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TOLERANCE AND RESPONSE OF THE KNEE-FEMUR-PELVIS COMPLEX TO AXIAL IMPACT

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16. Abstract

This report is intended to define the tolerance and response of the human patella-femur-pelvis complex to axial impact force applied to the knee of seated vehicle occupants. The results of direct impact and driving point impedance measurements of the flexed legs of seated unembalmed human cadavers is presented. Comparisons of the cadaver responses are made with similar tests on a Part 572 test dummy. A total of 58 individual impact tests to the knees of cadavers were conducted for various impact test conditions -- rigid, lightly padded and thickly padded impact surfaces. Accident investigation data analysis is used as an aid to interpreting the test results.

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INTRODUCTION

The bones of the lower extremities (pelvis, femur, patella, tibia, fibula, and the bones of the foot) can be subjected to a variety of types of loads in automobile crashes. This is true for both unrestrained and restrained vehicle occupants. Improvements in the design of automobile interiors have significantly reduced some forms of lower extremity injuries (1),* However, as the crashworthiness of vehicle structures is upgraded, the protective requirements of the vehicle interior must also be upgraded and optimized. The proper use of belt restraint systems has been shown to reduce lower extremity injuries. Recent developments in passive restraint systems (the air cushion restraint system and the Volkswagen RA passive shoulder belt (2)) utilize the knees and upper legs as a means of restraining the lower body in lieu of a lap belt. Optimization of such methods of occupant restraint, and the minimization of lower extremity injury in general, requires a thorough knowledge of the biomechanics of the lower extremity skeletal system. The only injury criteria presently applied to the lower extremities in occupant protection evaluation is the 1700 lb.(7.56 kN) maximum axial femur force limit level set forth in FMVSS 208 (3).

This report is intended to define the tolerance and response of the human patella-femur-pelvis complex to axial impact force. Following sections on the anatomy of the system and a review of related research, the results of direct impact and driving point impedance measurements on the flexed legs of seated unembalmed cadavers is presented. Comparisons of the cadaver responses are made with similar tests on a Part 572 test dummy. A total of 28 unembalmed human cadavers were tested in this program for a total number of 58 individual impact tests.

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* Numbers in parentheses designate References at the end of this report.

ANATOMY OF THE KNEE-FEMUR-PELVIS COMPLEX

The skeletal structures of interest in the flexed knee impact problem are the pelvis or hip bones, the femur or thigh bone and the patella or knee cap. These bones are arranged in the body in the manner shown in Figure 1 for a seated vehicle occupant.

The pelvis is composed of the two hip bones, the sacrum, and the coccyx as shown in Figure 2. The hip bones form the lateral and anterior boundaries, meeting each other anteriorly at the pubic symphysis; posteriorly they are connected with the sacrum (the base of the spinal column). The hip bones consist of three parts, named the ilium, the ischium, and pubis, which are firmly united in the adult and meet together to form the acetabulum, a large, cuplike socket situated near the middle of the lateral surface of the bone, articulating with the head of the femur.

The femur is the largest and longest bone in the skeleton and transmits the weight of the trunk from the hip bone to the lower leg bones in the standing position. As shown in Figure 3, it consists of a proximal region which includes the head, neck and two trochanters, a shaft and, in Figure 4, a distal region which expands into two condyles which are part of the knee joint. The structure of the femur varies along its length. The shaft of the femur consists of a thick outer wall of compact bone while the interior is hollowed out by the medullary cavity. The ends of the femur (both proximal and distal) are composed of cancellous or porous bone covered by a thin layer of compact bone. These structural features are shown in Figures 3 and 4.

The patella is a triangular shaped bone situated anterior to the distal region of the femur. Structurally the patella consists of cancellous bone, which is dense in comparison to femoral cancellous bone, covered by a thin layer as shown in Figure 4. By its structure and its position, the patella performs an important function in protecting the knee joint from injury.

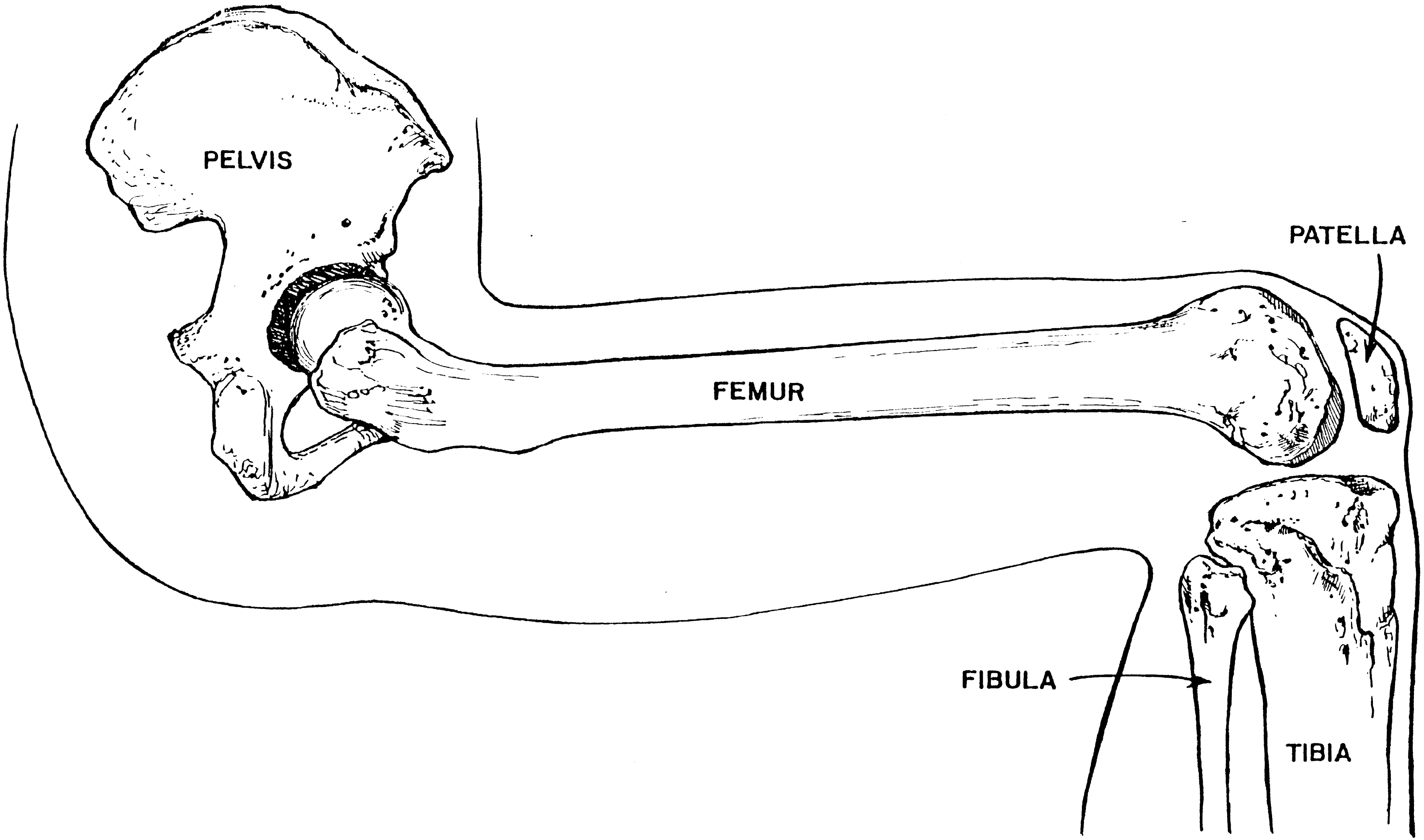


FIGURE I. CONFIGURATION OF THE KNEE–FEMUR–PELVIS FOR A SEATED PERSON

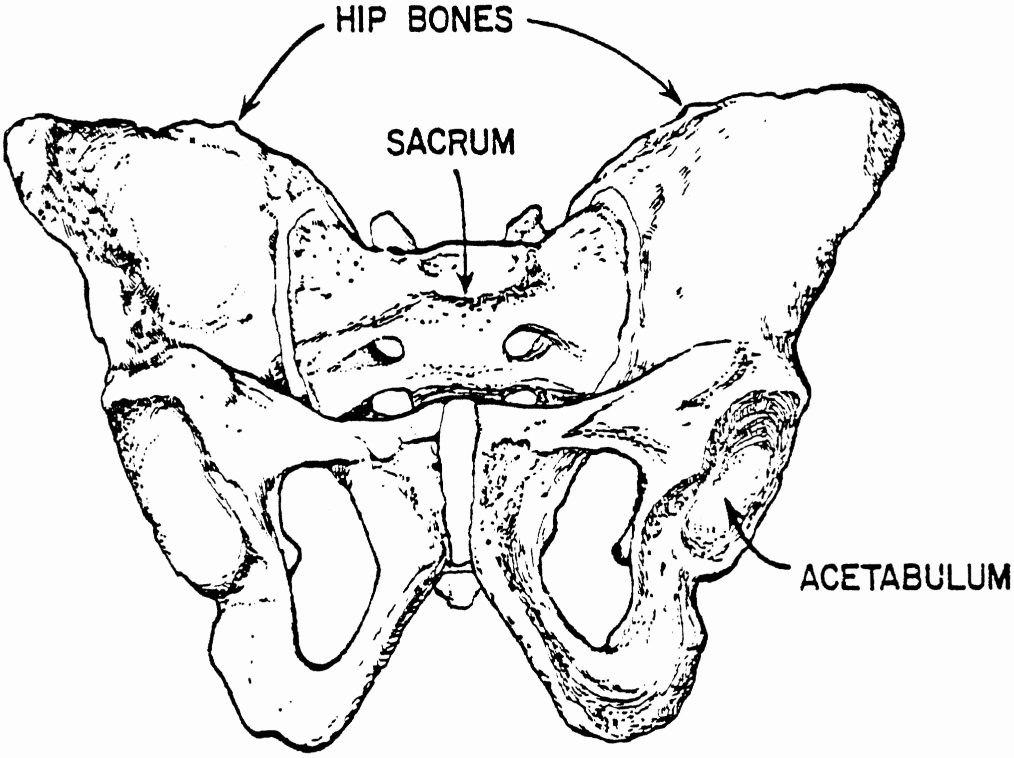


FIGURE 2. FRONTAL VIEW OF THE PELVIS

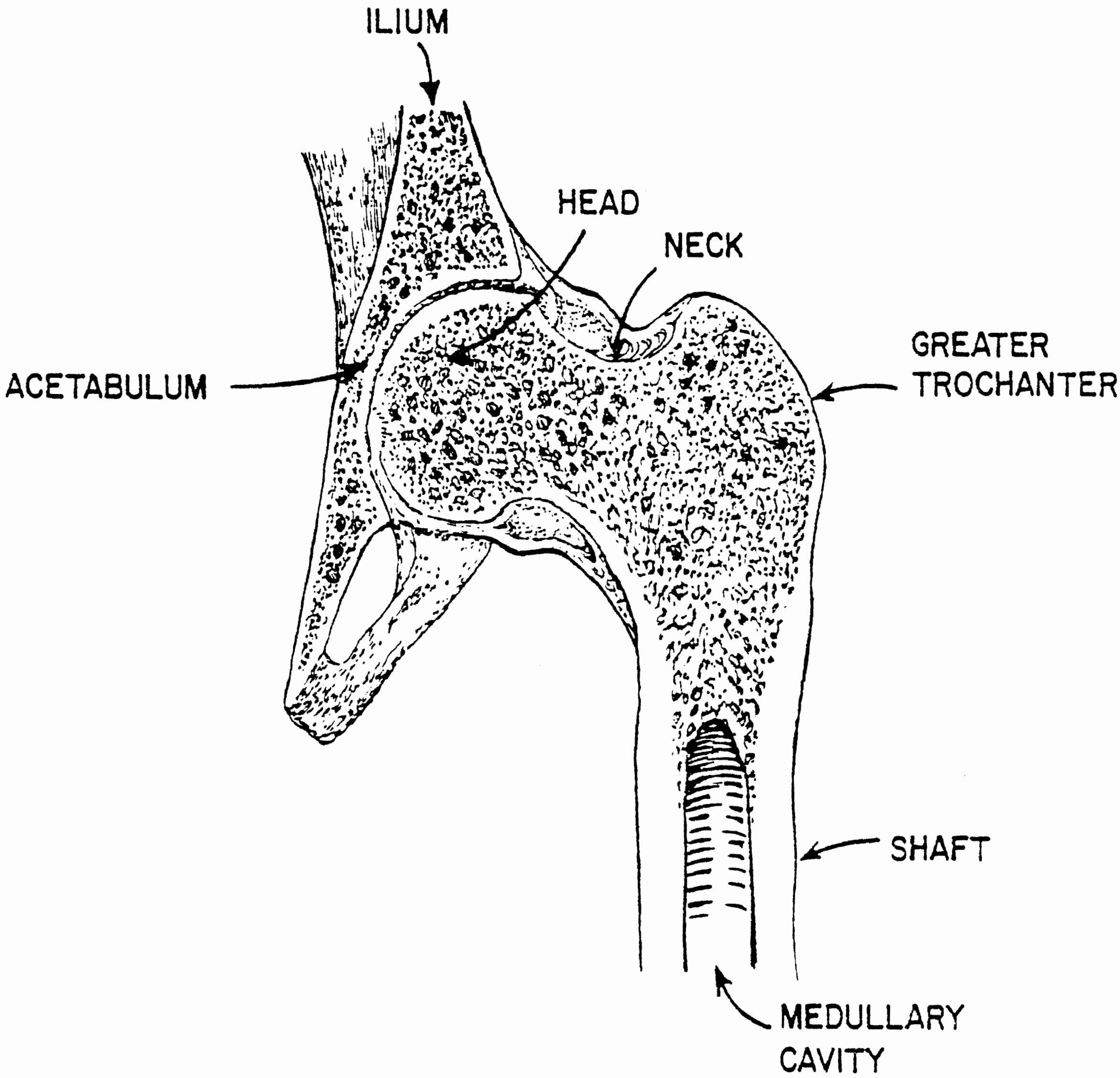


FIGURE 3. SECTIONAL VIEW OF THE PROXIMAL REGION OF THE FEMUR

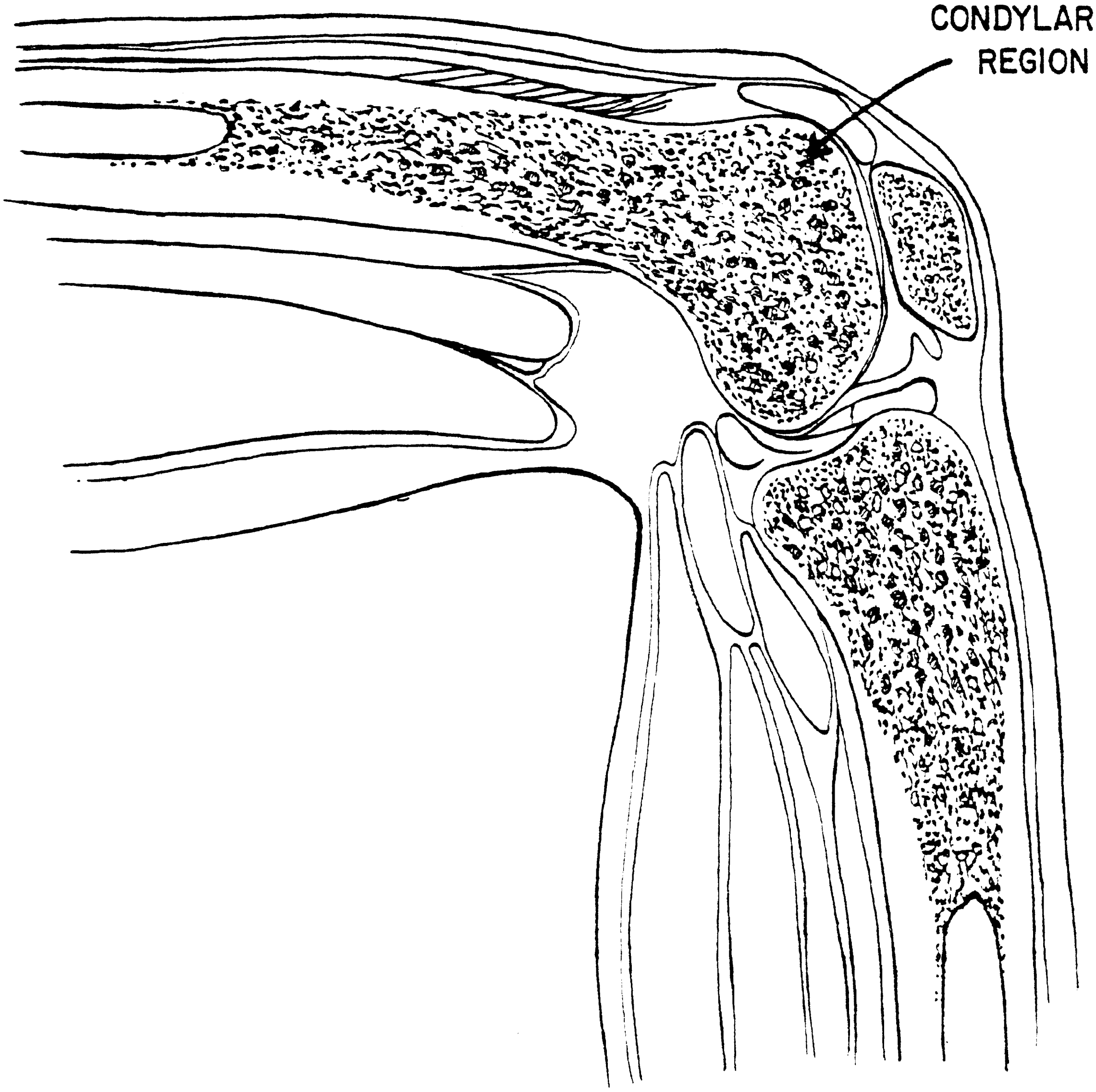


FIGURE 4. SECTIONAL VIEW OF THE DISTAL REGION OF THE FEMUR AND THE KNEE

RELATED RESEARCH

The first research on the impact tolerance of the lower extremities with respect to the automobile occupant was the work of Patrick, Kroell, and Mertz (4). Unrestrained seated embalmed cadavers were impacted into instrumented chest, head, and knee targets to simulate a vehicle interior. The knee targets were covered with 1.44 in. (3.65 cm.) of padding in most cases. Fractures of the femur were produced at a load as low as 1500 lbs (6.67 kN) while loads as high as 3850 lbs.(17.13 kN) were sustained with no fracture of the femur but with a fractured patella and pelvis. The majority of the femoral fractures were found to occur at the distal end of the bone. The authors concluded that failure of the femur occurred at slightly lower load levels than those either of the patella or pelvis. They suggested a conservative overall injury threshold load level of 1400 lb. (6.23 kN). In a later paper,(5) they raised this estimate to 1950 lbs. (8.86 kN). A great deal of the fracture load data presented in that work was obtained in experiments where multiple high-load-level tests were run on the subjects prior to obtaining fractures. This technique introduces uncertainty of possible progressive pre-damage to the skeletal structure, particularly to the pelvis.

Recently, Powell et al. (6, 7) reported the results of rigid impacts to the knee. Using seated cadavers, an impact load was applied to one flexed leg at a time by means of a striker pendulum with either a 34.3 lb. (15.6 kg) or 50 lb (22.7 kg) striker head with a flat rigid impact face. The cadaver was seated in a modified barber's chair which included back support. A total of fifteen tests on nine cadavers -- of which seven were embalmed and two were unembalmed -- were reported. The test results were as follows.

a. Patella fractures were observed in twelve of the fifteen legs tested, often at force levels below those needed for femur fractures.

b. Condylar fractures were observed in five of the legs.

c. Shaft fractures occurred in only one of the legs.

d. Hip (pelvic and femoral neck) fractures were observed in two legs.

Excluding patellar fractures, femur fractures were produced in seven of the fifteen legs at an average load of 2250 lbs (10.04 kN) with range of 1600-2812 lbs. (7.1 - 12.5 kN). The patellar fractures occurred at an average load of 2470 lbs (10.75 kN) with a range of 1782-2970 lbs. (7.9 - 1.32 kN). The authors felt that the localization of most of the fractures to the knee region was due to the use of a rigid impactor. Their analysis of the bending behavior of the femur during knee impact concluded that medial-lateral bending behavior of the femur was the dominant type of bending response which is in general a beam-column behavior with bending in two planes as well as axial compression.

Horsch and Patrick (8) have recently completed an interesting study on cadaver and dummy knee impact response at sub-fracture levels. Using rigid pendulum impactors of various masses ranging from 0.53 - 55 lbs. (0.24 - 25 kg), knee impacts along the femoral axis of unembalmed male cadavers and Part 572 dummies were performed. The dummy was found to exhibit significantly higher knee impact forces (1.5 - 3.7 times as great) than the cadaver subjects. This difference in response was shown to be due to differences of effective leg mass and knee padding (that is, soft tissue simulation). The dummy having a heavy rigid metal skeleton while the human has the major leg weight composed of loosely coupled flesh. The authors recommended that the "skeletal" weight of the Part 572 dummy leg should be substantially reduced (by a factor of approximately 10), with the weight difference being added to a properly simulated leg flesh and that the knee flesh simulation be modified to reduce the peak force resulting from rigid body impacts.

Two dimensional mathematical modelling of the midsection of the femur has been reported by Viano and Khalil (9). A plane strain analysis was performed by finite element techniques to study the static and dynamic response of the femur to axial compression. Dynamic load pulse histories were considered to follow a sine-squared function with pulse durations varying from 3 - 75 msec. Peak stress responses were found to exhibit a load-time dependence which produced overshoots of static stress levels for pulse durations 15 - 60 msec. (+30% for a 30 msec. pulse) and undershoots for pulse durations of 3 - 15 msec. (-30% for a 7.5 msec. pulse). The authors attributed the pulse time dependence of the response to stimulation of lower modes of structural vibration.

ACCIDENT INVESTIGATION DATA ON LOWER EXTREMITY INJURIES

As an aid to interpreting and guiding the laboratory research on knee impacts conducted during this program, the accident investigation data files at HSRI were utilized.

The Collision Performance and Injury Reports (CPIR) file was searched for cases with pelvis and lower extremity injuries which satisfied the following conditions:

(a) Primary damage of case vehicle - front

(b) Case vehicle direction of primary impact force - 11 o'clock to 1 o'clock.

(c) Case vehicle had to be a passenger car.

(d) Case vehicle collision deformation classification (CDC) had to be 1 through 5. (Note: CDC of six means windshield involvement and it was felt that it was best to eliminate any possible interactions of the occupants with collapsing occupant compartment structures due to intrusion.)

(e) Only front and rear seat sitting unbelted passengers 12 years or older could be included.

(f) AIS injury levels of 0, 8, and 9 for the legs and pelvis were excluded.

Out of the 13,088 cases in the CPIR file, there were 2,024 cases which satisfied the above requirements. These cases included injuries to the lower legs and the feet. Three hundred and eighty two of the cases had an AIS of 2 or more for at least a leg or the pelvis. The computer printout listed the following variables for each case from the CPIR file:

(1) Investigating team
(2) Report sequence number
(3) Multiple case vehicle number
(4) Case vehicle make/model, and year and body style
(5) Case vehicle primary CDC
(6) Case vehicle secondary CDC
(7) Seat location
(8) Occupant age
(9) Occupant Weight
(10) Occupant sex
(11) Overall occupant injury severity
(12) Degree of ejection
(13) Pelvic girdle contacts
(14) Pelvic girdle injury
(15) Right leg contacts
(16) Right leg injury
(17) Left leg contacts
(18) Left leg injury

The Multidisciplinary Accident Investigation (MDAI) accident listing was then searched for those cases which were identified as being of interest by the CPIR search. The MDAI data files, which contain detailed accounts of accidents, were obtained for the accidents identified in the search. The individual data files were examined and those which involved either knee fractures, femur fractures, or pelvis fractures were selected for in-depth, detailed study. A total of 142 cases were identified in this manner. The analysis of the cases involved a careful review of the accident investigator's narrative account of the accident, the reported vehicle kinematics, occupant contact points and occupant injuries. From this review, a subjective picture of the occupant kinematics was developed, in so far as was possible, given the indeterminacies of accident investigation data. The relative frequency of occurrence of specific injury sites in the 142 cases were as follows:

Pelvis and both femurs fractured - 2.7%
Pelvis and one femur fractured - 6.3%
Only pelvis fractured - 19.8%
One femur fractured - 46.8%
Both femurs fractured - 8.1%
Only patella fractured - 16.2%

In an effort to determine if there were characteristic crash severities which produced patellar and distal femur fractures rather than proximal and middle femur, pelvis and lower leg fractures, a separation of the data into the two classes was made and listed as a function of Vehicle Deformation Index. The resulting distribution of lower extremity injuries with respect to VDI is shown in the following table.

TABLE 1. DISTRIBUTION OF LOWER EXTREMITY INJURIES WITH RESPECT TO VEHICLE DEFORMATION INDEX (VDI)

Vehicle Deformation Index (VDI)	Patellar and Distal Femur Fractures Only N = 39 Mean VDI - 3.4		Proximal and Middle Femur, Pelvis, and Upper Tibia Fractures Only N = 103 Mean VDI = 3.6	
	n	n/N	n	n/N
1	0	0	2	1.9%
2	8	20.5%	14	13.6%
3	12	30.8%	31	30.1%
4	13	33.3%	37	35.9%
5	6	15.4%	19	18.4%

Examination of this table reveals that the frequency of occurrence of the two classes of injuries are distributed with respect to the VDI levels in a similar manner and that the occurrence of patellar and distal femur fractures is approximately 2-3 times less frequent than the other class of injury at the same VDI level. This information indicates that above a crash severity level of VDI = 1 there is sufficient occupant kinetic energy to cause some unrestrained front seat occupants to impact the instrument panel area of the vehicle at fracture producing load levels. At the VDI = 2 level, it appears that patellar and distal femur fractures are slightly more frequent in occurrence when compared to the other class of injury (8/14 = .57) than at higher VDI levels (12/31 - .39, 13/37 = .35, and 6/19 = .32. Thus it is concluded that the crash severity level alone is not responsible for producing one class of injury to the exclusion of the other.

The detailed examination of the actual MDAI files produced the following generalizations about the characteristics of the estimated occupant kinematics during the crash and their influence upon the type of upper leg injury that resulted:

a. Distal femoral and patellar fractures appeared to occur when the occupants' kinematics cause the upper legs to move generally straight ahead, impacting the instrument panel or seat back (rear passengers) with little subsequent upper body forward pitching.

b. Hip dislocations tended to occur when there is frontal impact combined with torso rotation to the left or right.

c. Pelvis fractures and proximal femur fractures probably occur when there is steering wheel involvement and forward torso rotation for the driver, or for the passenger, pitching of the torso upward after trapping the legs under the instrument panel.

The conclusion, which is drawn from the above analyses, is that the major factors in determining the type of leg fracture which will occur in a frontal crash are the initial position of the occupant and the subsequent kinematics of the occupant during the crash.

EXPERIMENTAL METHODS

Impact Tests

All impact tests in this program were conducted using a pneumatically operated testing machine specially constructed for impact studies. The machine consists of an air reservoir and a ground and honed cylinder with two carefully fitted pistons. One piston is a transfer piston which is propelled by compressed air through the cylinder from the air reservoir chamber and transfers its momentum to the impact piston. A striker surface with an inertia-compensated load cell is attached to the impact piston. The impact piston is allowed to travel up to 6 inches (15.2 cm.) and then its motion is arrested by an inversion tube which absorbs the remaining kinetic energy of the piston. The desired impactor stroke can be precisely controlled by initial positioning of the impact piston with respect to the inversion tube. The impactor velocity is controlled by reservoir pressure and the ratio of the masses of the transfer and impact pistons. The load cell is a Kistler 904A piezoelectric load washer with a Kistler 805A piezoelectric accelerometer mounted internally for inertially compensating the load cell for the striker mass between the load cell and the impact surface. The effective mass of the impact-piston load-cell striker assembly was varied during the program to achieve desired impact energy and momentum conditions. Two basic configurations were used; one used a 24.1 lb (10.95 kg) striker piston with a 21.6 lb (9.8 kg) transfer piston while the other used a 9.5 lb (4.3 kg) striker piston with a 7.7 lb (3.5 kg) transfer piston. The first combination was used in the majority of the tests while the latter combination was used for a few special high energy tests. The striker was a 6-inch (15.2 cm.) diameter rigid disc upon which materials of various crush characteristics could be placed. The output of the load cell was filtered at channel class 1000 (SAE Standard J211). High speed motion pictures (3000 frames/second) were taken in many of the tests with a Hy Cam movie camera.

All of the test subjects in the program were unembalmed human cadavers -- with the exception of dummy tests which were performed on a Part 572 test dummy. The cadavers were stored under refrigeration at 4° C except when being prepared for testing and were generally tested within 7 days after death. The general descriptive data on the test subjects is listed in Table 2. The average age of the cadavers was 65 years with a range of 45-90 years. In some of the tests, strain gages were applied to the shafts of the femurs. This preparation consisted of making a careful longitudinal incision in the soft tissue of the upper leg near the distal end of the femur and spreading the tissue to expose the shaft of the femur, applying strain gages to the surface of the femur with a cyano-acrylate adhesive (M-Bond 200), and then waterproofing the installation. The gages were applied approximately 4 inches (10.2 cm.) from the distal end of the femur to approximate the load cell location in test dummies. In many of the tests, two strain gage rosettes and one uniaxial gage were installed in the same transverse plane to allow the strain distribution to be determined from the strains at three points on the periphery of the femoral shaft cross-sectional plane. Following preparation, the cadaver was seated in front of the impactor and positioned with the thigh horizontal and in line with the impactor axis with the knee flexed to 90° (as shown in Figure 5). In some tests, the thigh was not lined up along the impactor axis, but was abducted (rotated laterally) relative to the axis to study oblique frontal impacts. Another variation was to abduct the thigh but orient the cadaver such that the impact axis was along the femoral axis rather than the A-P axis of the cadaver torso. In all tests, the cadaver was supported such that the lower torso was free to translate rearward while being impacted. To insure relatively free motion, the cadaver was seated on two layers of polyethylene sheeting.

The impactor surface characteristics can be grouped into three categories:

1. Rigid - no padding or a maximum of 0.5 in. (1.3 cm.) of Ensolite padding.
2. Lightly padded - 1.0 in. (2.54 cm.) of Ensolite padding.
3. Thickly padded - 1.0 in. (2.54 cm.) of Ensolite padding backed by 2.0 in. (5.08 cm.) of aluminum honeycomb (Hexcel).

The general goals of the impact tests were to study the axial impact response of the knee-femur-pelvis complex under the following situations:

1. High force inputs with short (5-10 msec.) total pulse durations (Rigid impacts).
2. High force inputs with medium (10-30 msec.) total pulse durations (Lightly padded impacts).
3. Low force inputs with medium total pulse durations (thickly padded impacts.)

The techniques used to obtain the various loading conditions involved the type of padding used, the available stroke of the impactor, the test velocity, and in some cases, the impactor mass.

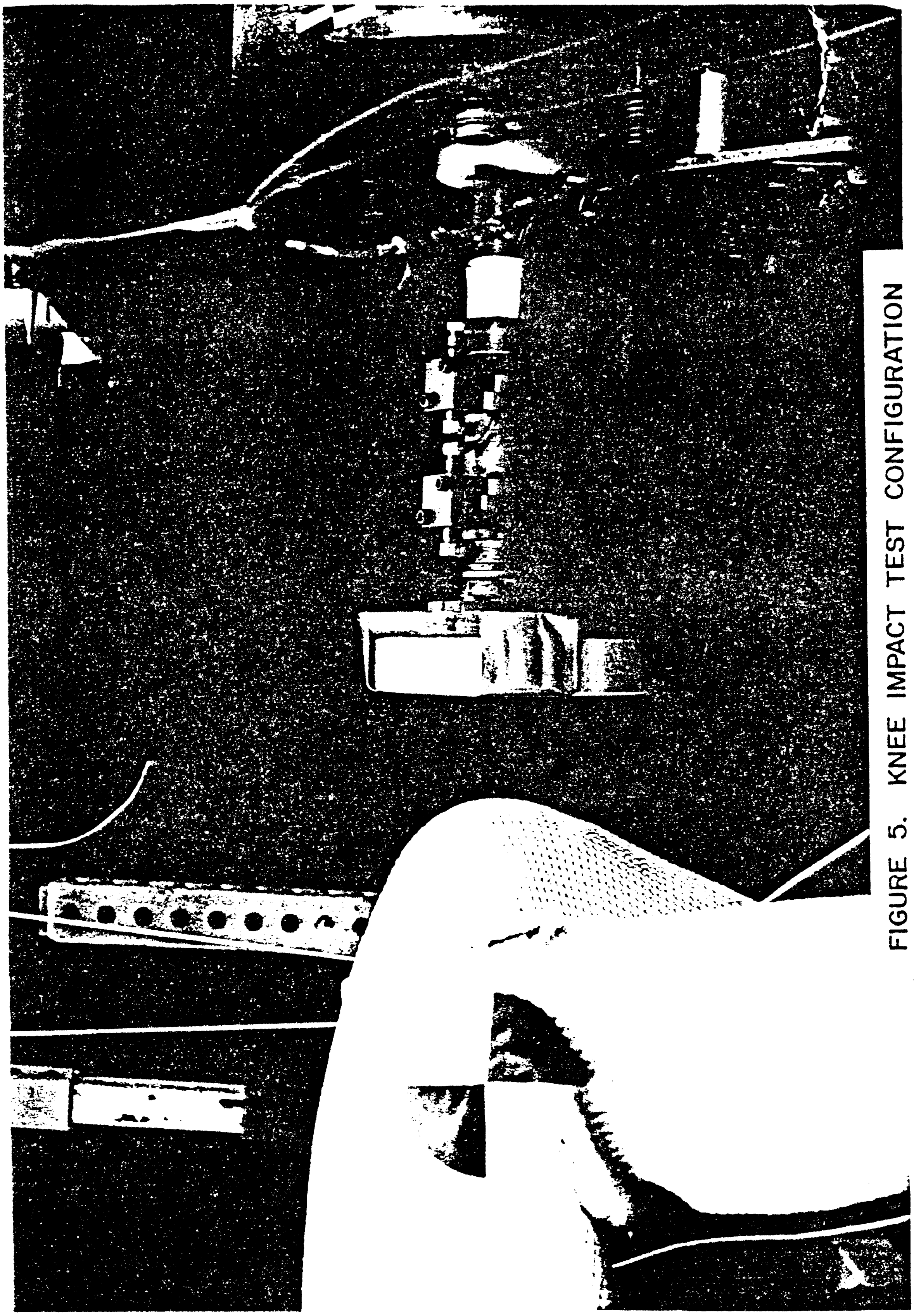


FIGURE 5. KNEE IMPACT TEST CONFIGURATION

Impedance Tests

A limited number of driving point and transfer impedance tests were conducted on cadavers and a Part 572 dummy. A test fixture was designed to allow coupling of the knee of a cadaver to the head of an Unholtz-Dickey electromagnetic shaker of 300 lb. (1335 N) capacity. The fixture consisted of two threaded T-bolts which were fastened into the distal shaft of the femur, a knee plate which was attached to the shaker head, and two threaded bolts which attached the T-bolts to the knee plate and allowed the patella to be preloaded against the femoral condyles as shown in Figures 6a and 6b. In all cases, the shaker axis was along the femoral shaft axis. A uniaxial accelerometer was attached in the A-P direction on the rear of the pelvis across the sacrum. As in the impact tests, the test subject was seated on a hard surface on two layers of polyethylene sheeting to reduce frictional coupling between the cadaver and the seat. In the dummy tests, a modified fixture was used to couple the knee to the shaker in a manner similar to the cadaver tests.

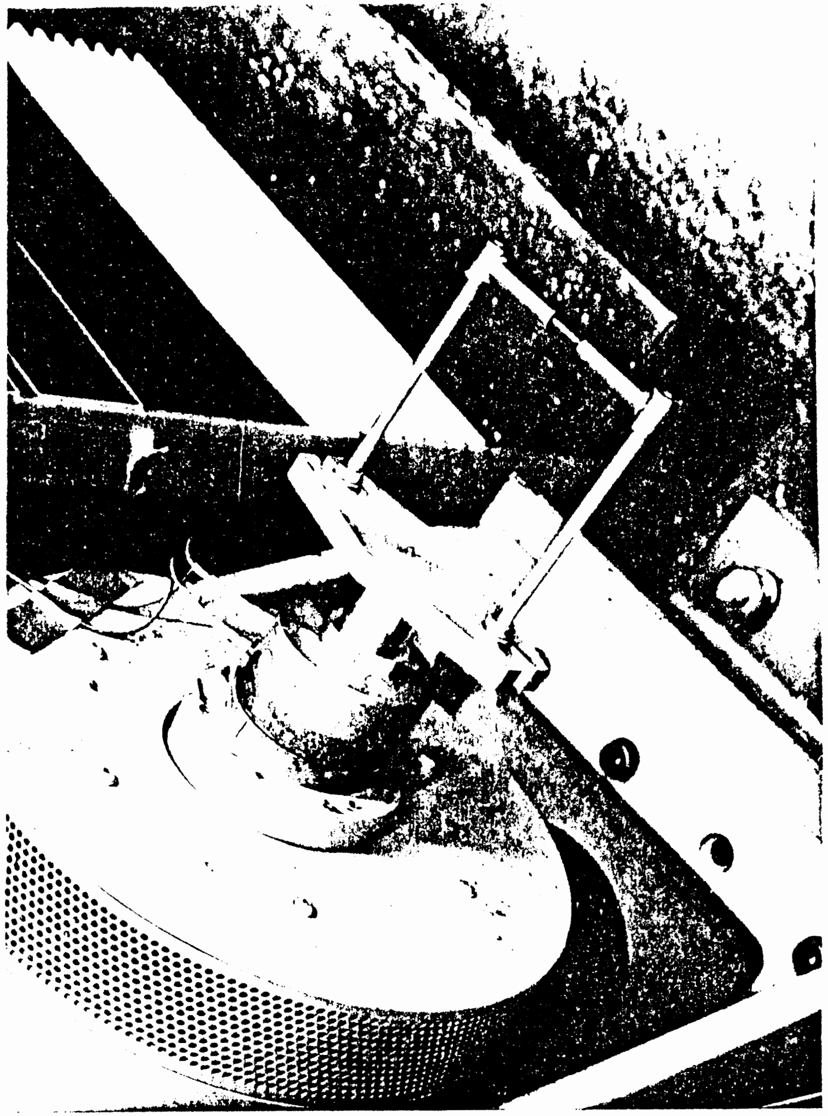


FIGURE 6a. KNEE IMPEDANCE TEST FIXTURE

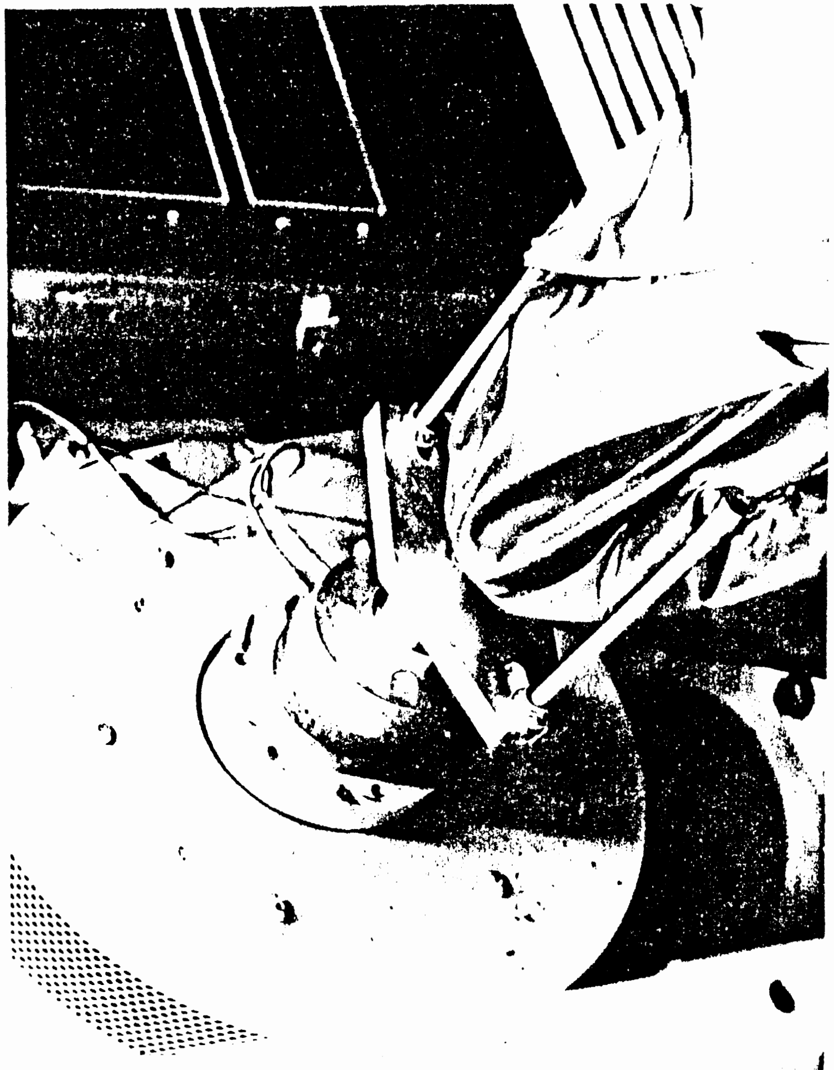


FIGURE 6b. KNEE IMPEDANCE TEST CONFIGURATION

EXPERIMENTAL RESULTS

Impact Tests

The results of the impact tests are presented here in groups according to the pertinent features of the test set-up and test subject. The test data are summarized in Tables 3, 4, 5, 6, 7 and 8.

General Impact Characteristics - Non-fracture producing impacts typically exhibited a double peaked waveform consisting of an initial high load peak followed by a lower, longer duration secondary peak. Such a waveform is shown in Figure 7a. Analysis of the mechanics of the impact cannon method of operation indicates that the first load peak is associated with the striker piston, while the second load peak is associated with the transfer piston. Thus, the two impact masses are not coupled at the initiation of impact with the knee. Comparison of the integral of the total force-time history (impulse) for high load level non-fracture test waveforms with the total available momentums of the two piston system indicates that the total momentums of the two piston masses were transferred to the knee. Exceptions to this occurred when very low level impacts were attempted and when short stroke limits were used in early tests. The transfer of momentum at low impact levels appears to depend on the cadaver mass also.

Fracture producing impacts typically exhibited only the first load peak with the secondary load peak diminished greatly in magnitude or not present at all. This is shown in Figure 7b. Fractures usually occurred during the first load portion of the test and, as discussed above, are associated with the loading due to the striker piston. In the fracture producing tests the failure of the skeletal structure precluded the interaction of the knee and striker piston with the transfer piston. In the test result tables the force durations listed are for the initial high load waveform and are designated primary force durations.

A typical strain gage rosette output set for a subfracture test is shown in Figure 8.

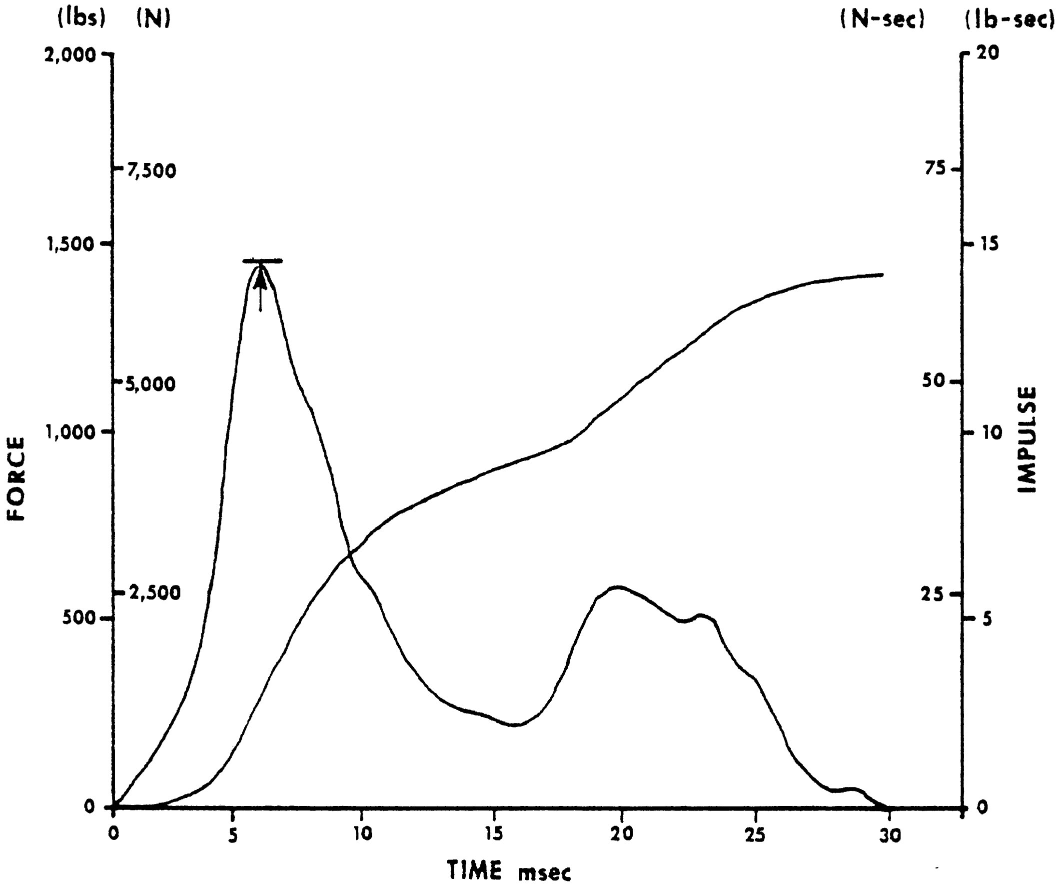


FIGURE 7a. SUBFRACTURE DATA TRACE
TEST NO. 75A033

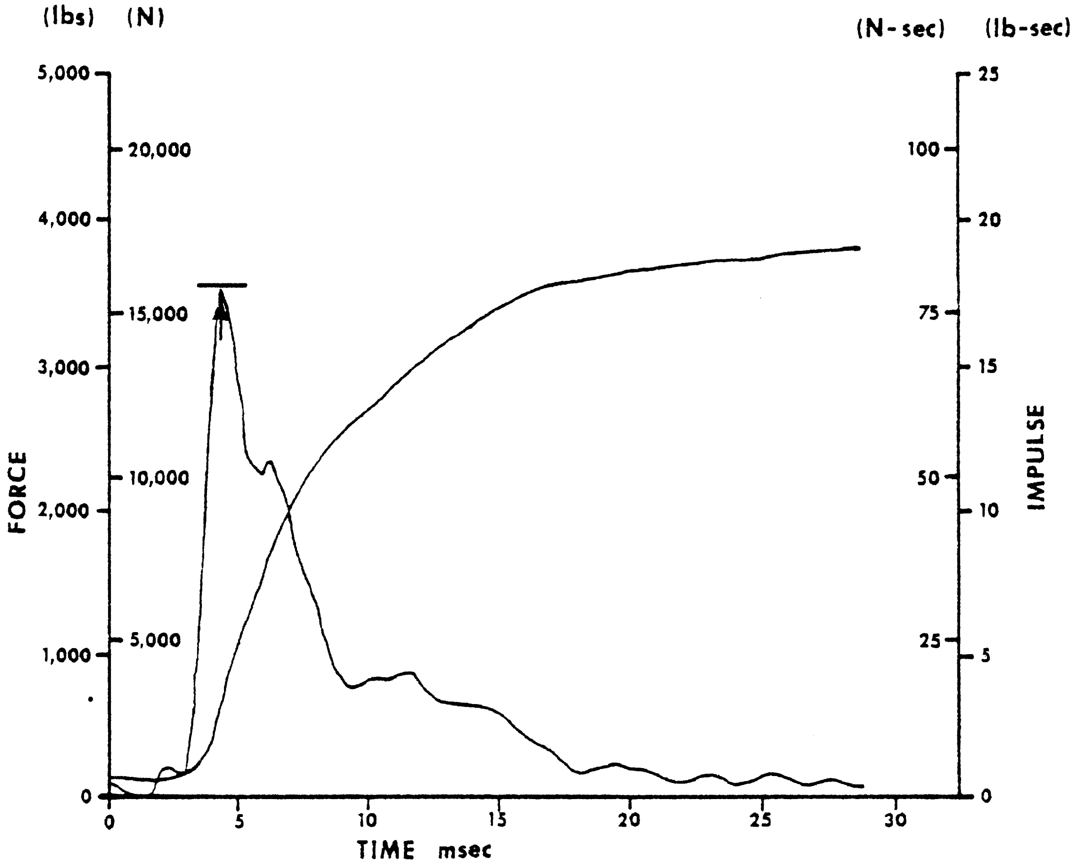
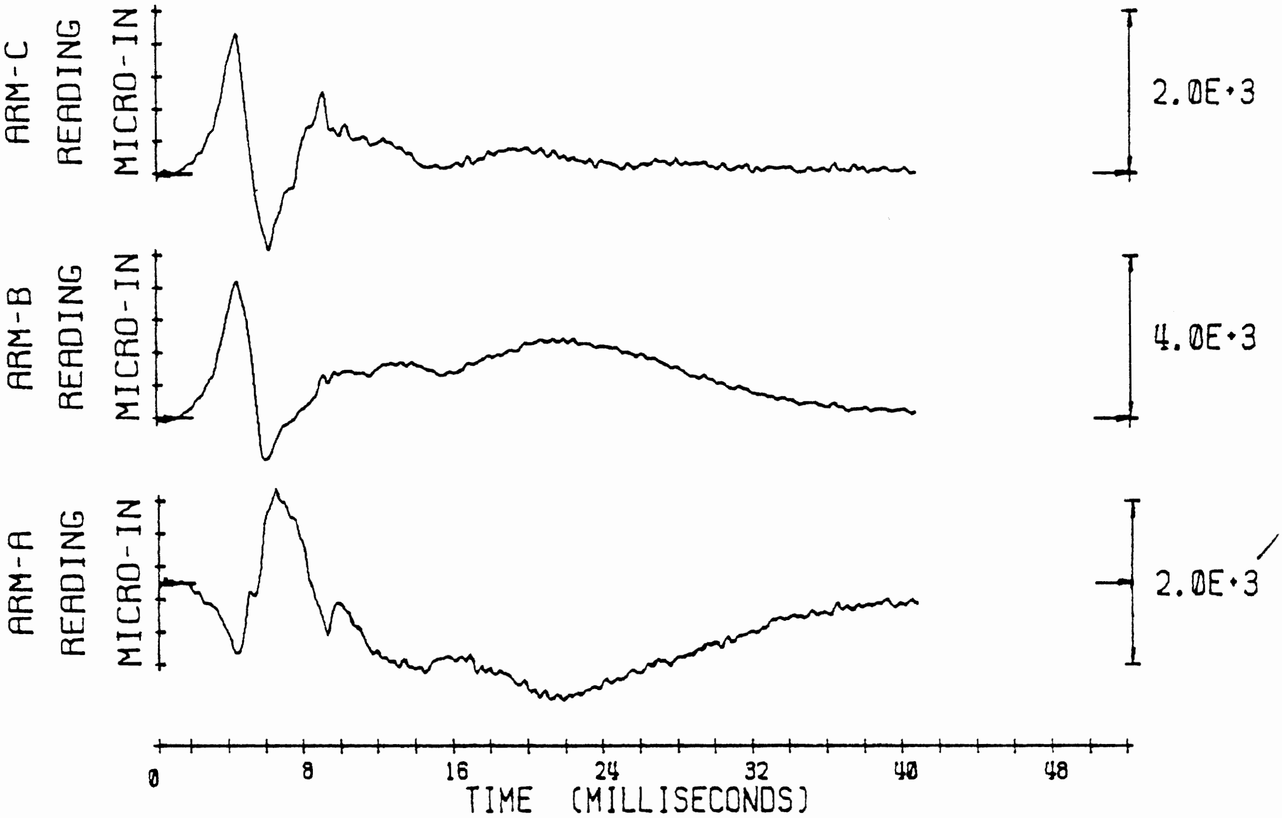


FIGURE 7b. FRACTURE DATA TRACE
TEST NO. 75A034
(SAME LEG AS IN FIG. 7a)



DELTA ROSETTE STRAIN GAGE

FIGURE 8. TYPICAL STRAIN GAGE DATA TRACE
TEST NO. 75A040

Lightly Padded Impacts - The largest number of tests -- thirty separate impacts -- were conducted with the lightly padded impact surface which consisted of 1 in. (2.54 cm.) of Ensolite padding. The test results are summarized in Table 3. In early tests, the impact velocity was kept low (in the 20-23 ft/sec (6.1 - 7.0 m/sec.) range) as was the impactor stroke (2.5 in. (6.4 cm.)) in order to prevent expected overdriving of the knee structure based on the existing data from other studies. The results were quite the contrary, however, with loads well in excess of the FMVSS 208 level and yet no fractures were produced. Five tests were conducted on five separate legs with the same general results. On the sixth test (V-4 in Table 3) both the impact velocity and the impactor stroke were increased and a fracture of the femur was produced. Subsequent to that test, it was decided to conduct a low velocity impact to each knee for subfracture response data and then follow up with a higher velocity impact to obtain fracture loads. It was also found that the orientation of the lower leg relative to the upper leg influenced the position of the patella to a great extent and that a lower leg position slightly greater than a 90° flexion was desirable to position and align the patella along the central axis of the femur. The average maximum force sustained by the test subjects where no damage occurred was 4023 lbs. (17.7 kN) with a range Of 2300-5560 lbs. (10.2 - 24.7 kN). The average maximum fracture-producing force was 4134 lbs. (18.4 kN) with a range of 3000 - 6400 lbs. (13.3 - 28.5 kN).

Lightly Padded Impacts with Abnormal Test Subject Conditions - It is well known that the strengths of skeletal structures in the body tend to decrease with age after 30 - 40 years. The data presented in Table 3 do not appear to reflect this factor. Another influence on the strength of long bones of the leg has been shown to be cyclic loading associated with everyday activity. The general condition of the majority of the cadavers used in the test program were indicative of relatively little inactivity prior to death. A few cadavers which were tested were obviously emaciated and otherwise characteristic of long-term disabling illness prior to death. The data from such cases was not included in Table 3 because of the special circumstances of the subject's condition. A third factor in bone strength is the presence of degenerative bone disease (known generally as osteoporosis). Examination of the cross-sectional characteristics of the shaft of the femur after testing was used to check for degeneration. In such cases the cross-sectional changes include an increased diameter of the cross-section accompanied by a marked decrease in the cortical bone thickness. Those tests where such conditions were found to exist were also excluded from Table 3.

An additional abnormal factor was introduced in two tests where the test subject (which had been used on another project which did not involve loads being applied to the legs) had screws inserted laterally into the femoral shaft for motion analysis. The two tests with screw holes in the femur represent an unnatural situation in the bone structure but one not unlike the effect of orthopedic implants. The fracture loads were less than one-half the average value obtained in Table 3 and are indicative of the stress concentration effect in a brittle material such as bone. These tests were also excluded from Table 3.

Table 4 lists the summarized results of the knee impact tests in which abnormal test subject conditions were judged to play a significant role in the test results. The mean value of the fracture loads was 1730 lbs. (7.7 kN) with a range of 1400-2356 lbs. (6.2 - 10.5 kN).

<u>Rigid Surface Impacts</u> - A series of seven axial knee impacts with minimal or no surface padding on the impactor were performed. The purpose of the tests was to study the effects of short duration-high force level localized loading on the fracture response of the knee. Fractures of the patella only were produced in two cases, fractures of patella and femur occurred in one case as did a femur fracture without patellar fracture. In three cases, no fractures were produced. The test data are summarized in Table 5. The average value of peak axial force for the cases where no fracture occured was 4487 lbs. (19.9 kN) with a range of 3640 - 5100 lbs. (16.2 - 22.7 kN). The average value of peak axial fracture load was 4408 lbs. (19.6 kN) with a range or 3840 - 5530 lbs. (17.1 - 23.7 kN).

Thickly Padded Impacts - A series of five tests with thickly padded impact surfaces were performed. The padding consisted either of one inch (2.5 cm.) of Ensolite backed by two inches (5.1 cm.) of aluminum honeycomb (Hexcel) or in some tests just the honeycomb material. The summary of the test data is listed in Table 6. Fractures of the femur were produced in three of the five tests -- no patellar injury was produced in any of the tests. Due to malfunctions of the test equipment, only one of the three fracture loads was obtained -- however, it was the most interesting one of the test series, in that the mode of failure appeared to be related to the shaft bending rather than supracondylar fractures which the other two fractures exhibited. This failure occurred at a load of 4420 lbs (19.7 kN).

Knee Impacts with Laterally Rotated Thighs - A series of nine impact tests (summarized in Table 7) were conducted with the thigh of the subject abducted (rotated laterally). The purpose of the tests was to investigate the influence of this rotated position in producing pelvic and proximal femur fractures. Initial tests were conducted with the thigh at an angle to the direction of impactor travel (that is, the impact direction was parallel to the anterior-posterior direction of the subject's body, while the leg was at an angle to that direction). It was found that it was not possible to transfer much load to the knee in this configuration at an angle of 25 degrees -- it simply moved with the impactor and rotated out of the way of the impact. At an angle of 11 degrees, the femurs of one test subject were fractured, but at relatively low load levels. Post-test examination indicated that an osteoporotic condition contributed to the low fracture load levels. Subsequent tests were performed with the subject's thigh abducted but with the body axis rotated such that the impactor direction was along the femoral axis. As shown in Table 7, these tests were successful in producing femoral fractures but still of the distal region of the femur -- no pelvic or proximal femur injuries were found. Thus these two tests (75A058 and 75A059) should be considered the same type as the lightly padded tests of Table 3.

Dummy Knee Impact Tests - In order to compare the response of the Part 572 test dummy leg structure to knee impact conditions similar to those producing fractures in the cadaver tests, a short series of knee impacts (listed in Table 8) were performed. In the rigid impact, the dummy produced striker input loads on the order of 60% greater than the comparable average cadaver striker input load. For the lightly padded knee impacts, the response difference was more pronounced with an 86.5% higher load produced for the same input momentum level. The striker input loads produced were greater than the calibrated range of the dummy femur load cell and therefore no comparison could be made between them.

In the thickly padded tests, the comparison between dummy and average cadaver striker input loads was reversed -- the dummy produced peak loads on the order of 74% of the average peak cadaver load. This difference was judged to be due to the knee construction of the Part 572 dummy which features a narrow, rigid load surface covered by minimal padding. Penetration of the padding used on the impactor was more localized with the dummy when compared with the deformations produced by the cadavers. The loads indicated by the femur load cell in the dummy were also 74% of the measured input load in the thickly padded tests.

Impedance Tests

A total of four impedance tests were conducted on two unembalmed cadavers not used in impact tests. The driving point impedance of two of the subjects is shown in Figure 9. Two live volunteers were also tested by removing the threaded rods and T-bolts of the test fixture and pressing their knee voluntarily against the knee plate in a semi-squatting position. A Part 572 dummy was also tested. The driving point impedance of the two volunteers and the dummy are also shown in Fig. 9. A constant peak acceleration level of 12 G was used as the input in all tests and the frequency range was swept from 50 to 500 Hz. The main feature of the driving point impedance tests was the occurrence of pronounced resonance in the femur at frequencies between 150 and 400 Hz for the cadavers and between 100 and 200 Hz for the volunteers. In the transfer impedance tests of the cadavers, with a constant driving acceleration of 12 G, the ratio of transfer point

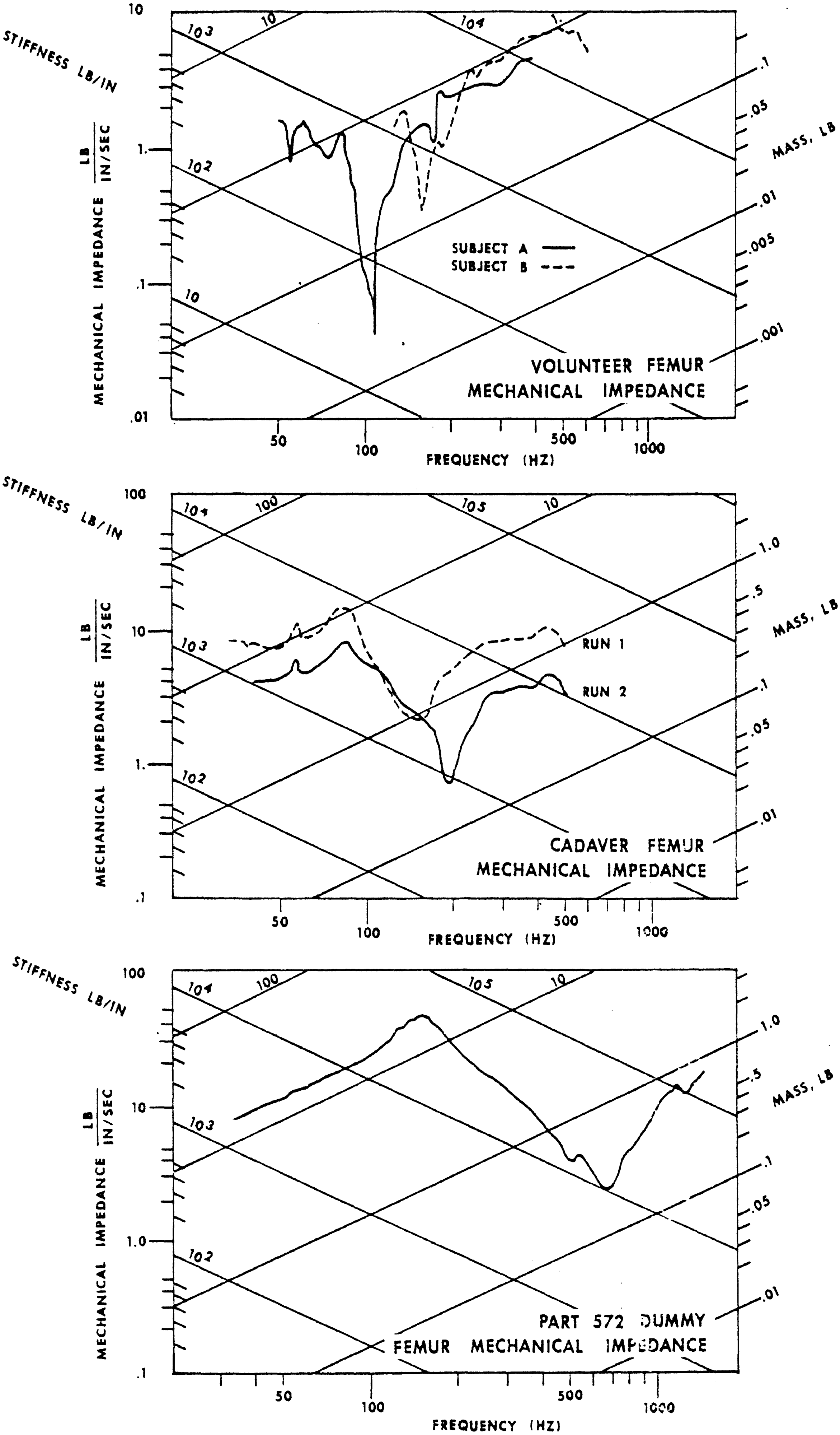


FIGURE 9. FEMUR MECHANICAL IMPEDANCE

acceleration to driving point acceleration dropped to the 50% level by the 100-200 Hz range and to the 10% level above 500 Hz. The Part 572 dummy exhibited a different response than the cadavers and volunteers -- primarily a higher effective mass response at frequencies below 200 Hz and a very high resonant frequency of 700 Hz.

DISCUSSION OF RESULTS

The majority of fractures produced in this study have been in the distal third and supracondylar region of the femur and patella. A typical fracture is shown in Figure 10. No discernible damage has been produced in the proximal end of the femur or pelvis as determined by radiographic examination and dissection. In view of the findings of the accident data analysis presented earlier in this report, the well-controlled geometry of the test situation used in this study should tend to produce distal region failures. In those tests where oblique impacts were applied to the knee, it was not possible to transfer a great deal of impact momentum to the knee using the present test techniques. Instead, the upper leg would just rotate away from the impactor. Axial impacts to abducted legs still produced distal failures with no apparent damage or fracture to the pelvis shaft or proximal end of the femur.

In most tests the fracture occurred during the first loading peak (assessed by the fall-off of the trace after the first peak and by the diminution or non-existence of the second peak). Two notable exceptions to this were test number 75A123 (a high velocity-low mass striker piston) where fracture of the patella occurred during the second peak -- apparently due to insufficient kinetic energy of the striker piston -- and in test number 75A104 (a thickly padded test) where the padding crushed in a manner which allowed the two pistons to become coupled during the loading and which produced a bending failure of the shaft of the femur. A plot of peak force versus available striker piston kinetic energy is shown in Figure 11 for the various test conditions used in the program. The kinetic energy was calculated from the velocity and mass of the striker piston except for the two previously noted tests where the masses of both pistons were included. (The data from the abnormal test subject conditions, listed in Table 4, are not included in Figure 11). Examination of the graph indicates that peak force alone is not an adequate indicator of potential fracture and that the available kinetic energy of the impact must also be above a threshold level for fractures of the knee region to occur. From the data shown in Figure 11, it appears that

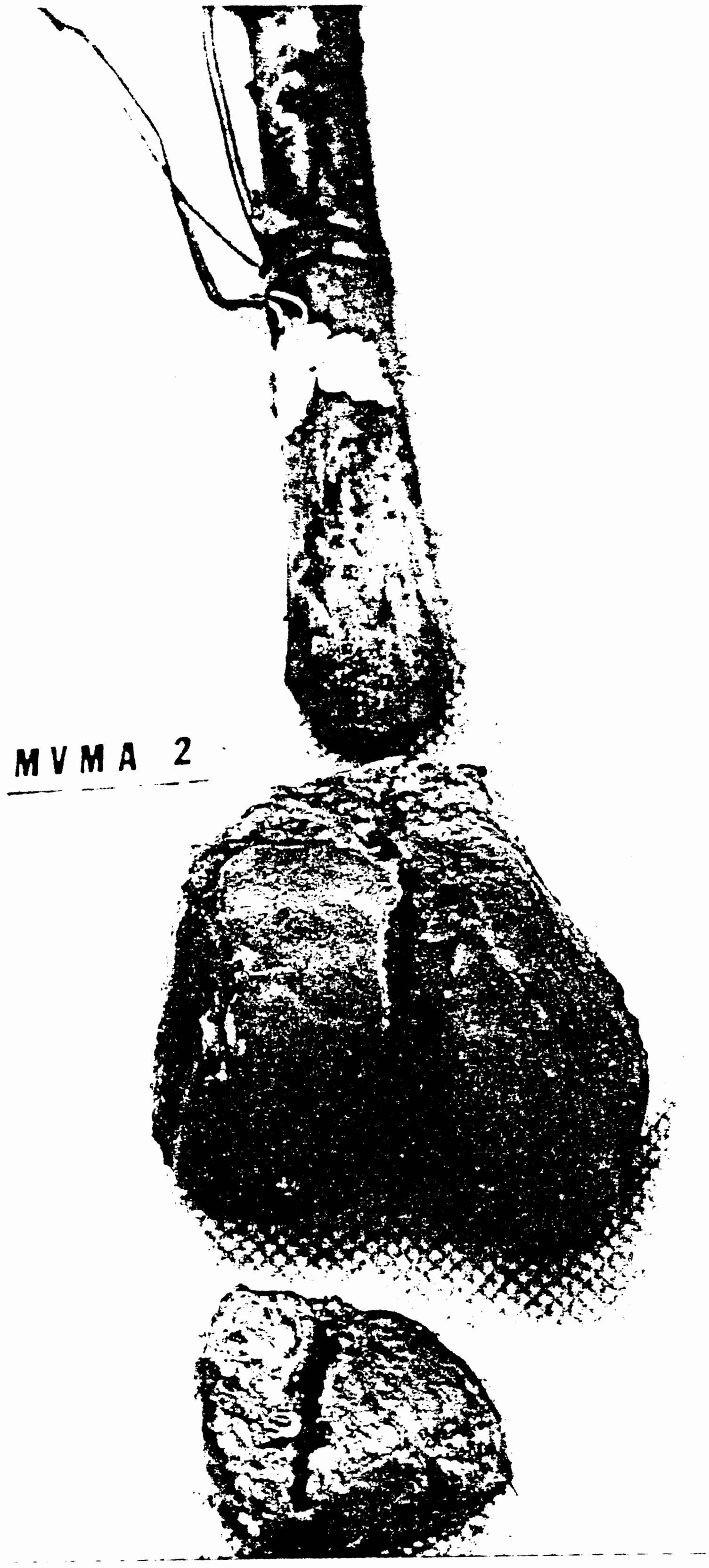


FIGURE 10. TYPICAL SUPRACONDYLAR FRACTURE

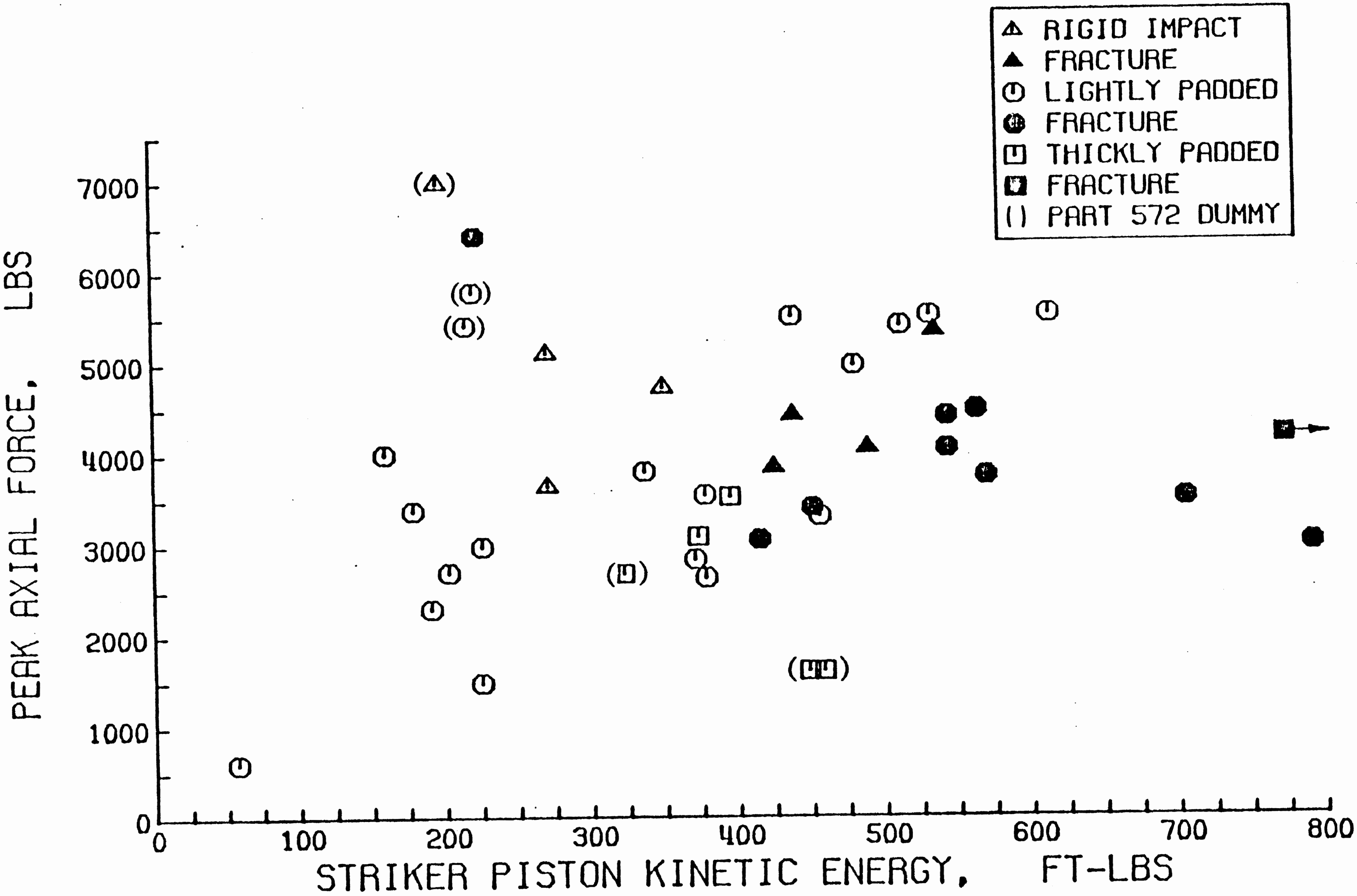


FIGURE II. PEAK AXIAL FORCE VERSUS AVAILABLE STRIKER PISTON KINETIC ENERGY a minimum axial force level of 3000 lbs. (13.35 kN) and a threshold kinetic energy level of 400 ft. lb. (542 J) are necessary to produce distal failures of the femur or patella.

Direct application of the data generated in this study to the interpretation of dummy test results cannot be made due to the lack of biomechanical equivalence of the dummy knee-femur-pelvis complex when compared to that of the human. The dummy structure is at variance with the human structure in terms of mass distribution, mechanical stiffness, and, in the knee, shape. These variances manifest themselves in the following manner:

a. In both the rigid and lightly padded impacts the Part 572 dummy produced considerably higher forces of shorter duration when compared to average cadaver test data at the same input energy level -- this can be the result of both higher stiffness and mass of the structure.

b. The driving point impedance test with the Part 572 produced a response which indicated a higher active mass and a higher resonant frequency (a higher stiffness and mass indication) than found in the human.

c. In the highly padded impact test, the knee shape of the Part 572 dummy localized the loading of the padding and produced a slightly lower crush load than obtained with the cadavers.

An additional factor which complicates the interpretation of dummy crash test knee loading data, even with a biomechanically correct lower extremity structure, is that it is not possible to determine the input kinetic energy level of the impact directly from the transducer data. As an alternative, it is possible to consider the momentum transfer associated with the impact. Although the transferred momentum is not as effective an indicator of the nature of the impact as the kinetic energy level is, it can be inferred from the integral of the force-time trace (the impulse associated with the impact).

In Figure 12 the peak axial force data is plotted versus the approximate impulse (obtained by idealizing the first load-time peak in terms of a triangle whose height is the peak force and whose base is the initial force peak duration) associated with the first load peak. Only the non-fracture data is plotted since when fracture occurs, the waveform no longer represents the response of the total system. Examination of the data shown in Figure 12 indicates that, at the 3000 lb (13.35 kN) force level, the estimated impulse produced in the tests ranges from 8 lb. sec. upward. This value corresponds to a time duration of 5.33 msec. The creation of force-time waveforms of shorter duration using cadavers would require test conditions which would be quite remote from the automotive interior impact situation (that is, it would require very rigid impact surfaces with very high impact velocities). The presence of high force peaks of short duration (less than 5 msec.) in dummy crash test data would appear, then, to be artifacts which are due to lack of biomechanical similarity and the general rigidity of the structural components of the dummy knee-femur-pelvis complex.

Analysis of the strain gage data has shown pronounced bending strain distributions in the shaft of the femur under axial knee impact. The results of such an analysis are shown in Figure 13 in terms of the orientation of the neutral axis of the strain distribution with respect to the axis of the femoral neck. The eccentricity produced by the femoral neck appears to be responsible for the resulting bending strains. The bending effect is most pronounced in the results of the thickly padded impact test 75A104 in which the deformable padding tended to pocket the knee and produce eccentric loading with the result that a bending failure of the shaft of the femur occurred at a load level of 4420 lbs. (19.7 kN). This is indicative of the need to differentiate between axial force levels in the femur without large bending moment inputs due to loading eccentricity and those cases where the input loads also produce input bending moments acting on the femoral shaft when discussing tolerance to the femur "force."

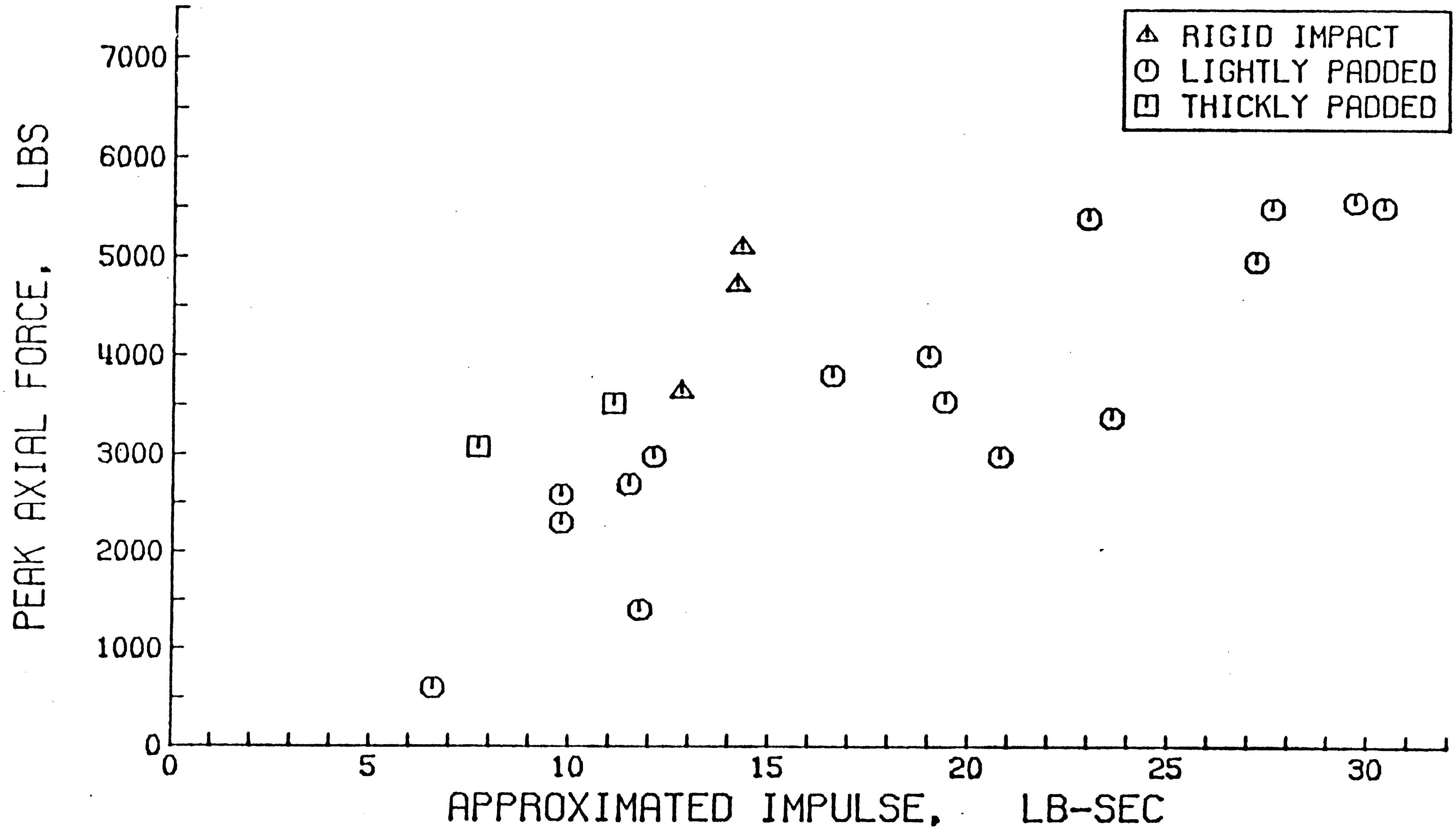


FIGURE 12. PEAK AXIAL FORCE VERSUS APPROXIMATED IMPULSE

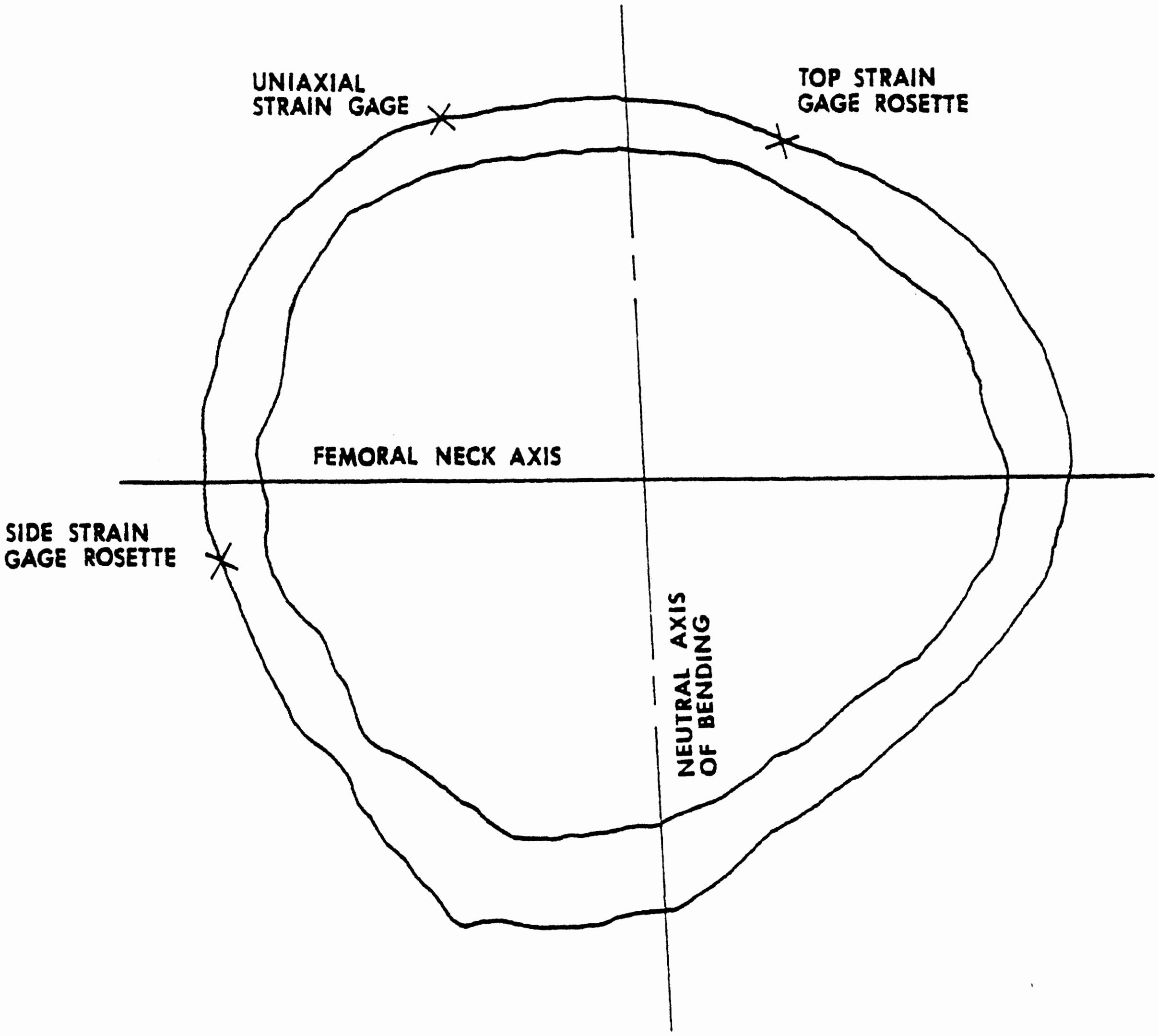


FIGURE 13. LOCATION OF BENDING AXIS RELATIVE TO THE FEMORAL NECK AXIS - TEST NO. 75A040

The characteristic fracture pattern shown in Figure 10 is much less comminuted than those shown by Powell, et al. (6) for embalmed bones. This may indicate the basic reason for higher fracture loads in this study using unembalmed subjects. The degree of comminution or shattering of the bone material could be interpreted as an indicator of the fracture toughness of the bone material. That is, the fracture toughness of embalmed bone may be much lower than that of unembalmed bone, and thus embalmed bone may not be a good model of the living human femur for purposes of determining load-bearing tolerance. The embalming process replaces the water in bone with the embalming chemicals and in this way could modify the bonding of the bone microstructure. Such effects would influence the fracture toughness of the bone material more significantly than it would the ultimate tensile strength of strain (10).

CONCLUSIONS

The results of the tests performed in this program indicate the following conclusions:

1. The axial load carrying ability of the knee-femur-pelvis complex of unembalmed cadavers is greater than that determined by other researchers using embalmed cadavers.

2. The femur load response of the Part 572 test dummy cannot be directly related to the responses of cadavers due to a lack of bio-mechanical equivalence of the dummy structure.

3. For distal failures of the femur and patella the peak axial force is not an adequate indicator of potential fracture and the kinetic energy level associated with the impact must also be considered.

4. Analysis of the state of strain existing in the femoral shaft during axial knee impact indicates that significant bending moments are produced.

TABLE 2 TEST SUBJECT DATA

TEST NUMBER	CADAVER NUMBER	HEIGHT in (cm)		WEIGHT lbs (kg)		AGE yrs.	SEX
V-1,L-R	LOD	66	(168)	149	(55.6)	90	M
V-2	LOD	LOD		133	(49.6)	57	M
V-3;L-R	LOD	69.5	(177)	178	(66.4)	51	M
V-4	LOD	LOD		128	(47.8)	85	F
V-5	LOD	LOD		184	(68.7)	77	M
M-2-4	20033	LOD		LOD		62	M
74A006-74A009	20089	64	(163)	237	(88.5)	55	M
75A033-75A036	20122	64	(163)	150	(56.0)	45	F
75A037-75A040	20117	70	(178)	106	(39.6)	66	M
75A058-75A059	20166	65	(165)	155	(57.9)	67	F
75A062	20185	70	(178)	135	(50.4)	46	M
75A069-75A070	20218	67	(170)	118	(44.0)	60	M
75A071-75A072	20219	LOD		116	(43.3)	74	F
75A073-75A074	20225	70	(178)	198	(73.9)	57	M
75A075-75A078	20229	68.4	(174)	188	(70.2)	68	M
75A097-76A098	20272	65.2	(166)	81	(30.2)	69	F
75A099-75A100	20282	67.6	(172)	168	(62.7)	64	M
75A101-75A102	20291	64.3	(163)	177	(66.1)	72	M
75A103-75A104	20289	64.4	(164)	125	(46.7)	55	F
75A117-75A118	20333	60	(152)	97	(36.2)	66	F
76A122-76A123	20375	LOD		LOD		53	M
76A131-76A132	20401	71	(180)	179	(66.8)	65	M
76A142-76A143	20429	60.3	(153)	48	(21.9)	89	F
76A150-76A151	20459	62.8	(159.5)	177	(65.9)	78	F
76A157-76A158	20460	63.1	(160)	LOD		66	F
76A163	20474	59	(150)	107	(39.9)	76	F

LOD = Loss of Data

TABLE 3. CADAVER AXIAL KNEE IMPACT DATA - LIGHT PADDING (ONE INCH OF ENSOLITE)

TEST NUMBER (CADAVER NUMBER)	LEG	IMPACT VELOCITY	STROKE	STROKE PISTON KINETIC ENERGY	PEAK AXIAL FORCE	PRIMARY FORCE DURATION	TEST RESULTS
		ft/sec (m/sec)	inches (cm)	ft lbs. (joules)	lbs (kN)	msec	
V-IL (-)	L	22.6 (6.9)	2.5 (6.4)	191 (259)	2300 (10.23)	8.5	No fractures.
V-1R (-)	R	23.3 (7.1)	2.5 (6.4)	203 (275)	2700 (12.01)	9.0	No fractures.
V-2 (-)	L	20.7 (6.3)	2.5 (6.4)	160 (217)	4000 (17.79)	9.5	No fractures.
V-3L (-)	L	21.9 (6.7)	2.5 (6.4)	179 (243)	3376 (15.02)	14.0	No fractures.
V-3R (-)	R	35.8 (10.9)	2.5 (6.4)	480 (651)	4961 (22.07)	11.0	No fractures.
V-4 (-)	R	38.1 (11.6)	4.25 (10.8)	543 (736)	4400 (19.57)	8.0	Fracture.
V-5 (-)	R	34.2 (10.4)	2.25 (5.7)	438 (594)	5500 (24.47)	10.0	No fractures.
M-2 (20033)	R	-	2.0 (5.1)	-	860 (3.83)	18.0	No fractures.
M-3 (20033)	R	30.0 (9.1)	2.0 (5.1)	337 (457)	3800 (16.90)	14.0	No fractures.
M-4 (20033)	R	38.1 (11.5)	2.0 (5.1)	543 (736)	4050 (18.01)	8.0	Fracture.

TABLE 3. CADAVER AXIAL KNEE IMPACT DATA - LIGHT PADDING (ONE INCH OF ENSOLITE) (Continued)

TEST NUMBER (CADAVER NUMBER)	LEG	IMPACT VELOCITY	STROKE	STRIKER PISTON KINETIC ENERGY	PEAK AXIAL FORCE	PRIMARY FORCE DURATION	TEST RESULTS
		ft/sec (m/sec)	inches (cm)	ft lbs (joules)	lbs (kN)	msec	
74A006 (20089)	R	12.4 (3.8)	4.0 (10.2)	57 (77)	600 (2.67)	22.0	No fractures.
74A007 (20089)	R	31.8 (9.7)	4.0 (10.2)	378 (513)	3540 (15.74)	11.0	No fractures.
74A008 (20089)	L	24.6 (7.5)	4.0 (10.2)	226 (306)	2980 (13.25)	14.0	No fractures.
74A009 (20089)	L	37.7 (11.5)	4.0 (10.2)	532 (721)	5510 (24.51)	11.0	No fractures.
75A033 (20122)	R	24.5 (7.5)	4.0 (10.2)	225 (305)	1480 (6.58)	15.9	No fractures.
75A034 (20122)	R	43.4 (13.2)	4.0 (10.2)	705 (956)	3500 (15.57)	9.4	Fracture - supracondylar shaft fracture - no patellar fracture.
75A072 (20219)	L	34.9 (10.6)	4.5 (11.4)	456 (618)	3300 (14.68)	-	No fractures.
75A099 (20282)	R	38.8 (11.8)	4.0 (10.2)	563 (763)	4470 (19.88)	8.2	Fracture - supracondylar shaft fracture - no patellar fracture.
75A100 (20282)	L	33.3 (10.1)	4.0 (10.2)	415 (563)	3050 (13.56)	7.3	Fracture - condylar and supracondylar shaft fractures - no patellar fracture.
75A103 (20289)	R	40.5 (12.3)	4.0 (10.2)	614 (833)	5560 (24.73)	10.7	No fractures.

TABLE 3. CADAVER AXIAL KNEE IMPACT DATA - LIGHT PADDING (ONE INCH OF ENSOLITE) (Continued)

TEST NUMBER (CADAVER NUMBER)	LEG	IMPACT VELOCITY	STROKE	STRIKER PISTON KINETIC ENERGY	PEAK AXIAL FORCE	PRIMARY FORCE DURATION	TEST RESULTS
		ft/sec (m/sec)	inches (cm)	ft lbs (joules)	lbs (kN)	msec	
75A117 (20333)	R	31.7 (9.7)	4.0 (10.2)	376 (510)	2920 (12.98)	8.5	No fractures.
75A118 (20333)	L	32.0 (9.8)	4.0 (10.2)	383 (519)	2680 (11.92)	7.3	No fractures.
75A122 (20375)	L	37.0 (11.3)	4.0 (10.2)	512 (694)	5400 (24.02)	8.5	No fractures.
75A123 (20375)	R	55.6 (16.9)	4.0 (10.2)	223 (302)	6400 (28.46)	5.3	Fracture - condylar and supracondylar shaft fractures - comminuted patellar fracture.
76A131 (20401)	R	62.0 (18.9)	4.0 (10.2)	567 (769)	3800 (16.90)	4.7	Fracture - severely comminuted patellar fracture.
76A132 (20401)	L	58.8 (17.9)	4.0 (10.2)	510 (692)	-	-	Fracture - severely comminuted patellar fracture.
76A150 (20459)	R	39.4 (12.0)	2.0 (5.1)	581 (788)	-	-	Fracture - patellar fracture.
76A151 (20459)	L	46.0 (14.0)	2.0 (5.1)	791 (1073)	3000 (13.34)	7.4	Fracture - condylar and supracondylar shaft fractures - comminuted patellar fracture.

TABLE 4. CADAVER AXIAL KNEE IMPACT DATA - ABNORMAL TEST SUBJECT CONDITIONS

TEST NUMBER (CADAVER NUMBER)	LEG	IMPACT VELOCITY	STROKE	STRIKER PISTON KINETIC ENERGY	PEAK AXIAL FORCE	PRIMARY FORCE DURATION	TEST COMMENTS AND RESULTS
		ft/sec (m/sec)	inches (cm)	ft lbs (joules)	lbs (kN)	msec	
75A069 (20218)	R	31.8 (9.7)	2.0 (5.1)	378 (512)	1690 (7.52)	10.0	Light Padding - Femur Fractured at a target screw hole.
75A070 (20218)	L	23.8 (7.3)	2.0 (5.1)	212 (287)	1600 (7.12)	12.0	Light Padding - Femur Fractured at a target screw hole.
76A142 (20429)	R	76.0 (23.2)	4.0 (10.2)	852 (1154)	-	-	Light Padding - Osteoporotic Bone - Comminuted Condylar Fracture.
76A143 (20429)	L	65.8 (20.1)	4.0 (10.2)	639 (866)	1660 (7.38)	4.0	Minimal Padding - Osteoporotic Bone - Comminuted Condylar Fracture.
76A157 (20460)	R	35.5 (10.8)	1.0 (2.5)	472 (639)	1800 (8.01)	5.9	Minimal Padding - Osteoporotic Bone - Patellar Fracture.
76A158 (20460)	L	36.7 (11.2)	1.0 (2.5)	504 (683)	1740 (7.74)	4.3	Minimal Padding - Osteoporotic Bone - Supracondylar Shaft Fracture.
76A163 (20474)	R	45.6 (13.9)	1.0 (2.5)	778 (1054)	1400 (6.23)	5.3	Minimal Padding - Osteoporotic Bone - Condylar Fracture.

TABLE 5. CADAVER AXIAL KNEE IMPACT DATA - RIGID IMPACT SURFACE

TEST NUMBER (CADAVER NUMBER)	LEG	IMPACT VELOCITY	STROKE	STRIKE PISTON KINETIC ENERGY	PEAK AXIAL FORCE	PRIMARY FORCE DURATION	TEST RESULTS
		ft/sec (m/sec)	inches (cm)	ft lbs (joules)	lbs (kN)	msec	
75A071 (20219)	R	35.4 (10.8)	4.0 (10.2)	469 (636)	4050 (18.02)	2.6	Fracture - condylar fracture - patellar fractures.
75A073 (20225)	L	33.7 (10.3)	3.0 (7.6)	425 (576)	3840 (17.08)	6.6	Fracture - comminuted patellar fracture.
75A074 (20225)	R	37.8 (11.6)	3.0 (7.6)	535 (725)	5330 (23.7)	6.3	Fracture - comminuted patellar fracture.
75A075 (20229)	R	26.9 (8.2)	3.0 (7.6)	271 (367)	5100 (22.69)	5.6	No fracture.
75A076 (20229)	L	26.9 (8.2)	3.0 (7.6)	271 (367)	3640 (16.19)	7.0	No fracture.
75A077 (20229)	L	30.6 (9.4)	3.0 (7.6)	350 (475)	4720 (21.0)	6.0	No fracture.
75A078 (20229)	L	34.2 (10.5)	3.0 (7.6)	438 (594)	4410 (19.62)	5.2	Fracture - comminuted condylar fracture.

TABLE 6. CADAVER AXIAL KNEE IMPACT DATA - THICK PADDING

TEST NUMBER CADAVER NUMBER	LEG	IMPACT VELOCITY	STROKE	STRIKER PISTON KINETIC ENERGY	PEAK AXIAL FORCE	PRIMARY FORCE DURATION	TEST COMMENTS AND RESULTS
		ft/sec (m/sec)	inches (cm)	ft lbs (joules)	lbs (kN)	msec	
75A097 (20272)	L	31.5 (9.6)	4.0 (10.2)	371 (503)	-	-	Fracture - comminuted condylar and supracondylar fractures - no patellar fracture. Padding - one inch of Ensolite plus 2 inches of 1/4 inch cell Hexcel.
75A098 (20272)	R	29.9 (9.1)	4.0 (10.2)	335 (454)	-	-	Fracture - comminuted condylar fracture - no patellar fracture. Padding - one inch of Ensolite plus 2 inches of 1/4 inch cell Hexcel.
75A101 (20291)	R	32.5 (9.9)	4.0 (10.2)	395 (536)	3520 (15.66)	6.3	No fractures. Padding - 2 inches of 3/16 inch cell Hexcel.
75A102 (20291)	L	31.6 (9.6)	4.0 (10.2)	374 (507)	3080 (13.70)	5.0	No fractures. Padding - One inch of Ensolite plus 2 inches of 3/16 inch cell Hexcel.
75A104 (20289)	L	40.1 (12.2)	4.0 (10.2)	602 (816)	4420 (19.66)	10.7	Fracture - distal third shaft fracture. Padding - 2 inches of 3/16 inch cell Hexcel.

TABLE 7. CADAVER ABDUCTED KNEE IMPACT DATA

TEST NUMBER (CADAVER NUMBER)	LEG	ABDUCTION ANGLE	IMPACT VELOCITY	STRIKER PISTON KINETIC ENERGY	PEAK FORCE	PEAK AXIAL FORCE	PRIMARY FORCE DURATION	TEST RESULTS
			ft/sec (m/sec)	ft lbs (joules)	lbs (kN)	lbs (kN)	msec	
75A035 (20122)	L	25°	25.0 (7.6)	234 (317)	1200 (5.34)	1088 (4.84)	13.0	No fractures.
75A036 (20122)	L	25°	48.6 (14.8)	884 (1198)	3280 (14.59)	2972 (13.21)	13.1	No fractures.
75A037 (20117)	L	11°	18.7 (5.7)	131 (178)	720 (3.20)	706 (3.14)	13.7	No fractures.
75A038 (20117)	L	11°	45.8 (14.0)	785 (1064)	1860 (8.27)	1825 (8.12)	10.9	Fracture - osteoporotic bone - supracondylar fracture.
75A039 (20117)	R	11°	20.2 (6.2)	153 (207)	880 (3.91)	864 (3.84)	12.8	No fractures.
75A040 (20117)	R	11°	49.6 (15.1)	921 (1248)	2400 (10.68)	2356 (10.48)	10.9	Fracture - osteoporotic bone - supracondylar fracture.
75A058 (20166)	L	25° (Axial Load)	32.4 (9.9)	393 (533)	4800 (21.35)	4800 (21.35)	14.0	No fractures.
75A059 (20166)	R	25° (Axial Load)	34.7 (10.6)	451 (611)	4540 (20.19)	4540 (20.19)	8.0	Fracture - supracondylar fracture.
75A062 (20185)	L	25° (Axial Load)	51.3 (15.6)	985 (1335)	1350 (6.00)	1350 (6.00)	15.0	Thick padding (one inch of Ensolite plus four inches of styrofoam) No fractures.

TABLE 8. PART 572 DUMMY AXIAL KNEE IMPACT DATA

TEST NUMBER	LEG	IMPACT VELOCITY	STROKE	STRIKER PISTON KINETIC ENERGY	PEAK AXIAL FORCE	PRIMARY FORCE DURATION	TEST CONDITONS AND RESULTS
		ft/sec (m/sec)	in. (cm)	ft lbs (joules)	lbs. (kN)	msec	
75A079	R	23.0 (7.0)	3.0 (7.6)	198 (268)	6985 (31.07)	2.4	Rigid Impactor Surface - No Damage
75A080	R	24.3 (7.4)	3.5 (8.9)	221 (299)	5780 (25.71)	7.4	Lightly Padded (one inch Ensolite) - no damage.
75A081	L	24.0 (7.3)	3.5 (8.9)	216 (293)	5410 (24.06)	6.5	Lightly Padded (one inch Ensolite) - no damage.
76A182	L	35.0 (10.6)	4.0 (10.2)	458 (620)	1600 (7.12)	16.0	Thickly padded (one inch Ensolite + 2 inches of 1/4 inch cell Hexcel) - femur load cell indicated 1254 lbs (5.58 kN) peak load.
76A183	L	34.6 (10.5)	4.0 (10.2)	448 (607)	1600	16.0	Thickly padded (one inch Ensolite + 2 inches of 1/4 inch cell Hexcel) - femur load cell indicated 1123 lbs (5.00 kN) peak load.
77A219	L	30.9 (9.4)	4.0 (10.2)	320 (434)	2720 (12.10)	12.5	Thickly padded (one inch Ensolite + 2 inches of 3/16 inch cell Hexcel).

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