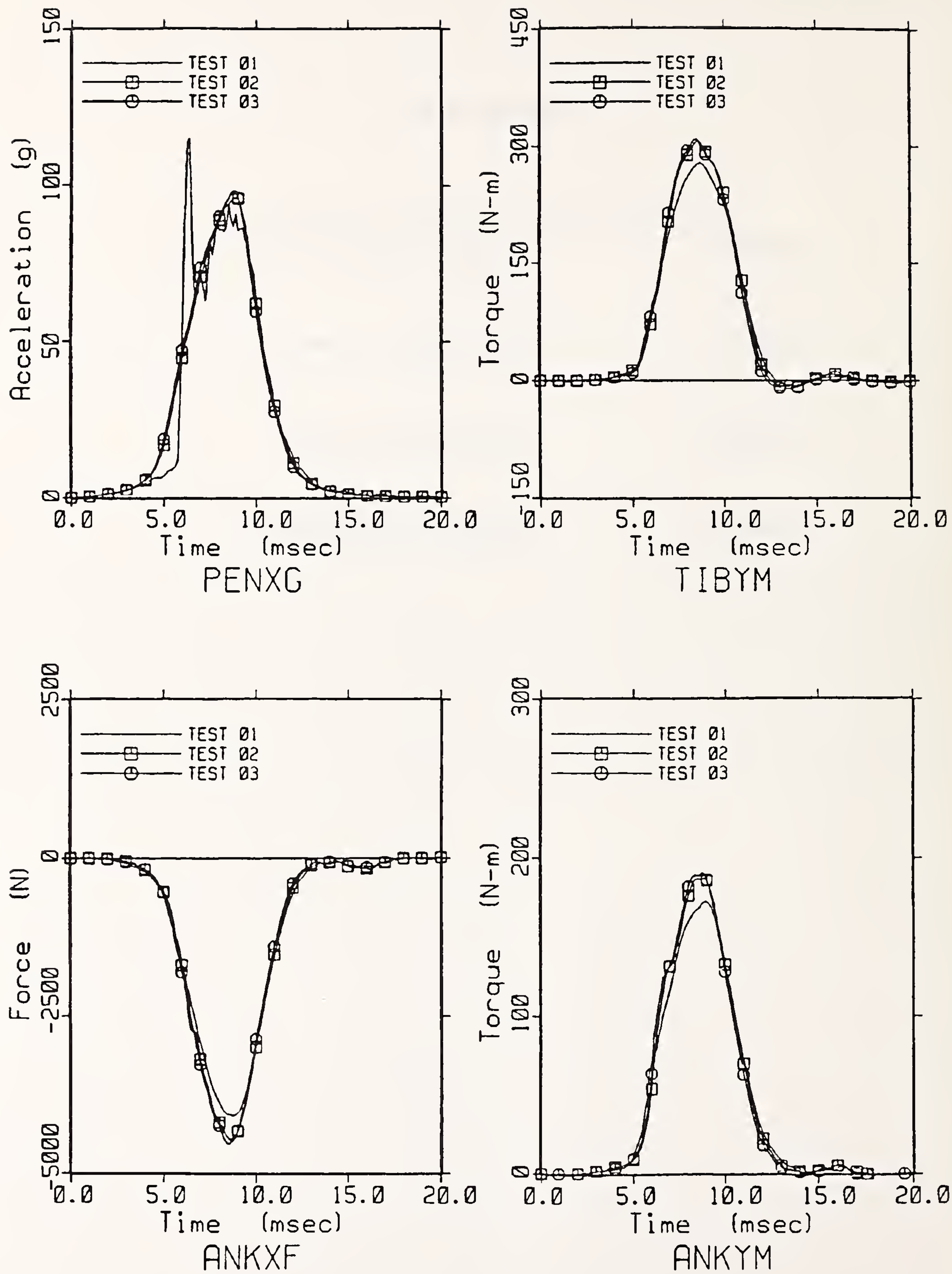

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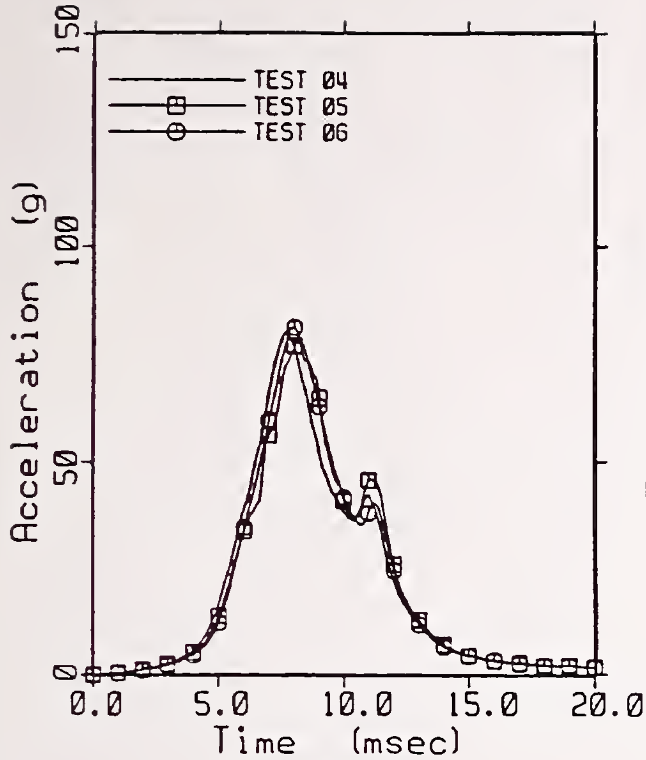

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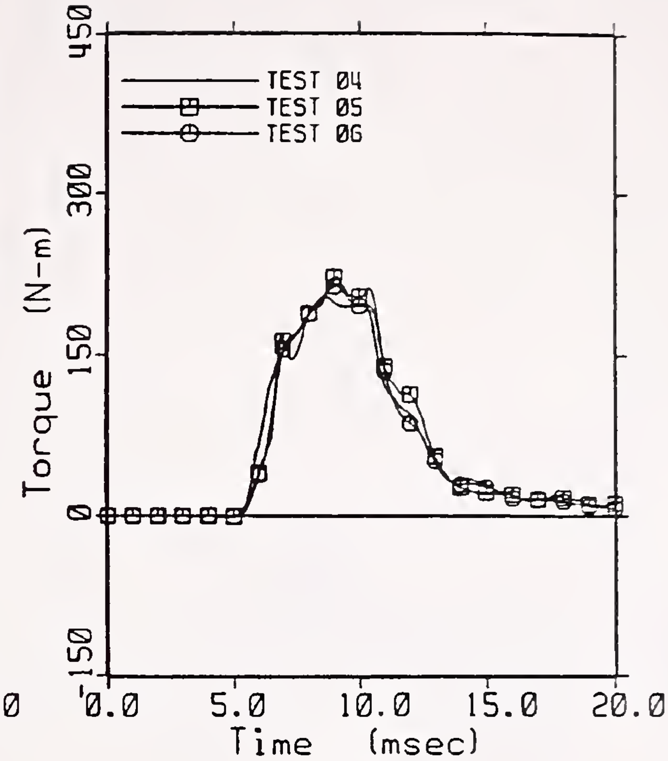

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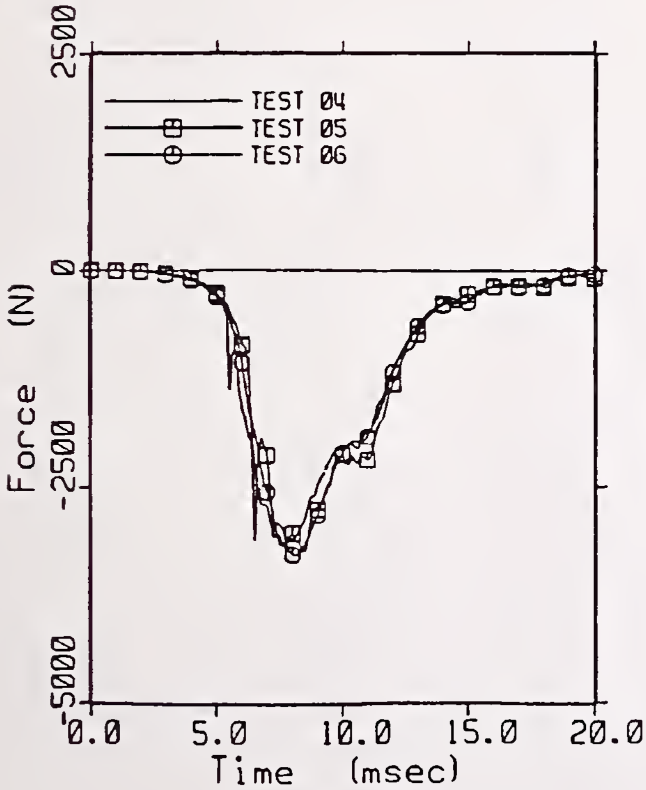

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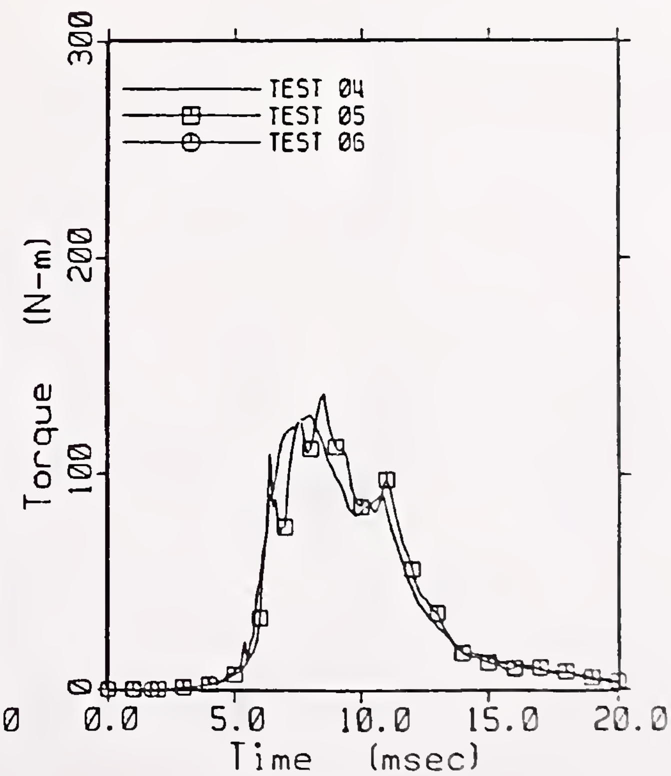

ANKYM

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