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16. Abstract

A series of six whole-body sled tests were conducted with unembalmed cadavers to study knee impact phenomena under simulated car crash conditions. The purpose of the study was to investigate the occurrence of upper leg fracture types not seen in stationary subject knee impact tests (see UM-HSRI-76-33) using a moving-mass impactor technique, and to extend the pulse durations of the knee forces to times greater than 20 ms. The tests were successful in achieving both goals. Major conclusions drawn from the test series were:

- Proximal upper leg injuries (femoral neck and shaft and pelvic fractures), which account for most upper leg injuries in real crashes, occurred with the whole-body knee impact test conditions used in this study.
- Femoral neck and acetabular fractures appear to produce a change in the rate of load transfer from the knee to the pelvis, while femoral shaft and extensive condylar fractures produce an abrupt drop-off in the load transferred from the knee to the pelvis. In these tests, neck and acetabular fractures, when they occurred, preceded the shaft and condylar fractures.
- The forces necessary to produce proximal leg fractures are similar in magnitude to those that produce distal knee injuries in impactor tests.

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Tolerance and Response of the Knee-Femur-Pelvis Complex to Axial Impacts - Impact Sled Tests

Draft Report
MVMA Project No. 1142

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INTRODUCTION

HSRI has been active in studying the impact tolerance and response of the knee-femur-pelvis complex for a number of years. The primary configuration of interest has been that of the seated automotive occupant undergoing a knee impact that is axially oriented with respect to the femoral shaft. An extensive study using a moving instrumented impactor which directly impacted the knee of the flexed leg of stationary, seated unembalmed cadavers has been reported as an earlier phase of this program (1)*. In that study it was found that the impact force and impactor energy levels necessary for the threshold of fracture of the femur or patella (knee cap) were 13.4 kN (3000 lbs) and 542 J (400 ft. lbs.), respectively, for bones without serious degeneration of the bone structure due to either disuse or disease. The impact force-time histories produced in those tests were characterized by time durations of 2.6 to 22 msec for the significant force waveforms.

Analytical modeling of axial femoral impact has indicated that for load durations above 20 ms. the failure loads for the femur approach static strength values (2). Viano (3) has suggested a femur injury criterion which includes the effect of load pulse duration in the following form:

$$F(\mathrm{kN}) = 23.14 - 0.71\,T(\mathrm{ms}), \quad T < 20 \text{ ms.}$$

$$F(\mathrm{kN}) = 8.90, \quad T > 20 \text{ ms.}$$

or

$$F(\mathrm{lb}) = 5200 - 160\,T(\mathrm{ms}), \quad T < 20 \text{ ms.}$$

$$F(\mathrm{lb}) = 2000, \quad T > 20 \text{ ms.}$$

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

The long duration load limit was based on static load values due to a lack of substantive experimental data.

The purpose of the research presented in this report is to investigate the effects of a more realistic occupant loading situation on knee impact response and tolerance. These effects include momentum effects and load duration effects. Sled testing techniques were used with unembalmed human cadavers to achieve a simulation of knee loading due to occupant motions during a car crash.

EXPERIMENTAL PROCEDURES

The test subjects in this study were unembalmed human cadavers.* The cadavers were kept under refrigeration at 4°C except when being prepared for testing or when being tested. The general descriptive data on the test subjects are listed in Table 1.

Preparation of the cadavers for testing involved surgical attachment of a pelvic accelerometer mount rigidly to the sacrum by bone screws and clothing the cadaver in a vinyl exercise suit followed by cotton thermal underwear, head cover, gloves and socks. After preparation, the cadaver was transported from the HSRI Biomedical Area to the Impact Sled Area.

A knee impact test configuration was developed to allow whole-body knee impact tests to be performed on the HSRI Impact Sled. A hard seat buck was modified for the purpose of allowing the test subject to translate forward such that the knees struck a load cell arrangement, mounted

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*The protocol for the use of cadavers in this study was approved by the Committee to Review Grants for Clinical Research and Investigations Involving Human Beings of the University of Michigan Medical Center and follows guidelines established by the U.S. Public Health Service and recommended by the National Academy of Sciences/National Research Council. The cadaver specimens were obtained through the gross anatomy program of the Department of Anatomy at the University of Michigan Medical School.

on the sled frame. In addition, a foot platform was constructed to locate the feet of the test subject and to allow adjustment of the leg-knee configuration at impact. The knee impact structure consisted of two uniaxial load cells (Kistler 933A piezoelectric force links) mounted horizontally and supporting a single impact surface plate. The test configuration is shown in Figure 1. The upper torso was fitted with a construction worker safety harness which was attached to the sled by a slack tether, such that the upper torso was restrained from forward motion only after full knee impact had taken place. The test subject was allowed to slide forward on the seat until knee contact occurred. The full momentum of the body was available to participate in the knee impact. Adjustment of the knee impact load plate was made to produce a duplication of the leg configuration used in the previous impactor tests (that is, horizontal femurs with the lower legs flexed to slightly greater than 90°).

The load cell arrangement, shown in Figure 2, uses two load sensing elements which are coupled by a flat plate attached across the cells. Because of this arrangement it is not possible to separate the load produced by one knee from the other. This configuration was chosed to minimize eccentric loading effects on the load cells which could appear if a single load cell and individual plate were used for each knee. Piezoelectric load cells are sensitive to eccentric loading (the maximum recommended bending moment for the 933A size load cell is 68nM) and it was felt that precise alignment of each knee with individual load cells was not feasible in this type of impact test. The plate which couples the two load cells is sufficiently stiff to minimize the bending moments on the load cells yet low enough in mass (3.4 lbs) to avoid load cell artifacts due to plate inertia. The plate also serves as a mounting surface for load-distributing foam materials used in the study.

Miniature piezoresistive accelerometers (Endevco 2264-200C) were mounted in a triaxial array on the pelvic accelerometer mount. The three directions of the axes of the array corresponded to the inferior-superior (I-S), right-left (R-L) and posterior-anterior (P-A) direction of the pelvis.

The HSRI Impact Sled is a rebound-type sled which uses a complete change of direction during impact to produce a desired velocity change. The test configuration and spacing of the knees of the test subject were chosen to allow essentially free forward motion of the subject relative to the sled during the time the sled decelerates, stops, accelerates, and rebounds from the sled programmer. Impact of the knees takes place after the sled has reversed its direction, and thus the forward motion of the subject is added to the rebound velocity of the sled to produce a desired approach velocity of the knees relative to the impact surface. At the time of knee impact there is no sled acceleration and thus the forces generated by the knee impact are solely due to the momentum of the test subject. High-speed movie coverage (1000 frames/sec) consisted of a lateral view, and accelerometer signals were recorded unfiltered on a FM analog tape recorder.

Following the test, the subject was returned to the Biomedical Area where detailed dissection of the knee, femur, and pelvis were conducted. The condition of the pertinent skeletal structures was noted and fractures were recorded.

Data Analysis Methods

The analysis of the test data produced by the tests in this program required careful consideration of both the force-time histories of the load cells and the acceleration-time histories of the pelvic accelerometers. The load cell force-time histories are the indicators of skeletal fracture events. Abrupt changes in the force-time waveform are related to the changes in the skeletal load-transmitting ability due to fractures of the bones in the load path between the subject's torso and the knee impact surface. In addition, the shape and nature of the force traces may be indicative of the type and/or sequence of fractures along the load path. The pelvic accelerations are useful as an aid in the interpretation of the kinematics of the test subject during the knee impact, even though complete three-dimensional acceleration data is necessary for a total analysis of the pelvic motions. Analysis of the individual acceleration traces in conjunction with the force-time histories allows indications of load transfer from the femur to the pelvis and of the occurrence of skeletal fractures in terms of abrupt changes in some of the components of pelvic acceleration.

TEST RESULTS

A total of six sled tests were conducted using the experimental techniques described in the preceding section. The following paragraphs summarize the test conditions and results.

Test 77A218: A baseline test was performed to simulate a typical impact cannon test condition with 2.5 cm of Ensolite vinyl closed-cell foam padding placed on the impact surface of the load cell plate. The test subject was a 75 year old male cadaver with a weight of 77.1 kg and a height of 179.6 cm. The sled velocity change was 8.3 m/sec. The unfiltered data traces are shown in Figure 3. The ranges of loads acting on the knee of each leg during the production of fractures were as follows:

Right Leg - An initial peak load of 15.3 kN was followed by various fracture activities with a final load level of 10.2 kN with subsequent drop-off in load. The skeletal fractures produced during the load sequence involved the neck and the condyles of the femur. The duration of the significant loading was 9 msec.

Left Leg - An initial peak load of 18.9 kN was followed by fracture activities leading to a final peak load of 23.0 kN before rapid drop-off in the load. The skeletal fractures included the neck and shaft (supracondylar) of the femur and the patella. There was condylar cracking in addition to the complete fractures noted above. The duration of the significant loading was 11 msec.

Because of the rapid rise in the load-time histories this test was considered to be more like a rigid (non-padded) cannon impact test in that respect, and it was decided to double the thickness of the padding in the next test.

Test 77A220: The test subject was a 49 year old male cadaver with a weight of 87 kg and a height of 188.4 cm. The sled velocity change was 9.5 m/sec, and five cm of Ensolite padding were used to extend the duration of the impact loads. The test data are shown in Figure 4. The range of loads acting on the knee of each leg during the production of skeletal fractures were:

> Right Leg - An initial peak load of 19.4 kN was followed by fracture activities leading to a final load level of 18.4 kN with subsequent rapid drop-off of the load. The skeletal fractures included the neck, medial condyle, and the shaft of the femur. The duration of the significant loading was 19 msec.
>
> Left Leg - An initial load peak of 21.3 kN was followed by fracture activities leading to a final peak load of 25.6 kN and then rapid drop-off in load. The skeletal fractures included the neck, medial condyle, and the shaft of the femur. The duration of the significant loading was 21 msec.

The duration of the impact loads was increased in this test as planned, but it was decided to produce a lower rate of loading by adding a crushable padding material in the next test.

Test 77A221: The test subject was a 79 year old male cadaver with a weight of 83 kg. The sled velocity change was 9.3 m/sec. The impact surface padding consisted of 2.5 cm of Ensolite padding backed with 2.5 cm of low-density construction insulation polystyrene foam. The unfiltered test data are shown in Figure 5. The range of loads acting on the knee of each leg during the production of skeletal fractures were:

Right Leg - The load reached an initial peak of 21.0 kN, followed by an immediate drop and recovery back to a secondary peak of 20 kN, followed by a rapid drop-off to about the 9 kN level and then diminished gradually after that. The skeletal fractures consisted of the patella, medial condyle, and shaft of the femur. The duration of the significant loading was 17 msec.

Left Leg - An initial peak of 19.8 kN was reached with subsequent fracture activity leading to a final peak load of 17.4 kN, followed by a rapid drop-off to about the 8 kN level with a gradual fall in load after that. The skeletal fractures occurred in the acetabulum of the pelvis, the condyles of the femur, and the patella. The duration of the signficant loading was 16 msec.

Since there was no major change in the load duration compared to the previous test, a greater depth of crushable padding was chosen for the next test.

Test 77A222: The test subject was a 58 year old female cadaver with a weight of 47.3 kg and a height of 159.0 cm. The sled velocity change was 9.5 m/sec and the impact surface padding consisted of 2.5 cm of Ensolite backed by 5 cm of low-density polystyrene foam. The unfiltered test data are shown in Figure 6. The load-time histories were unimodal in nature and the right knee load reached a peak of 6.2 kN while the left knee sustained a peak load of 8.1 kN. There were no fractures produced in this test. The low mass of the test subject and the increased depth of padding combined to limit the knee loads generated in this test. The durations of the significant loads were 33 msec for the right knee and 32 msec for the left knee. It was decided to retain this padding combination in subsequent tests.

Test 77A223: The test subject was a 71 year old female cadaver with a weight of 94.3 kg and a height of 164.5 cm. The sled velocity change was 9.8 m/sec and the impact surface padding was 2.5 cm of Ensolite backed by 5 cm of polystyrene foam. The test data are shown in Figure 7. The loads acting on each knee were as follows:

> Right Leg - The load increased gradually to a peak of 14.2 kN followed by a rapid drop-off. The shaft of the femur was fractured. The duration of the significant loading was 25 msec.
>
> Left Leg - The load increased gradually to a peak of 15.0 kN and then gradually decreased. This load peak preceded the peak of the right knee load by approximately 2 msec. A fracture of the pelvis near the acetabulum was produced by this loading. The duration of the significant loading was 31 msec.

During the autopsy, the bone structure of the subject was judged to be very osteoporotic, as indicated by the nature of the cortical bone geometry in the shafts of the femurs.

Test 77A224: The test subject was a 65 year old male cadaver with a weight of 61.1 kg and a height of 163.2 cm. The sled velocity change was 10.1 m/sec and the impact surface padding was 2.5 cm of Ensolite backed by 5 cm of low density polystyrene foam. The test data are shown in Figure 8. The left side load cell malfunctioned in this test, only right side load data were obtained. The load on the right knee increased gradually to a peak of 8.9 kN and then gradually diminished. The right leg sustained comminuted fractures of the intertrochanteric region of the femur. The left leg had a fracture of the neck and a supracondylar fracture of the shaft of the femur. The duration of the significant loading of the right knee was 28 msec.

During autopsy the bone structure of the subject was judged to be very osteoporotic by examination of the configuration of the cortical bone of the femoral shafts.

DISCUSSION

The pertinent impact data from these experiments are summarized in Table 2 and the associated injury information is listed in Table 3. The goal of this study was to compare the types of injuries produced by the moving-mass impactor test method with those types of injuries produced by the whole-body sled test method. Only injuries distal to the upper leg (that is, only in the knee area) were produced in the impactor study. These injuries included patellar fractures, condylar fractures,and supracondylar fractures. No involvement of the hip joint, femoral neck,or midshaft of the femur was found. The durations of the forces in the impactor tests tended to be short (less than 22 ms.) because of the low impactor mass and the high velocity necessary to achieve a sufficient impactor energy level for fractures to be produced. The experiments reported here used the test subjects' mass as the impact mass and thus could produce sufficient energy levels at lower impact velocities. The configuration of the test subject was intended to simulate that of a seated motor vehicle occupant striking the knees on the lower instrument panel in a crash. Previous analysis (1) of actual crash injuries has shown that injuries to the proximal upper leg and pelvis accounted for the majority (103 out of 142 cases - 72.5%) of injuries produced under conditions that could be considered similar to the sled test condition. It was of interest in this program to see if such a shift in injury patterns would occur when going from the test conditions of the impactor test method to the more realistic whole-body test.

The data presented in Tables 2 and 3 indicate that the whole-body sled test technique was successful in producing some load-time histories with durations greater than those of the impactor tests and in producing proximal upper leg fractures. In those tests which produced a combination of distal and proximal upper leg injuries a particular load-time waveform was noted to occur. This waveform, which is trapezoidal in general form, is best exemplified by the right and left femur force traces of Test 77A220 (Figure 4). It occurs in somewhat modified form in the right and left femur force traces of Test 77A218 (Figure 3) and the left femur force trace of Test 77A221 (Figure 5). The waveform occurs whenever a femoral neck or pelvic fracture is produced in combination with femoral shaft or condylar fractures. The trapezoidal nature of the waveform suggests the occurrence of two major fracture events. The first event initiates an abrupt break in the slope of the loading trace to form the trapezoidal shape. The second major event causes the abrupt drop-off in load which ends the trapezoidal portion of the load-time history. Consideration of the probable effects of the various types of skeletal fractures on the load carrying ability of the upper leg leads to the hypothesis that the first fracture event is most likely associated with femoral neck or pelvic fractures while the second or terminal event is the fracture of the femoral shaft or condylar region. The femoral neck fracture can give rise to an instantaneous change in load-carrying ability but is followed closely by a resumption in loading at a lower rate or by a gradual decrease in load. The ligamentous structures around the hip joint and the proximal end of the femur can carry load around such fractures and thereby continue the loading of the body through the upper leg. Subsequent fractures in other regions of the femur can occur. In contrast, when a fracture of the shaft of the femur or an extensive fracture of the condyles occurs, there is an abrupt loss in load-carrying ability with no immediate alternative load path. This results in a severe drop-off in load. The results of Test 77A223 (Figure 7) demonstrate these effects. In that test the right leg sustained a femoral shaft fracture only, while the left leg sustained a fracture of the pelvis near the acetabulum. The waveforms in Figure 7 exhibit the differing types of force-time behavior discussed above.

It is important to note that the peaks in the force traces which correspond to fracture events, in most cases, also correspond with the major pelvic accelerations. Therefore, the major pelvic accelerations can be associated with structural failures of the hip and legs. This shows the relative loading capability of the pelvis due to transfer of load from the knee-femur system. Furthermore, these accelerations are not all typical of motion along the femoral axis. The dominance of the R-L accelerations in Test 77A218 seems to indicate much lateral motion, including rotations about the hips.

The femoral neck fractures were not seen in the impactor tests reported previously (1), apparently due to the momentum levels used and the technique of testing one leg at a time. The impacting of both knees at the same time may produce a more limited pelvic rotational motion, thereby creating a more severe loading of the femoral neck. Pelvic rotational motion, similar to that seen in the impactor tests, was observed in the high-speed movies of the sled tests. It occurred in those cases where one of the subjects' legs failed structurally such that the subject was forced to pivot about the other leg.

Although the types of fractures produced by the sled testing were different in some respects than those produced in the impactor tests, they did include the types seen in the impactor tests when the force-time histories were similar (Tests 77A218, 77A220, and 77A221). Figure 9 is a plot of the peak knee loads versus primary force duration. On it is drawn the Femur Injury Criterion (FIC) suggested by Viano (3). Even with the data from osteoporotic subjects the FIC appears conservative for durations greater than 20 ms. The fracture loads denoted by arrows indicate the initial fracture load peak (x) and the resulting load range (either up to, or down to, the arrowhead).

The force levels at which fractures occurred in these tests are consistent with findings of the previous tests (1). In that study, fracture-producing forces for lightly padded impacts (2.5 cm Ensolite) ranged from 13.3 - 28.5 kN. Though the sled tests used some polystyrene foam padding in addition to the 2.5 cm Ensolite, the fracture-producing forces were consistent with that load range. This includes those types of fractures which did not appear in the impactor study.

As discussed in the Data Analysis section, it was helpful to use the pelvic acceleration data to aid in estimating when fractures occurred. Since the data were triaxial data at a point on the pelvis, it is only partial information on the motion of the pelvis. Still the data were relevant to our analysis. Future studies, though, should include the use of the nine accelerometer method for more precise description of pelvic motions.

SUMMARY AND CONCLUSIONS

A series of six whole-body sled tests were conducted with unembalmed cadavers to study knee impact phenomena under simulated car crash conditions. The purpose of the study was to investigate the occurrence of upper leg fracture types not seen in stationary subject knee impact tests using a moving-mass impactor technique and to extend the pulse durations of the knee forces to times greater than 20 ms. The tests were successful in achieving both goals.

The following conclusions can be drawn from the test series presented here:

1) Proximal upper leg injuries (femoral neck and shaft and pelvic fractures), which account for most upper leg injuries in real crashes, occurred with the whole-body knee impact test conditions used in this study.

2) Femoral neck and acetabular fractures appear to produce a change in the rate of load transfer from the knee to the pelvis, while femoral shaft and extensive condylar fractures produce an abrupt drop-off in the load transferred from the knee to the pelvis. In these tests, neck and acetabular fractures, when they occurred, preceded the shaft and condylar fractures.

3) Pelvic accelerations are influenced by the occurrence of femoral fractures and are indicative of the transfer of load from femur to pelvis during knee impact.

4) The combination of 2.5 cm of Ensolite padding for force-distribution backed by 5 cm of low-density polystyrene foam as an energy absorber proved to be effective in controlling knee impacts. The padding

combination produced knee loads near the tolerance limits while extending the duration of the force waveform to greater than 20 ms.

5) The forces necessary to produce proximal leg fractures are similar in magnitude to those that produce distal knee injuries in impactor tests.
6) The Femur Injury Criterion appears to be conservative for knee force pulse durations greater than 20 ms. when compared with the limited data base sample of these tests.
7) Future studies of leg injury should include the use of the nine accelerometer method on the pelvis to give more precise kinematic data and aid in the analysis of the measured force data.

ACKNOWLEDGEMENTS

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TABLE 1

KNEE IMPACT SLED TEST SUBJECT DATA

TEST NO.	SUBJECT NO.	AGE yrs.	HEIGHT cm.	WEIGHT kg.	SEX
77A218	20718	75	179.6	77.1	M
77A220	20733	49	188.4	87.0	M
77A221	20735	79	--	83.0	M
77A222	20744	58	159.0	47.3	F
77A223	20741	71	164.5	94.3	F
77A224	20750	65	163.2	61.1	M

TABLE 2

CADAVER AXIAL KNEE IMPACT SLED TEST DATA SUMMARY

TEST NO.	SLED ΔV	KNEE LOADING RANGE AND DURATION				FRACTURE OUTCOME	
		RIGHT		LEFT			
	m/sec	kN	ms	kN	ms	LEFT	RIGHT
77A218	8.3	15.3-10.2	9	18.9-23.0	11	Fx	Fx
77A220	9.5	19.4-18.4	19	21.3-25.6	21	Fx	Fx
77A221	9.3	21.0	17	19.8-17.4	16	Fx	Fx
77A222	9.5	6.2	33	8.1	32	No	No
77A223*	9.8	14.2	25	15.0	31	Fx	Fx
77A224*	10.1	8.9	28	--	--	Fx	Fx

*Osteoporotic subject

TABLE 3

CADAVER AXIAL KNEE IMPACT SLED TEST INJURY DATA

TEST NUMBER	LEG INJURIES
77A218	RIGHT LEG - FRACTURES OF THE NECK AND CONDYLES OF THE FEMUR. LEFT LEG - FRACTURES OF THE NECK, SHAFT (SUPRACONDYLAR) AND PATELLA. CRACKING OF THE CONDYLES.
77A220	RIGHT LEG - FRACTURES OF THE NECK, SHAFT AND MEDIAL CONDYLE OF THE FEMUR. LEFT LEG - SAME TYPE FRACTURES AS IN THE RIGHT LEG.
77A221	RIGHT LEG - FRACTURES OF THE PATELLA, MEDIAL CONDYLE AND SHAFT OF THE FEMUR. LEFT LEG - FRACTURES OF THE ACETABULUM, PATELLA AND FEMORAL CONDYLES.
77A222	RIGHT LEG - NO INJURY LEFT LEG - NO INJURY
77A223	RIGHT LEG - FRACTURE OF THE FEMORAL SHAFT (OSTEOPOROTIC SUBJECT) LEFT LEG - MINIMAL PELVIC FRACTURE NEAR HIP JOINT (OSTEOPOROTIC SUBJECT)
77A224	RIGHT LEG - INTERTROCHANTERIC FRACTURES (OSTEOPOROTIC SUBJECT) LEFT LEG - FRACTURES OF THE NECK AND THE SHAFT OF THE FEMUR (OSTEOPOROTIC SUBJECT)

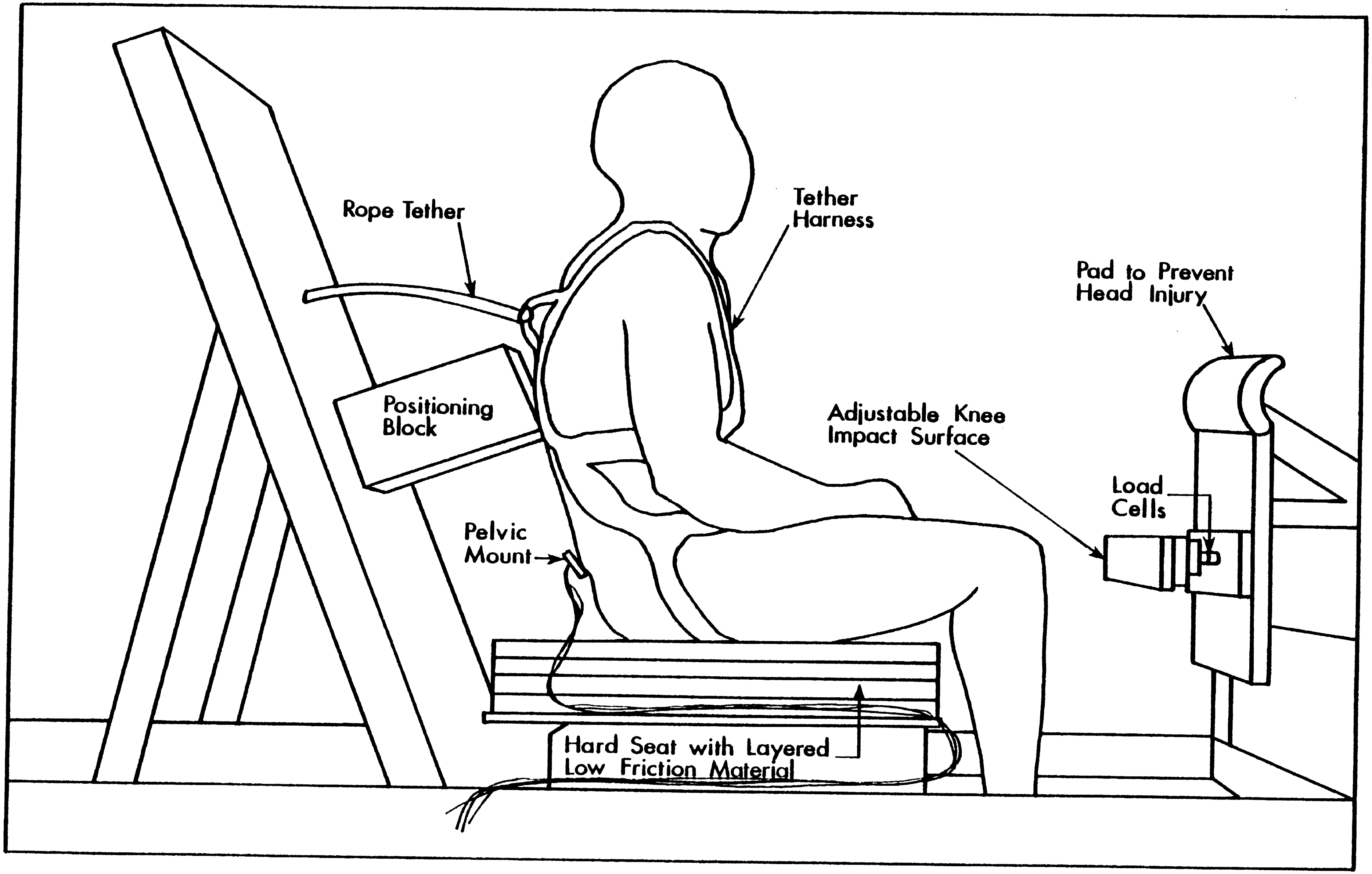

Figure 1 - Test set-up

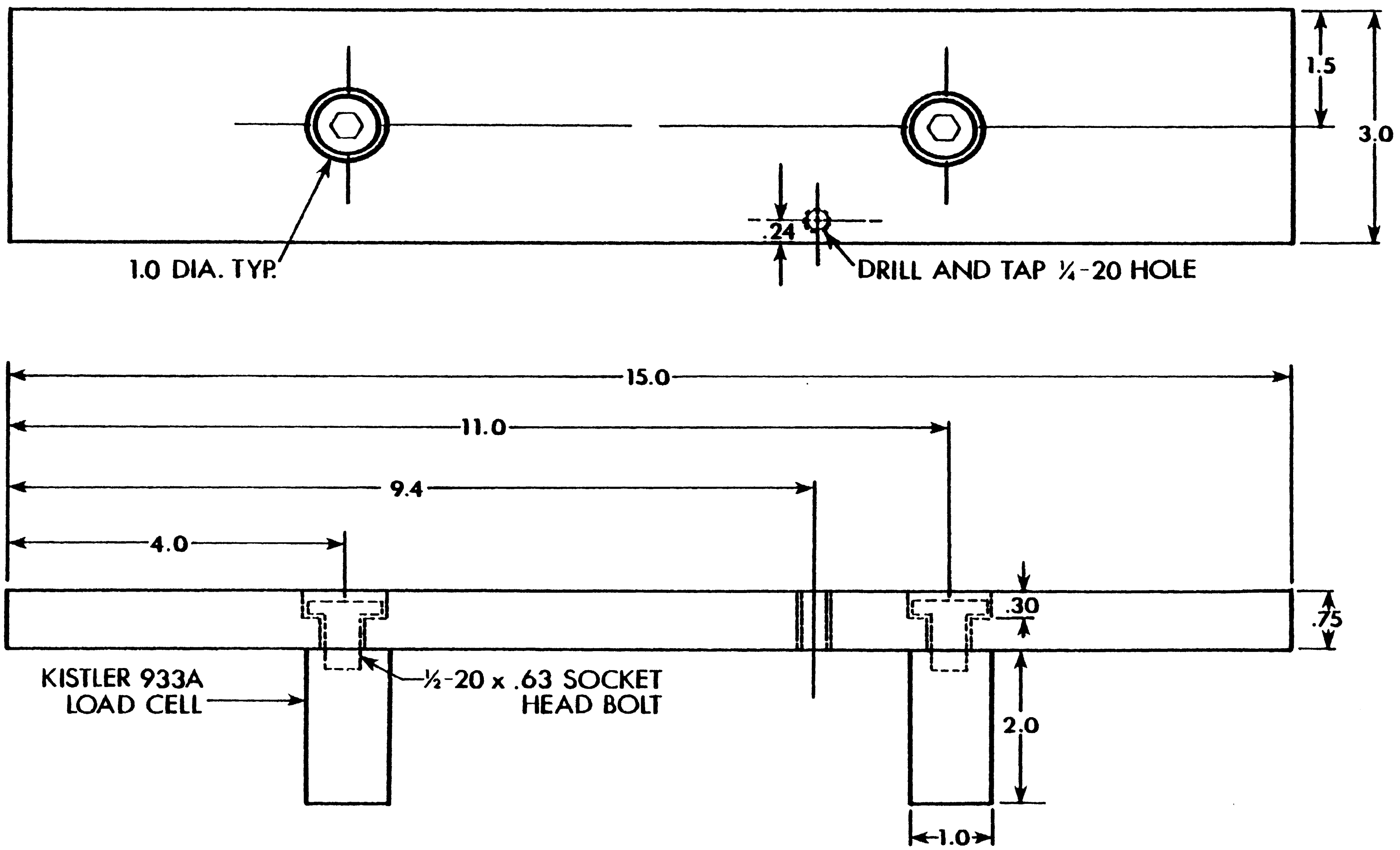

Figure 2 - Load cell configuration

TEST NO. 77A218

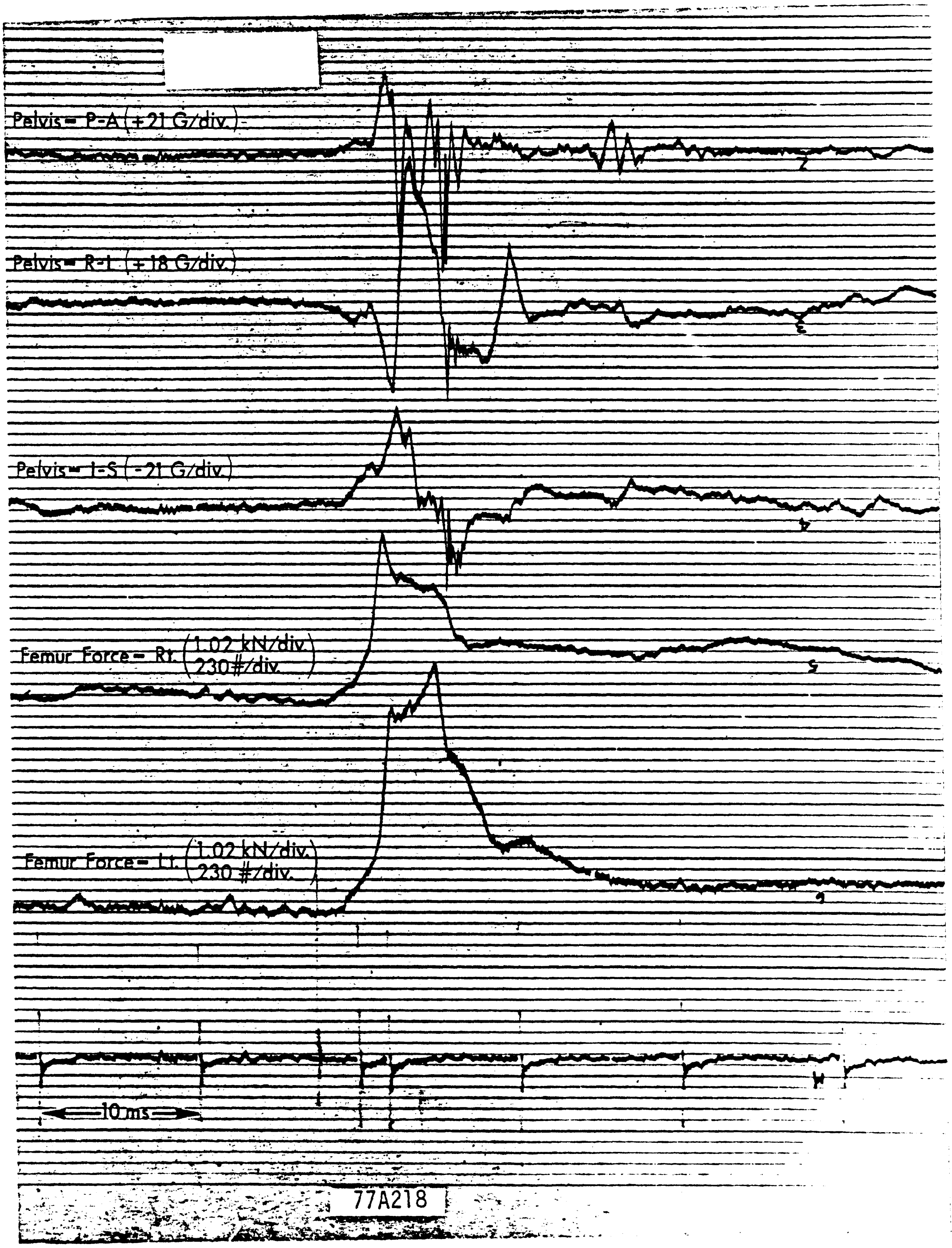

Figure 3 - 77A218 Transducer time histories

TEST NO. 77A220

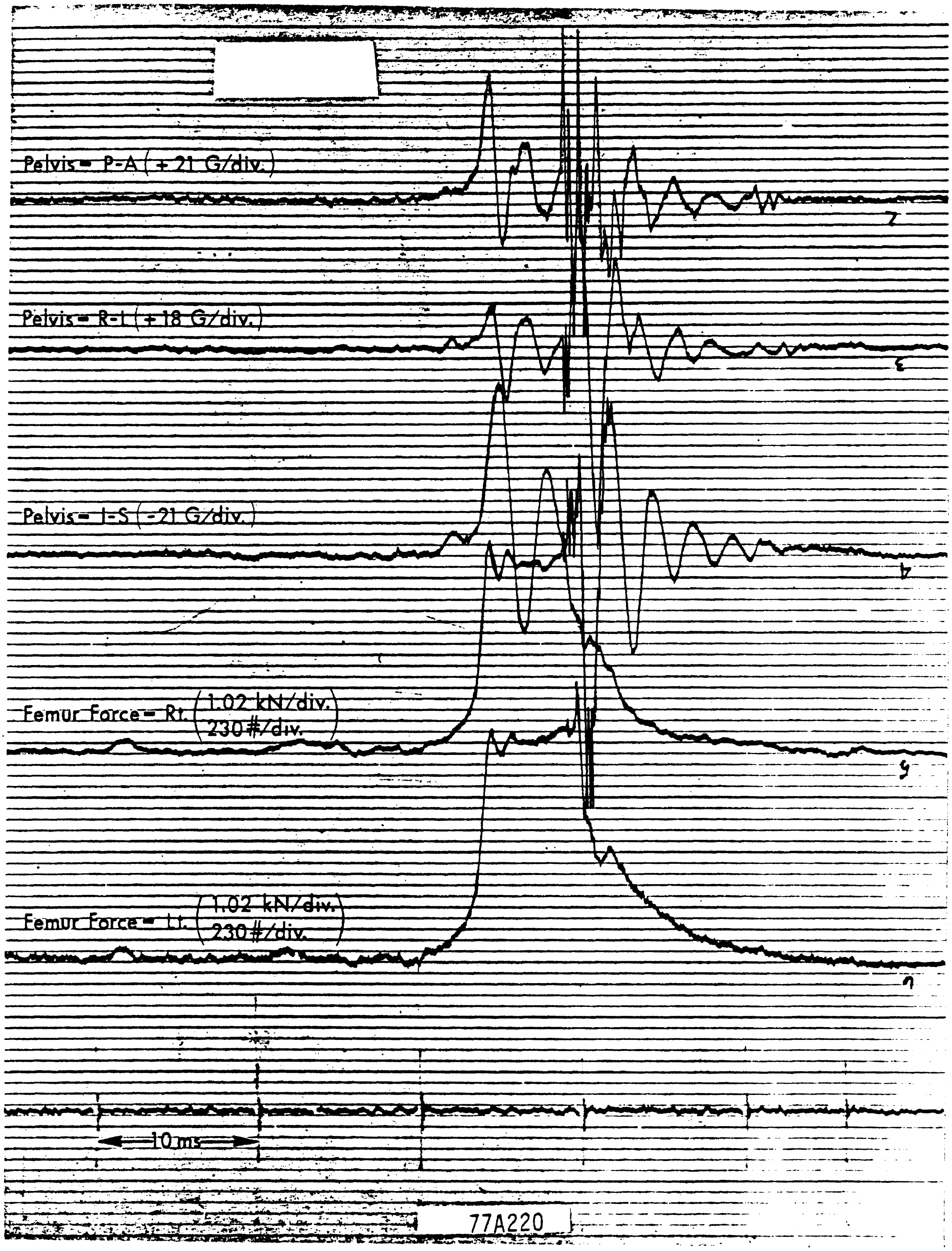

Figure 4 - 77A220 Transducer time histories

TEST NO. 77A221

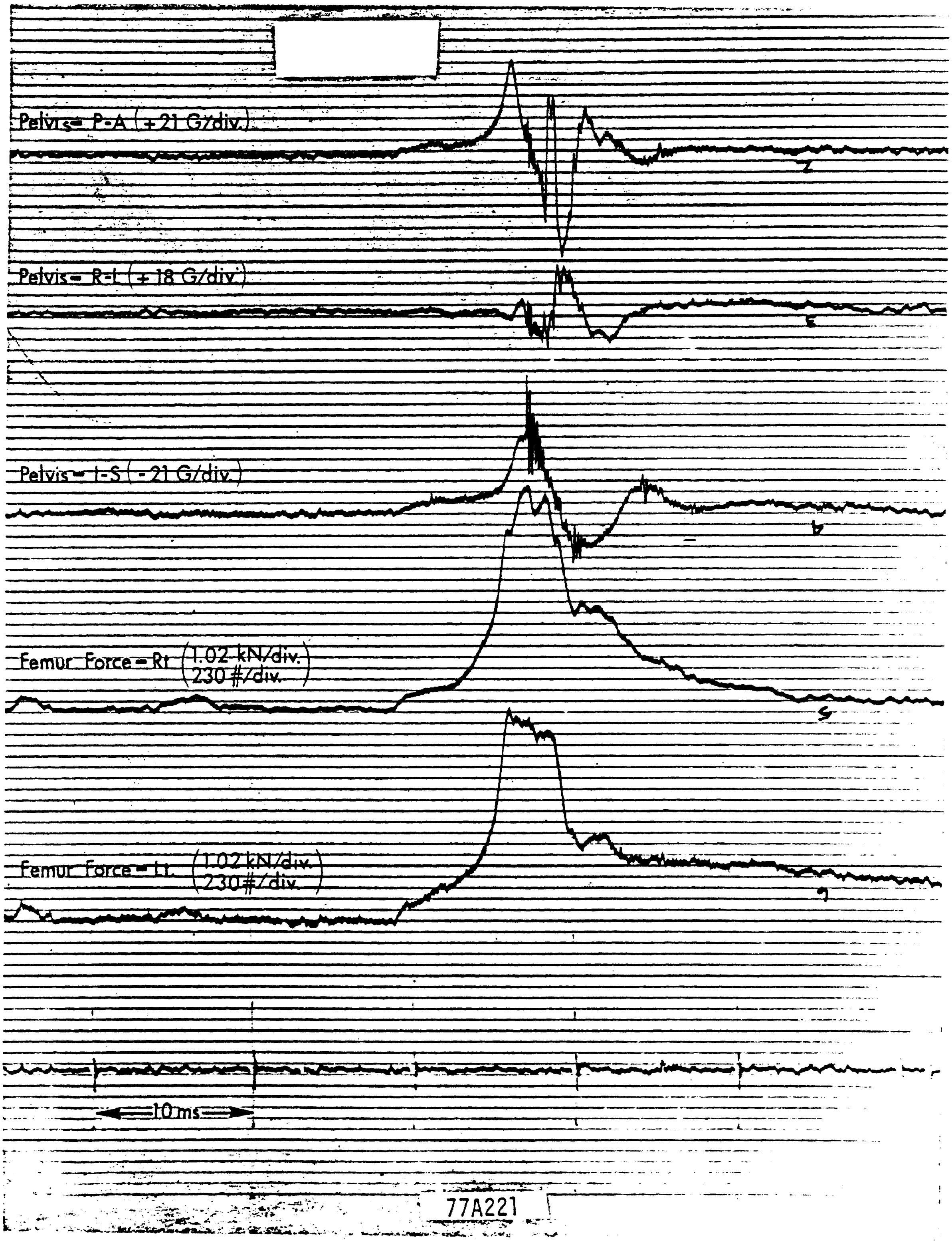

Figure 5 - 77A221 Transducer time histories

TEST NO. 77A222

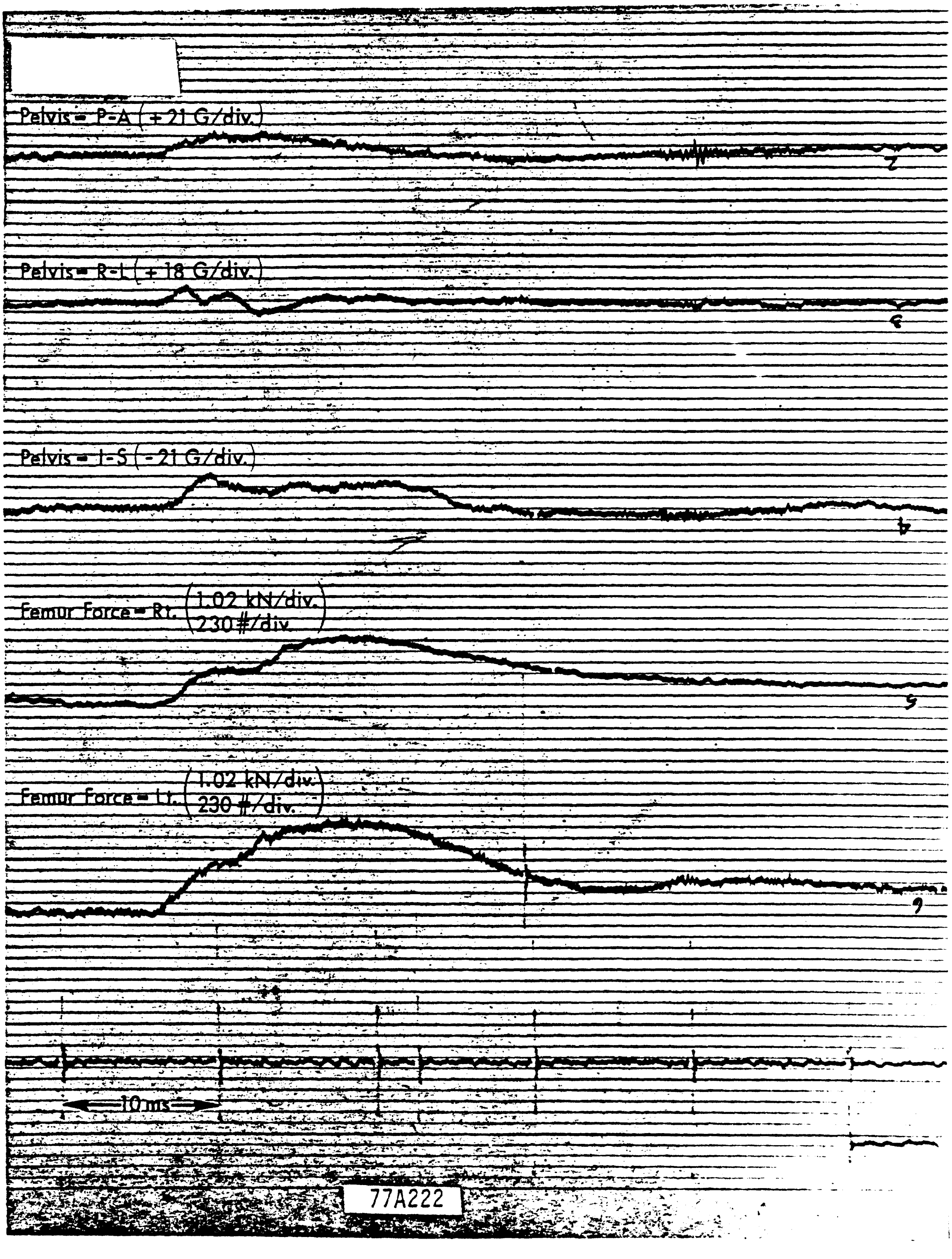

Figure 6 - 77A222 Transducer time histories

TEST NO. 77A223

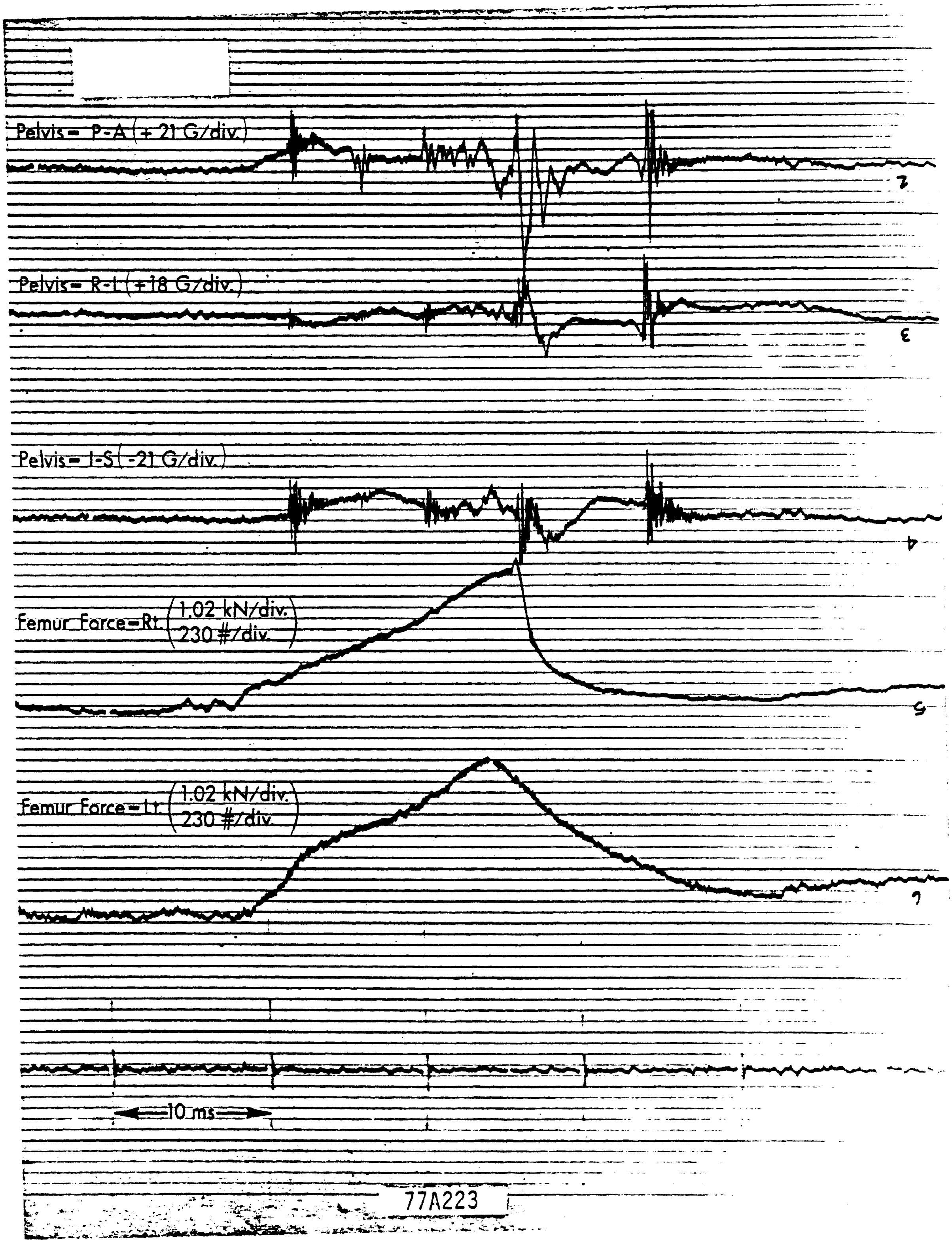

Figure 7 - 77A223 Transducer time histories

TEST NO. 77A224

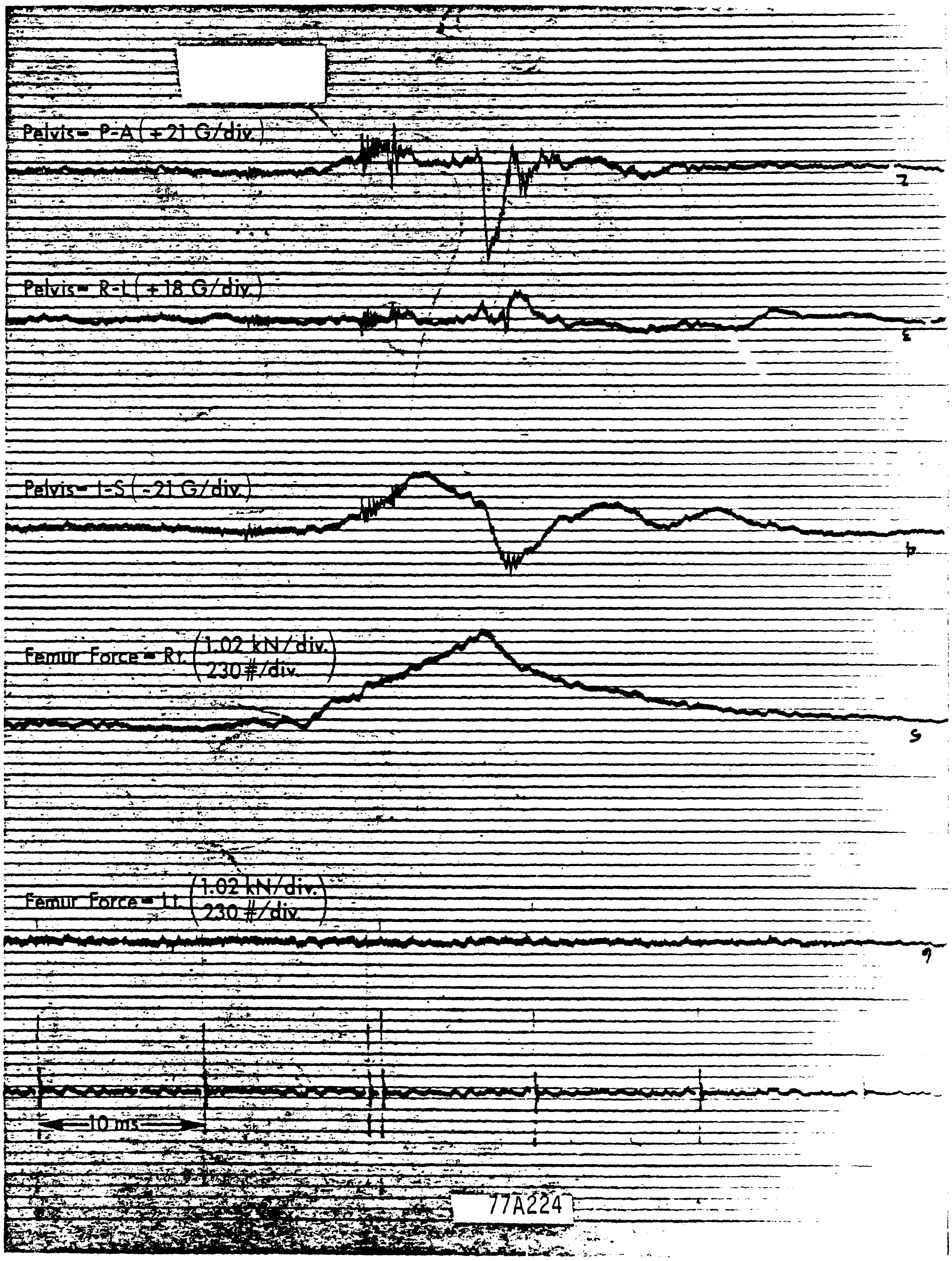

Figure 8 - 77A224 Transducer time histories

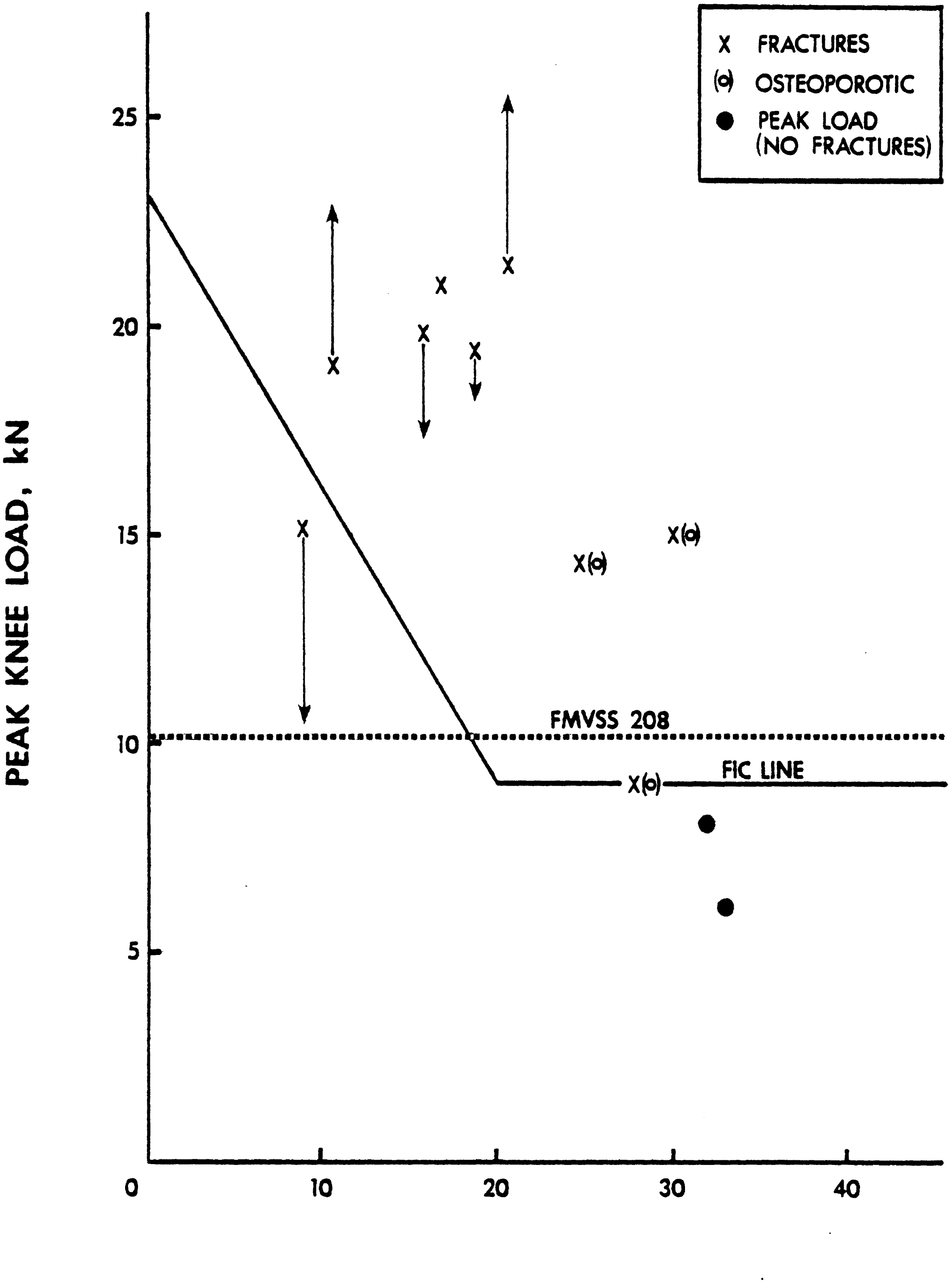

Figure 9 - Peak knee load vs. primary pulse duration. Arrows denote ranges of fracture loads, from initial fracture load (x) to initiation of load drop off (arrowhead).