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Road vehicles — Anthropomorphic side impact dummy — Lateral impact response requirements to assess the biofidelity of the dummy

Véhicules routiers — Mannequin anthropomorphe pour essai de choc latéral — Exigences de réponse en choc latéral pour évaluer la biofidélité du mannequin

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this Technical Report may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 9790, was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 12, *Restraint systems*.

This first edition cancels and replaces the ISO/TR 9790 parts 1 to 6 (1989), which have been reviewed, updated and organized into a single Technical Report.

Road vehicles — Anthropomorphic side impact dummy — Lateral impact response requirements to assess the biofidelity of the dummy

1 Scope

This Technical Report describes laboratory test procedures and impact response requirements suitable for assessing the lateral impact biofidelity of the head, neck, shoulder, thorax, abdomen and pelvis of crash test dummies, subcomponent test devices, and math models that are used to represent a 50th percentile adult male. The method used by ISO to determine an overall biofidelity rating for a given side impact surrogate has been added to this Technical Report.

2 Biomechanical basis

The impact response requirements presented in this Technical Report are the result of a critical evaluation of data selected from experiments agreed to by experts as being the best and most up-to-date information available. The following describes the biomechanical data used to describe response requirements for the head, neck, shoulder, thorax, abdomen and pelvis.

2.1 Head Tests

Two lateral head impact tests are defined. Head Test 1 is based on the rigid surface cadaver impacts conducted by Hodgson and Thomas (1). Head Test 2 is based on the padded surface cadaver impacts of the Association Peugeot-Renault (APR) (2). Padded surface impact tests of Hodgson and Thomas (1), McElhaney et al. (3), Nahum et al. (4), Nahum et al. (5), Schneider et al. (6) and Got et al. (7) were not used since either the padding characteristics were not specified or a given piece of padding was subjected to multiple impacts, changing its response characteristics. Detailed discussions of the influences of these factors on head acceleration data are given by Mertz (8), Mertz et al. (9) and Mertz (10). The rigid surface impacts of McElhaney et al. (3) were not used because the impact velocities were not given for each test. The rigid surface impact data of Got et al. (7) were not used since significant skull fractures were produced.

2.2 Neck Tests

Three lateral neck bending tests are defined. Neck Test 1 is based on the human volunteer data of Ewing et al. (11), and the requirements are based on the analysis of Wismans et al. (12). Neck Test 2 is based on the human volunteer data of Patrick and Chou (13). Neck Test 3 is based on the cadaver tests of the APR (2). To evaluate if the biofidelity requirements are met, the respective sled test environments that were used to obtain the human volunteer and/or cadaver data must be duplicated.

2.3 Shoulder Tests

Four lateral impact test conditions are defined for the shoulder. Shoulder Test 1 is based on impactor tests conducted by the APR using unembalmed cadavers (14). Shoulder Test 2 is based on the Ewing et al. (11) volunteer sled tests. Shoulder Test 3 is based on the cadaver sled tests of Tarriere (30). In both of these sled tests, the dummy must mimic the shoulder reaction with the rigid vertical side board in order for the kinematics of its upper thoracic spine to meet the T1 response requirements. Shoulder Test 4 is based on the cadaver sled tests of Wayne State University (WSU) (15, 16). Shoulder response data from the APR and WSU were normalized to represent the response characteristics of a 50th percentile adult male using the method described by Mertz (17). No adjustments were made to the cadavers' responses to account for muscle tone.

2.4 Thorax Tests

Six lateral thoracic impact test conditions are defined. Thorax Tests 1 and 2 are based on cadaver impactor tests conducted by the Highway Safety Research Institute (HSRI) (18) and WSU (19). Thorax Tests 3 and 4 are based on the cadaver drop tests of the APR (20, 21, 22). Thorax Test 5 is based on cadaver sled tests of the University of Heidelberg (23). Thorax Test 6 is based on cadaver sled tests of WSU (15, 16). All thoracic data were normalized to represent the response characteristics of a 50th percentile adult male using either the method described by Mertz (17) or an extension of the method developed by Lowne (24). The force versus time response corridors for Thorax Tests 1 and 2 were constructed around the normalized cadaver curve and then shifted 700 N upward to account for muscle tone. The force versus time response corridors of Thorax Tests 3 - 6 were not adjusted to account for muscle tone. Cadavers with more than 5 rib fractures were not used in defining the response requirements, except for Thorax Test 5 where results from cadavers with 2, 7 and 9 fractured ribs were all used.

2.5 Abdomen Tests

Five lateral abdominal impact test conditions are defined. Abdomen Tests 1 and 2 are based on the lateral cadaver drop tests conducted by the APR (25, 14). Abdomen Tests 3 - 5 are based on cadaver sled tests of WSU (16). All data were normalized to represent the responses of a 50th percentile adult male using the method described by Mertz (17).

2.6 Pelvis Tests

Thirteen lateral pelvic impact test conditions are defined. Pelvis Tests 1 and 2 are based on impactor tests of ONSER (26, 27, and 28). Pelvis Tests 3 - 6 are based on free fall cadaver tests of the APR (29). Pelvis Tests 7 - 9 are based on cadaver sled tests of the University of Heidelberg (23). Pelvis Tests 11 - 13 are based on cadaver sled tests of WSU (16). All pelvic data were normalized to represent the responses of a 50th percentile adult male using the method described by Mertz (17).

Note that it may be difficult to develop a dummy that meets all of the prescribed requirements. For example, some of the neck response requirements are based on the responses of volunteers, while others are based on the response of a cadaver whose neck fractured. In some thoracic requirements, the force has been increased to account for muscle tone present in the driving population, but absent in flaccid, unembalmed cadavers used to define the requirements. In conducting the tests, especially the whole body tests, it is important to duplicate the timing of the impacts to the various body regions in order to meet the requirements.

The response requirements are arranged in terms of the type of tests. Clause 4 requirements are based on pendulum impacts, Clause 5 requirements are based on lateral drop tests, and Clause 6 requirements are based on sled tests. Table 1 lists the various requirements by body region, gives the corresponding clause number that describes each requirement, and identifies which annex describes how the requirements were derived.

3 Overall biofidelity calculation

An overall biofidelity rating of the impact responses of any 50th percentile adult male surrogate (dummy or math model) which is proposed for evaluating side impact collision occupant protection can be calculated using the following formula:

$$B = \frac{\sum_{i=1,2,\ldots 6} U_i B_i}{\sum_{i=1,2,\ldots 6} U_i}$$

where

B The overall rating which will have a value between 0 (poorest) and 10 (best).

B_i The biofidelity rating of each of the six body regions (B_1 - Head, B_2 - Neck, B_3 - Shoulder, B_4 - Thorax, B_5 - Abdomen, and B_6 - Pelvis).

U_i The weighting factor for each body region.

i A subscript which takes on integer values from 1 to 6 to represent specific body regions (i=1 Head, i=2 Neck, i=3 Shoulder, i=4 Thorax, i=5 Abdomen, and i=6 Pelvis).

Values for the body region weighting factors, U_i, were determined by averaging the results of a poll of the ISO/TC22/SC12/WG5 experts and are given in Table S.1 of annex S.

The biofidelity ratings for the six body regions, B_i, are calculated using the following formula:

$$B_i = \frac{\sum_{j=1,2,\ldots m} V_{i,j} \left(\sum_{k=1,2,\ldots n} W_{i,j,k} R_{i,j,k} \Big/ \sum_{k=1,2,\ldots n} W_{i,j,k} \right)}{\sum_{j=1,2,\ldots m} V_{i,j}}$$

where

$V_{i,j}$ The weighting factor for each test condition for a given body region.

$W_{i,j,k}$ The weighting factor for each response measurement for which a requirement is given.

$R_{i,j,k}$ The rating of how well a given response meets its requirement.

i The subscript denoting the body region.

j The subscript denoting the test condition for a given body region, i.

k The subscript denoting the response measurement for a given test condition, j, and body region, i.

Values for the weighting factors for the various test conditions, $V_{i,j}$, and response measurements, $W_{i,j,k}$, were determined by averaging the results of a poll of the ISO/TC22/SC12/WG5 experts and are given in Tables S.2 through S.7 of annex S.

The experts agreed on the following method for assigning values to $R_{i,j,k}$.

$R_{i,j,k} = 10$ If response meets requirement.

$R_{i,j,k} = 5$ If response is outside requirement, but lies within one corridor width of the requirement.

$R_{i,j,k} = 0$ If neither of the above is met.

Using this method, the overall biofidelity rating, B, will have a value between 0 and 10. Five classifications indicating the degree of biofidelity were established for the overall biofidelity rating. These are,

Excellent Biofidelity: $8,6 \leq B < 10,0$
Good Biofidelity: $6,5 \leq B < 8,6$
Fair Biofidelity: $4,4 \leq B < 6,5$
Marginal Biofidelity: $2,6 \leq B < 4,4$
Unacceptable Biofidelity: $0,0 \leq B < 2,6$

Further, the WG5 experts stipulated that the overall biofidelity value, B, of a side impact dummy (or math model) had to be greater than 2,6 to be acceptable for assessing side impact occupant protection.

4 Pendulum impacts

4.1 Shoulder Test 1

4.1.1 Original Data

Researchers of the APR subjected 4 cadavers to lateral impact delivered to the shoulder by the flat end of a 23 kg rigid cylinder of 150 mm diameter (14). Each cadaver was seated on a horizontal hardwood surface with a vertical backrest. The impact was delivered laterally to the shoulder. The force of the impactor was recorded. Response data and normalization procedures are summarized in annex A.

4.1.2 Test Setup

A 23 kg rigid, 150 mm diameter cylinder with a flat impact face is required. Seat the dummy upright with its arm down and align the axis of the impactor with the center of the shoulder joint, as illustrated in Figure 1. Impact the dummy's shoulder laterally with an impact velocity between 4,4 and 4,6 m/s.

4.1.3 Instrumentation

Instrument the dummy to monitor acceleration of the thoracic spine. Instrument the impactor to measure its acceleration during impact. Filter the acceleration measurements at channel frequency class 1000 Hz, according to the requirements of SAE Recommended Practice J211. Calculate the impactor force versus time history by multiplying each impactor acceleration value by the impactor mass of 23,4 kg.

4.1.4 Response Requirements

The original force versus time histories of the impactor were normalized (see annex A) using the technique suggested by Mertz (17). The maximum deflection of the shoulder should lie within the bounds given in Table 2 and the force versus time history of the impactor should lie within the corridor described in Table 5.

4.2 Thorax Tests 1 and 2

4.2.1 Original Data

Cadavers were used in two series of impactor tests of the thorax. Lateral impacts were conducted by the HSRI (18) and oblique lateral impacts were conducted at WSU for the General Motors Research Laboratories (GMR) (19). Accelerations of the impactor and thorax were recorded in both studies. Response data and normalization procedures are summarized in annexes B and C for the HSRI and WSU/GMR test series, respectively.

4.2.2 Test Setup

A 23 kg rigid, 150 mm diameter cylinder with a flat impact face is required. Seat the dummy upright with its arm raised so that the side of its thorax can be impacted. Center the face of the impactor, both vertically and fore/aft, on the lateral aspect of the thoracic rib structure. Impact the dummy's thorax laterally at a velocity of 4,3 m/s for Thorax Test 1. Repeat the impact at 6,7 m/s for Thorax Test 2.

4.2.3 Instrumentation

Instrument the dummy with an accelerometer to measure the lateral acceleration of the thorax. Instrument the impactor to measure its acceleration during impact. Record all measurements according to the requirements of SAE Recommended Practice J211. Calculate the impactor force versus time history by multiplying each impactor acceleration value by the impactor mass of 23,4 kg. The impactor force and lateral thoracic spine acceleration must be filtered using the 100 Hz FIR filter (18) in order to compare to the response corridors.

4.2.4 Response Requirements

The original impactor force was normalized using an extension of the method described by Mertz (17), as developed by Lowne (24). The normalization procedure is summarized in annexes B and C for the HSRI and WSU/GMR impactor forces, respectively. For the HSRI tests, the lateral acceleration of T1 was also normalized as summarized in annex B. The lateral acceleration of T1 for the WSU/GMR impacts was not available.

For lateral impacts by a 23,4 kg rigid pendulum at 4,3 and 6,7 m/s, the force versus time histories must lie within the corridors described in Table 6. The thoracic acceleration versus time history for a 4,3 m/s lateral impact by a 23,4 kg rigid pendulum must lie within the corridor described in Table 4. No requirement has been set for the thoracic acceleration resulting from a 6,7 m/s impact.

4.3 Pelvis Tests 1 and 2

4.3.1 Original Data

Researchers of ONSER studied the responses of 22 unembalmed cadavers to lateral impacts delivered to the greater trochanter (26, 27, 28). Pelvic acceleration was measured by an accelerometer attached to the posterior of the sacrum. The unbelted cadavers were seated without lateral support. The impacts were delivered at various speeds by either a rigid or padded impactor. Accelerations of the impactor were measured. Data from these tests are summarized in annex D.

4.3.2 Test Setup

A 17,3 kg, rigid impactor with a spherical segment impact face (R=175 mm, r=60 mm) is required. Seat the dummy upright as illustrated in Figure 2. Impact the greater trochanter region with a velocity of 6 m/s for Pelvis Test 1. Repeat the impact at a velocity of 10 m/s for Pelvis Test 2.

4.3.3 Instrumentation

Instrument the dummy to monitor acceleration of the pelvis. Filter the acceleration measurements at channel frequency class 1000 Hz, according to the requirements of SAE Recommended Practice J211. Calculate the impactor force versus time history by multiplying each impactor acceleration value by the impactor mass of 17,3 kg.

4.3.4 Response Requirements

The peak impactor forces were normalized (see annex D) using the technique suggested by Mertz (17). For dummy impacts between 6 and 10 m/s, the peak impactor force should lie within the corridor described in Table 3.

5 Lateral drops

5.1 Head Test 1

5.1.1 Original Data

Hodgson and Thomas (1) conducted a series of non-fracture, cadaver head impact tests. In these tests, the cadavers were strapped on their sides to a pallet that was free to pivot about one end. The cadaver's head and neck were allowed to extend over the free end of the pallet. The pallet was rotated upwards to achieve a prescribed distance between the head and the impact surface. Then the pallet was released producing the desired head impact. Results from these tests are given in annex E.

5.1.2 Test Setup

A flat, rigid horizontal surface and a “quick-release” mechanism are required. Conduct the test using only the dummy's head. Position the dummy’s head with a 200 mm space between it and the impact surface. Orient the head so that its midsagittal plane makes an angle of 35° with the impact surface and its anterior-posterior axis is horizontal. The response requirement is for the peak resultant head acceleration of a point on the non-impacted side of the head. Also record the peak resultant acceleration of the center of gravity of the head.

5.1.3 Instrumentation

Instrument the dummy's head with a triaxial accelerometer located at the center of gravity of the head. Attach a second triaxial accelerometer, within the head cavity, to the non-impacted side at a point on the transverse axis that passes through the center of gravity of the head. Filter the accelerations at channel frequency class 1000 Hz, according to the requirements of SAE Recommended Practice J211.

5.1.4 Response Requirement

The peak resultant head acceleration of a point on the non-impacted side of the head should lie within the bounds given in Table 2 for a 200 mm free fall drop onto a flat, rigid surface.

5.2 Head Test 2

5.2.1 Original Data

The APR (2) conducted a series of lateral head impact tests. Four cadavers were dropped from a height of 1200 mm onto a rigid surface covered by a 5 mm thick rubber pad. Two of these cadavers received skull fractures. Results from the remaining two cadavers are given in annex F.

5.2.2 Test Setup

The impact surface consisting of a flat, rigid surface covered with a 5 mm thick pad of natural rubber (Shore A Hardness = 50, Rupture Strength = 14 MPa, Tear Strength = 15 kN/m) is required. Conduct the test using only the dummy's head. Position it with a 1200 mm space between it and the top of the padded impact surface. Orient the head so that its midsagittal plane makes an angle of 10° with the impact surface, thus impacting the temporal/parietal region.

5.2.3 Instrumentation

Instrument the dummy's head with a triaxial accelerometer located at the center of gravity of the head. Filter the accelerations at channel frequency class 1000 Hz, according to the requirements of SAE Recommended Practice J211.

5.2.4 Response Requirement

The peak resultant acceleration at the center of gravity of the head should lie within the bounds given in Table 2 for a 1200 mm drop onto the padded surface.

5.3 Thorax Tests 3 & 4 and Pelvis Tests 3 - 6

5.3.1 Original Data

Unembalmed cadavers were subjected to lateral free falls by researchers of the APR (20, 21 and 22). The cadavers were dropped from heights of 0,5 or 1 m onto rigid impact surfaces, or from heights of 2 or 3 m onto padded impact surfaces. The thoracic impact surfaces were instrumented to measure the contact forces for the 1 and 2 m drops only. Triaxial accelerations of T4 were recorded. Rib cage compression was determined from a high-speed movie of the impact for the 1 and 2 m drops only. Pelvic acceleration was measured by an accelerometer attached to the sacrum. Thoracic response data for the 1 m drop tests onto rigid impact surfaces and 2 m drop tests onto padded surfaces are summarized in annex G. Pelvic response data for the 0,5, 1, 2 and 3 m drops are given in annex H.

5.3.2 Test Setup

Two loading surfaces are required to intercept the dummy's thorax and pelvis separately. For the rigid tests, the thorax loading surface is to be large enough to insure that the shoulder is impacted. For the padded tests, 140 x 140 x 420 mm blocks of open cell urethane foam (APR padding) are to be used. The characteristics of this foam are described in annex I. A "quick-release" device is required to allow the dummy to drop freely. Suspend the dummy over the impact surfaces using ropes to support its shoulders, hips, and legs. This is illustrated in Figures 3 and 4 for the rigid and padded impacts, respectively. Position the dummy such that its sagittal plane is horizontal and its arms are rotated 20° forward of the thoracic spine.

5.3.3 Instrumentation

Instrument the thoracic impact surface with inertia-compensated load cells. Instrument the dummy with transducers to measure the lateral acceleration of the thoracic spine, triaxial acceleration of the pelvis, and the deflection of the impacted ribs relative to the thoracic spine. Filter the impact forces, chest and pelvic accelerations, and deflection measurements at channel frequency class 180 Hz, according to the requirements of SAE Recommended Practice J211. Take high-speed movies of the impact event.

5.3.4 Response Requirements

The normalization procedures are described in annexes G and H for the thoracic and pelvic data, respectively. The thoracic impact force versus time responses for the 1 m rigid and 2 m padded drops should lie within the corridors described in Table 5. Upper and lower bounds for peak deflection of the impacted rib and the peak pelvic accelerations are given in Table 2. The peak thoracic deflection and peak pelvic acceleration of the dummy should lie within these bounds.

5.4 Abdomen Tests 1 and 2

5.4.1 Original Data

Researchers of the APR subjected 11 unembalmed cadavers to lateral free falls onto simulated armrests (25). The cadavers were instrumented to monitor accelerations of T12 and the lateral aspects of their 9th ribs. The simulated armrests were secured to load cells, providing measurements of the force applied to the impacted surface. The data for these tests were provided by the APR (14) and are presented in annex J.

5.4.2 Test Setup

A simulated armrest, constructed of rigid hardwood, is required. The armrest is 70 mm in width and of sufficient height to protrude 41 mm above the surrounding surface. The length must be sufficient to prevent the dummy from striking the ends. The top edges are rounded with a 10 mm radius. Suspend the dummy with its midsagittal plane horizontal and its abdominal region including the "area of the 9th rib" in line with the top surface of the simulated armrest, as illustrated in Figure 5. Use a “quick-release mechanism” to drop the dummy the prescribed distance (1 or 2 meters).

5.4.3 Instrumentation

Instrument the dummy to monitor the acceleration of the spine at the level of T12, the acceleration of the impacted rib, and the deflection of the abdominal region relative to the spine (if such transducers are present). Instrument the simulated armrest with load cells. Filter the load and acceleration measurements at channel frequency class 180 Hz, according to the requirements of SAE Recommended Practice J211. Determine the abdominal penetration from high-speed films if it can not be measured directly.

5.4.4 Response Requirements

The original impact forces, and the peak T12 and impacted rib accelerations of the cadavers were normalized (see annex J) using the technique suggested by Mertz (17). The force versus time history of the dummy should lie within the corridors described in Table 5. The peak acceleration of the lower spine and the peak impacted rib acceleration should lie within the bounds given in Table 2. For both the 1 and 2 m drops, the abdominal penetration should be at least 41 mm, which is the height that the rigid simulated armrest protrudes above the surrounding surfaces.

6 Sled tests

6.1 Neck Test 1 and Shoulder Test 2

6.1.1 Original Data

Ewing et al. (11) conducted a series of lateral neck bending tests with volunteers. The volunteers were seated upright on a sled fixture that was mounted sideways to the direction of travel of a HYGE sled. They were positioned snugly against a lightly padded wooden board, which restricted upper torso rotation and supported the torso during sled translation. Both shoulders were restrained by straps. Their pelves were restrained by a lap belt and an inverted-V pelvis strap that was tied to the lap belt. They held their heads upright prior to sled acceleration. The data used for this requirement were taken from an analysis by Wismans et al. (12) of 9 tests with 9 subjects. annex K summarizes the most important test conditions.

6.1.2 Test Setup

Fasten a rigid chair, functionally similar to the one used by Ewing et al. (11), to a HYGE sled, facing sideways to the direction of sled travel. Attach a vertical side board to the seat to restrict upper torso rotation and to support the torso during sled translation. The top of the side board should be 40 to 50 mm below the top of the dummy's shoulder. Seat the dummy upright with its shoulder and hip against the side board and the anterior-posterior axis of its head horizontal. Position the dummy with its midsagittal plane vertical and perpendicular to the direction of sled travel. Secure the dummy to the seat with a belt restraint. Subject the dummy to the sled pulse shown in Figure 6.

6.1.3 Instrumentation

Instrument the dummy with triaxial accelerometers at the centers of gravity of the head and chest, a uniaxial accelerometer at the base of the neck with its sensitive axis directed laterally, and a six-axis neck transducer at the neck to head interface (at the level of the occipital condyles). In place of the six-axis neck transducer, the dummy's head may be instrumented with sufficient accelerometers to calculate the reactions at the head to neck interface. Use photographic targets to monitor the translation of the center of gravity of the head, lateral head rotation, head twist and horizontal translation of the base of the neck. Measure the sled acceleration and record the required dummy displacements with onboard cameras. Filter all response data according to the requirements of SAE Recommended Practice J211.

6.1.4 Response Requirements

A dummy subjected to the sled test described in subclause 6.1.2 Test Setup should meet the response requirements given in Table 2.

6.2 Neck Test 2

6.2.1 Original Data

Patrick and Chou (13) conducted a series of volunteer, lateral neck bending tests using their decelerator sled. A rigid seat with a 15° seat back angle was attached to the sled, sideways to the direction of travel. One side of the seat had a rigid, vertically-oriented, side support which restricted upper torso rotation and supported the torso during sled translation. The volunteer was seated in the chair with his shoulder and hip against the side board. A belt restraint system consisting of cross chest shoulder straps, lap strap, crotch strap and a horizontal chest strap was used to secure the volunteer to the seat. The sled was accelerated gently over a 60 foot distance and then abruptly decelerated at a prescribed constant deceleration level with a hydraulic shock absorber. The results of the most severe test are given in annex L.

6.2.2 Test Setup

Attach a rigid seat with a 15° seat back angle and a rigid vertical side board (similar to the seat used by Patrick and Chou 13) to a decelerator sled, sideways to the direction of sled travel. The top of the side board should be within 50 to 75 mm of the top of the dummy's shoulder. Seat the dummy with its shoulder and hip against the side board and the anterior-posterior axis of its head horizontal. The midsagittal plane of the dummy should be vertical and perpendicular to the direction of sled travel. Use a restraint system to secure the dummy, including its arms and legs, to the chair. Accelerate the sled to a velocity of 5,8 m/s without disturbing the dummy's position and then decelerate to zero velocity at a constant deceleration level of 6,7 G. Variations in sled velocity of 0,2 m/s and constant deceleration of 0,3 G are permitted. An accelerator type sled can be used if the appropriate sled kinematics can be obtained.

6.2.3 Instrumentation

Instrument the dummy with a triaxial accelerometer at the center of gravity of the head and either a six-axis neck transducer at the neck-to-head interface (occipital condylar level), or sufficient accelerometers attached to the head to calculate these reactions. Use photographic targets to monitor the specified head motion. Measure the sled acceleration and record the required dummy motions with onboard cameras. Filter all response data according to the requirements of SAE Recommended Practice J211.

6.2.4 Response Requirements

A dummy subjected to the sled test described in subclause 6.2.2 Test Setup, should meet the response requirements given in Table 2.

6.3 Neck Test 3 and Shoulder Test 3

6.3.1 Original Data

Tarriere (30) conducted four high-G cadaver tests to obtain data that could be used to define lateral neck bending response in a test environment of greater severity than used for volunteer testing. Unfortunately, each test had an abnormality. Tarriere selected one test as being the most appropriate test to use for defining a set of high-G response requirements. Based on ratios of cadaver response compared to volunteer response obtained for low-G sled tests, the cadaver data for maximum horizontal and vertical head displacement and peak head flexion and torsion angles were modified by Tarriere to reflect human response. annex M summarizes the data.

6.3.2 Test Setup

Fasten an upright rigid chair, functionally similar to the one used by Ewing et al. (11), to a HYGE sled, facing sideways to the direction of sled travel. Attach a vertical side board to the seat to restrict upper torso rotation and to support the dummy during sled translation. The top of the side board should be 40 to 50 mm below the top of the dummy's shoulder. Seat the dummy upright, with its shoulder and hip against the side board and the anterior-posterior axis of its head horizontal. The midsagittal plane of the dummy should be vertical and perpendicular to the direction of sled travel. Use a belt restraint to secure the dummy to the seat. Accelerate the sled to 22 ± 0,5 km/h with a pulse that is within the corridor shown in Figure 7.

6.3.3 Instrumentation

Instrument the dummy with a triaxial accelerometer at the center of gravity of the head, a triaxial accelerometer in the thoracic spine in the region of T1 and a six-axis neck transducer at the head-to-neck interface (occipital condylar level) or sufficient head accelerometers to calculate these reactions. Use photographic targets to track the translation of the center of gravity of the head, lateral head rotation, head twist and T1 translation. Measure the sled acceleration and record the required dummy displacements with onboard cameras. Filter all response data according to the requirements of SAE Recommended Practice J211.

6.3.4 Response Requirements

A dummy subjected to the sled test described in subclause 6.3.2 Test Setup should meet response requirements given in Table 2.

6.4 Thorax Test 5 and Pelvis Tests 7 - 9

6.4.1 Original Data

Researchers at the University of Heidelberg conducted sled tests using unembalmed cadavers (23). Rigid surface impacts were conducted at 6,8 and 8,9 m/s. Padded surface impacts were conducted at 8,9 m/s.

Thoracic impact surface force was recorded. Accelerations of T1, T12 and the 4th rib on the impacted side were recorded. Thoracic response data for the Heidelberg sled tests are summarized in annex N.

Pelvic acceleration was measured in all tests and pelvic impact surface force was measured in some tests. Pelvic response data from the Heidelberg tests are summarized in annex O.

6.4.2 Test Setup

Secure a seat with instrumented side panels to an impact sled, facing sideways to the direction of sled travel. The locations of the thoracic and pelvic impact surfaces are illustrated in Figure 8. The surface of the seat should have a low coefficient of friction to assure that the dummy will translate relative to the sled without rotating. Seat the dummy at a sufficient distance from the side board to assure that the sled is completely stopped prior to impact. For the padding tests, fasten 140 mm x 140 mm x 420 mm blocks of APR open cell urethane foam to the side board to form thorax and pelvis impact surfaces. The padding characteristics are defined in annex I. Conduct the rigid impacts at 6,8 and 8,9 m/s. Conduct the padded impacts at 8,9 m/s. The tolerances on the sled velocities are -0,0 and +0,3 m/s.

6.4.3 Instrumentation

Instrument the dummy to measure the lateral accelerations of the upper and lower spine, the impacted rib corresponding to the 4th rib of an adult male, and the pelvis. Instrument the dummy to measure the lateral deflection of the impacted ribs relative to the thoracic spine. Use inertia-compensated load transducers to measure the thoracic and pelvic forces independently. Filter the impact forces and accelerations at channel frequency class 1000 Hz, according to the requirements of SAE Recommended Practice J211. For comparison with the biomechanical response requirements, the data must be filtered using a 100 Hz FIR filter (18) since the FIR filter may have significantly distorted the amplitude and wave form of the cadaver data.

6.4.4 Response Requirements

The thoracic impact surface force and lateral thoracic accelerations were normalized using the procedure described by Mertz (17). The normalization procedure is summarized in annex N. For a 6,8 m/s rigid surface impact, the force versus time history of the dummy must lie within the corridor described in Table 5. The peak lateral acceleration of the upper spine, the peak lateral acceleration of the lower spine, and the peak lateral acceleration of the impacted rib, corresponding to the 4th rib of an adult male, should lie within the bounds given in Table 2.

The peak pelvic acceleration and pelvic impact surface force were normalized as described in annex O. Data from tests with similar impact velocities and impact surfaces were grouped and average values of the normalized peak pelvic acceleration and normalized peak impact force were calculated. These averages were used to define reasonable upper and lower bounds. The corresponding requirements for peak pelvic acceleration and peak pelvic impact surface force are given in Table 2.

6.5 Shoulder Test 4, Thorax Test 6, Abdomen Tests 3 - 5, and Pelvis Tests 10 - 13

6.5.1 Original Data

A series of lateral sled impacts was conducted at WSU and funded by a grant from the Centers for Disease Control (31, 32). These tests were similar to the sled tests conducted by the University of Heidelberg, except the impact wall had individual loading surfaces for the shoulder, thorax, abdomen, pelvis and knee; and paper honeycomb was used in the padded tests. Three-dimensional film analysis was performed on 7 of the 17 tests and the instrumentation and film data were normalized by Irwin (15, 16) according to the normalization procedure recommended by Mertz (17). The shoulder and thoracic response data are further described in annex P. The abdominal response data are further described in annex Q and the pelvic response data are further described in annex R.

6.5.2 Test Setup

Secure a seat, to an impact sled, sideways to the direction of sled travel. The surface of the seat should have a low coefficient of friction to assure that the dummy will translate relative to the sled without rotating. Configure an impact wall, as illustrated in Figure 9, and secure it to the sled, perpendicular to the direction of sled travel. Seat the dummy at a sufficient distance from the impact wall to assure that the sled is completely stopped prior to impact.

6.5.3 Instrumentation

Instrument the dummy to measure the lateral accelerations of the upper and lower spine, the ribs on the impacted side, and the pelvis. Instrument the dummy to measure the lateral deflection of the impacted ribs relative to the thoracic spine. Use inertia-compensated load transducers to measure the shoulder, thoracic, abdominal, pelvic and knee forces independently. Filter the impact forces and accelerations at channel frequency class 1000 Hz, according to the requirements of SAE Recommended Practice J211.

6.5.4 Response Requirements

The forces of the shoulder plus thoracic impact surfaces and lateral thoracic accelerations were normalized using the procedure described by Mertz (17). The normalization procedure is summarized in annex P. For a 8,9 m/s padded surface impact, the force versus time history of the dummy must lie within the corridor defined in Table 6. The peak lateral displacement of T12 should lie within the bounds given in Table 2.

The forces of the abdominal impact surface were normalized using the procedure described by Mertz (17). The normalization procedure is summarized in annex Q. The requirements for the force versus time histories of the abdominal impact surface are defined in Table 5 for the 6,8 m/s rigid impact. The requirements for the force versus time histories of the abdominal impact surface are defined in Table 6 for 8,9 m/s rigid and padded impacts.

The force versus time histories of the pelvic impact surfaces and peak lateral accelerations of the sacrum were normalized using the procedure described by Mertz (17). The normalization procedure is summarized in annex R. The requirements for the force versus time histories of the pelvic impact surface are defined in Table 5 for the 6,8 m/s and 8,9 m/s rigid impacts. The requirements for the force versus time histories of the pelvic impact surface are defined in Table 6 for the 8,9 m/s padded impact. The peak lateral accelerations of the sacrum should lie within the bounds given in Table 2.

7 References

1. Hodgson, V. R. and Thomas, L. M., 1975, "Head Impact Response," Vehicle Research Institute Report-VRI 7.2, Society of Automotive Engineers.

2. APR, 1986, "APR Lateral Cadaver Drop Test Involving the Head," ISO/TC22/SC12/WG5 Document N165.

3. McElhaney, J. H., Stalnaker, R. L. and Roberts, V. L., 1973, "Biomechanical Aspects of Head Injury," Human Impact Response - Measurement and Simulation, Plenum Press, N.Y.

4. Nahum, A., Ward, C., Raasch, E., Adams, S. and Schneider, D., 1980, "Experimental Studies of Side Impact to the Human Head," SAE 801301, Proceedings of the Twenty-fourth Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA.

5. Nahum, A., Ward, C., Schneider, D., Raasch, F. and Adams, S., 1981, "A Study of Impacts to Lateral Protected and Unprotected Head," SAE 811006, Proceedings of the Twenty-fifth Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA.

6. Schneider, D., Ward, C., and Newman, J., 1983, "ATD and Cadaver Head Response to Impact Loading," Proceedings of the 11th Workshop on Human Subjects for Biomechanical Research, San Diego, CA. (Note: Data provided by Dr. Schneider).

7. Got, C., Patel, A., Fayon, A., Tarriere, C., and Walfisch, G., 1978, "Results of Experimental Head Impacts on Cadavers: The Various Data Obtained and Their Relations to Some Physical Parameters," SAE 780887, Proceedings of the Twenty-second Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA.

8. Mertz, H. J., 1985a, "A Critique of Schneider's Test Program to Compare the Head Impact Responses of a Part 572 Dummy, Hybrid III Dummy and Four Cadaver Specimens," NHTSA Docket 74-14, GM Submission USG 2380 - Attachment I.

9. Mertz, H. J., Balser, J. S., Mai, H. A. 1985, "Hybrid III and Part 572 Responses to Padded Forehead Impacts," NHTSA Docket 74-14, GM Submission USG 2380 - Attachment II.

10. Mertz, H. J., 1985b, "Biofidelity of the Hybrid III Head," SAE 851245, Society of Automotive Engineers, Warrendale, PA.

11. Ewing, C. L., Thomas, D. J., Majewski, P. L., Black, R., and Lustik, L., 1977, "Measurement of Head, T1, and Pelvic Response to -Gx Impact Acceleration," SAE 770927, Proceedings of the Twenty-first Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA.

12. Wismans, J., Van Oorschot, H. and Woltring, J. H., 1986, "Omni-Directional Head-Neck Response," SAE 861893, Proceedings of the Thirtieth Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA.

13. Patrick, L. M. and Chou, C. C., 1976, "Response of the Human Neck in Flexion, Extension and Lateral Flexion," Final Report VRI-7.3, Society of Automotive Engineers, Warrendale, PA.

14. Bendjellal, F., Walfisch, G., Fayon, A., and Tarriere, C., 1984, "APR Biomechanical Data," Nanterre, France.

15. Irwin, A. L., Walilko, T. J., Cavanaugh, J. M., Zhu, Y., and King, A. I., 1993, "Displacement Responses of the Shoulder and Thorax in Lateral Sled Impacts," SAE 933124, Proceedings of the Thirty-seventh Stapp Car Crash Conference, P-269, Society of Automotive Engineers, Warrendale, PA.

16. Irwin, A. L., 1994, Analysis and CAL3D Model of the Shoulder and Thorax Responses of Seven Cadavers Subjected to Lateral Impacts, Ph.D. Thesis, Wayne State University, Detroit, MI.

17. Mertz, H. J., 1984, "A Procedure for Normalizing Impact Response Data," SAE 840884, Society of Automotive Engineers, Warrendale, PA.

18. Eppinger, R. H., Augustyn, K. and Robbins, D. H., 1978, "Development of a Promising Universal Thoracic Trauma Prediction Methodology," SAE 780891, Proceedings of the Twenty-second Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA.

19. Viano, D. C., 1989, "Biomechanical Responses and Injuries in Blunt Lateral Impact," SAE 892432, Proceedings of the Thirty-third Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA.

20. Stalnaker, R. L., Tarriere, C., Fayon, A., Walfisch, G., Balthazard, M., Masset, J., Got, C. and Patel, A., 1979, "Modification of Part 572 Dummy for Lateral Impact According to Biomechanical Data," SAE 791031, Proceedings of the Twenty-third Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA.

21. Walfisch, G., Fayon, A., and Rosey, J. P., 1978, "Determination Des Tolerances Humaines Et Des Caracteristiques Necessaires A L'Optimisation De La Protection En Choc Lateral," Laboratoire De Physiologie Et De Biomecanique Peugeot S. A./Renault, Marche 78029.

22. APR, 1989, "Review of the Data and Dummy Requirements Contained in ISO/TC22/SC12 Document DP-9790-3 Req. 1 (July, 1988)," ISO/TC22/SC12/WG5 Document N225.

23. Marcus, J. H., Morgan, R. M. and Eppinger, R., 1983, "Human Response to and Injury from Lateral Impact," SAE 831634, Proceedings of the Twenty-seventh Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA.

24. Lowne, R. W., 1986, "Normalizing Method for a Two Mass System," Personal Communication

25. Walfisch, G., Fayon, A., Tarriere, C., Rosey, J., Guillon, F., Got, C., Patel, A., and Stalnaker, R., 1980, "Designing of a Dummy's Abdomen for Detecting Injuries in Side Impact Collisions," Fifth International Conference on the Biomechanics of Impacts.

26. Cesari, D., Ramet, M., and Clair, P., 1980, "Evaluation of Pelvic Fracture Tolerance in Side Impact", SAE 801306, Proceedings of the Twenty-fourth Stapp Car Crash, Society of Automotive Engineers, Warrendale, PA.

27. Cesari, D. and Ramet, M., 1982, "Pelvic Tolerance and Protection Criteria in Side Impact," SAE 821159, Proceedings of the Twenty-sixth Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA.

28. Cesari, D., Ramet, M., and Bouquet, R., 1982, "Tolerance of Human Pelvis to Fracture and Proposed Pelvic Protection Criterion to be Measured on Side Impact Dummies," Ninth International Technical Conference on Experimental Safety Vehicles.

29. Tarriere, C., Walfisch, G., Fayon, A., Rosey, J., Got, C., Patel, A., and Delmas, A., 1979, "Synthesis of Human Tolerances Obtained from Lateral Impact Simulations," Seventh International Technical Conference on Experimental Safety Vehicles.

30. Tarriere, C., 1986, "Proposal for Lateral Neck Response Requirements for Severe Impact Conditions," ISO/TC22/SC12/WG5 Document N166-Draft 1.

31. Cavanaugh, J. M., Walilko, T. J., Malhotra, A., Zhu, Y., and King A. I., 1990a, "Biomechanical Response and Injury Tolerance of the Thorax in Twelve Sled Side Impacts," SAE 902307, Proceedings of the Thirty-fourth Stapp Car Crash Conference, P-236, Society of Automotive Engineers, Warrendale, PA.

32. Cavanaugh, J. M., Walilko, T. J., Malhotra, A., Zhu, Y., and King A. I., 1990b, "Biomechanical Response and Injury Tolerance of the Pelvis in Twelve Sled Side Impacts," SAE 902305, Proceedings of the Thirty-fourth Stapp Car Crash Conference, P-236, Society of Automotive Engineers, Warrendale, PA.

33. Krause, P., 1984, "Normalization of Side Impact Cadaver Dynamic Response Data Utilizing Regression Techniques," SAE 840883, Warrendale, PA.

34. USA Delegation, 1989, "WSU/GMR Cadaver Response Data for Oblique-Lateral Thoracic Pendulum Impacts," ISO/TC22/SC12/WG5 Document N234.

SAE, 1995, "Instrumentation for Impact Test," SAE J211/1 MAR 1995, 1995 SAE Handbook Volume 4 - On-Highway Vehicles & Off-Highway Machinery, Society of Automotive Engineers, Warrendale, PA.

Table 1 — Summary of the Biofidelity Requirements, a Brief Test Description, Location of the Requirements by subclause Number, and the Location of the Original Data by Annex

Biofidelity Test	Brief Test Description	Subclause	Annex
Head Test 1	200 mm Rigid Drop	5.1	E
Head Test 2	1200 mm Padded Drop	5.2	F
Neck Test 1	7.2 G Sled Test	6.1	K
Neck Test 2	6.7 G Sled Test	6.2	L
Neck Test 3	12.2 G Sled Test	6.3	M
Shoulder Test 1	Pendulum Impact at 4.5 m/s	4.1	A
Shoulder Tests 2 & 3	7.2 G Sled Test	6.1	K
Shoulder Test 4	WSU Type Sled Test	6.5	P
Thorax Tests 1 & 2	Pendulum Impacts at 4.3 and 6.7 m/s	4.2	B, C
Thorax Tests 3 & 4	1 m Rigid and 2 m Padded Drops	5.3	G
Thorax Test 5	Heidelberg Type Sled Tests	6.4	N
Thorax Test 6	WSU Type Sled Tests	6.5	P
Abdomen Tests 1 & 2	1 and 2 m Drops onto Rigid Armrest	5.4	J
Abdomen Tests 3 - 5	WSU Type Sled Test	6.5	Q
Pelvis Tests 1 & 2	Pendulum Impacts Between 6 and 10 m/s	4.3	D
Pelvis Tests 3 - 6	0.5 and 1m Rigid, and 2 and 3 m Padded Drops	5.3	H
Pelvis Tests 7 - 9	Heidelberg Sled Tests	6.4	O
Pelvis Tests 10 - 13	WSU Sled Tests	6.5	R

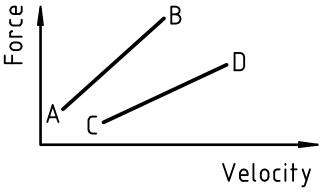
Table 2 — Biomechanical Response Requirements for Various Lateral Impact Conditions

Impact Condition	Measurement	Units	Lower Bound	Upper Bound
Head Test 1 200 mm Rigid Drop	Peak Resultant Acceleration at a Point on the Non-impacted Side of the Head	G	100	150
Head Test 2 1200 mm Padded Drop	Peak Resultant Head Acceleration at the C.G.	G	205	277
Neck Test 1 7,2 G Sled Impact	Peak Horizontal Acceleration of T1	G	12	18
	Peak Horizontal Displacement of T1 Relative to the Sled	mm	46	63
	Peak Horizontal Displacement of the Head C.G. Relative to T1	mm	130	162
	Peak Vertical Displacement of the Head C.G. Relative to T1	mm	64	94
	Time of Peak Head Excursion	s	0,159	0.175
	Peak Lateral Acceleration of the Head	G	8	11
	Peak Vertical (Downward) Acceleration of the Head	G	8	10
	Peak Flexion Angle	degrees	44	59
	Peak Twist Angle	degrees	-45	-32
Neck Test 2 6,7 G Sled Impact	Peak Flexion Angle	degrees	40	50
	Peak Bending Moment about A-P Axis at Occipital Condyles	N·m	40	50
	Peak Bending Moment about R-L Axis at Occipital Condyles	N·m	20	30
	Peak Twist Moment	N·m	15	20
	Peak Shear Force at Occipital Condyles	N	750	850
	Peak Tension Force at Occipital Condyles	N	350	400
	Peak P-A Shear Force	N	325	375
	Peak Resultant Head Acceleration	G	18	24
Neck Test 3 12,2 G Sled Impact	Peak Lateral Acceleration of the Head C.G.	G	25	47
	Peak Horizontal Displacement of the Head C.G. Relative to the Sled	mm	185	226
	Peak Flexion Angle	degrees	62	75
	Peak Twist Angle	degrees	62	75
Shoulder Test 1 4,5 m/s Pendulum Impact	Peak Shoulder Deflection	mm	34	41
Shoulder Test 2 7,2 G Sled Impact	Peak Horizontal Acceleration of T1	G	12	18
	Peak Horizontal Displacement of T1 Relative to the Sled	mm	46	63
Shoulder Test 3 12,2 G Sled Impact	Peak Lateral Acceleration of T1	G	17	23
Thorax Test 3 1,0 m Rigid Drop	Peak Deflection of the Impacted Rib	mm	26	38
Thorax Test 4 2,0 m Padded Drop	Peak Deflection of the Impacted Rib	mm	26	40
Thorax Test 5 6,8 m/s Rigid Sled	Peak Lateral Acceleration of the Upper Spine	G	82	122
	Peak Lateral Acceleration of the Lower Spine	G	71	107
	Peak Lateral Acceleration of the Impacted Rib (corresponding to the 4th rib of adult male)	G	64	100

Table 2 *(continued)*

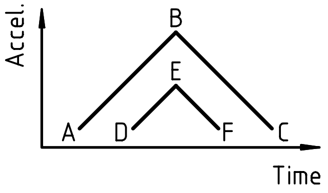
Impact Condition	**Measurement**	**Units**	**Lower Bound**	**Upper Bound**
Thorax Test 6 8,9 m/s Padded Sled	Peak Lateral Displacement of T12	mm	80	108
Abdomen Test 1 1 m Drop	Peak Acceleration of the Lower Spine	G	29	35
	Peak Acceleration of the Impacted Rib	G	100	125
	Peak Abdomen Penetration	mm	41	-
Abdomen Test 2 2 m Drop	Peak Acceleration of the Lower Spine	G	75	91
	Peak Acceleration of the Impacted Rib	G	160	200
	Peak Abdominal Penetration	mm	41	-
Pelvis Test 3 0,5 m Rigid Drop	Peak Pelvic Acceleration	G	37	45
Pelvis Test 4 1,0 m Rigid Drop	Peak Pelvic Acceleration	G	63	77
Pelvis Test 5 2,0 m Padded Drop	Peak Pelvic Acceleration	G	39	47
Pelvis Test 6 3,0 m Padded Drop	Peak Pelvic Acceleration	G	48	58
Pelvis Test 7 6,8 m/s Rigid Sled	Peak Pelvic Force	kN	6,4	7.8
	Peak Pelvic Acceleration	G	63	77
Impact Condition	Measurement	Units	Lower Bound	Upper Bound
Pelvis Test 8 8,9 m/s Rigid Sled	Peak Pelvic Force	kN	22,4	26.4
	Peak Pelvic Acceleration	G	96	116
Pelvis Test 9 8,9 m/s Padded Sled	Peak Pelvic Force	kN	11,6	13.6
	Peak Pelvic Acceleration	G	61	75
Pelvis Test 10 6,8 m/s Rigid Sled	Peak Lateral Pelvic Acceleration	G	85	115
Pelvis Test 11 8,9 m/s Rigid Sled	Peak Lateral Pelvic Acceleration	G	111	151
Pelvis Test 12 8,9 m/s 15 psi Padded Sled	Peak Lateral Pelvic Acceleration	G	37	51
Pelvis Test 13 8,9 m/s 23 psi Padded Sled	Peak Lateral Pelvic Acceleration	G	65	89

Table 3 — Coordinates for the Biomechanical Response Requirements for Various Lateral Impact Conditions



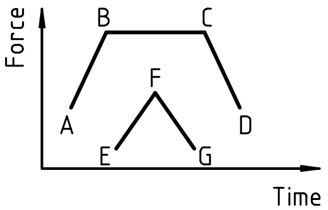
		Pelvis Tests 1 & 2 Pendulum Impact	
		Velocity (m/s)	Pendulum Force (kN)
Upper Boundary Coordinates	A	4.5	4.9
	B	11.5	11.3
Lower Boundary Coordinates	C	4.5	4.0
	D	11.5	9.2

Table 4 — Coordinates for the Biomechanical Response Requirements for Various Lateral Impact Conditions



		Thorax Test 1 4,3 m/s Pendulum Impact	
		Time (ms)	Upper Spine Lateral Acceleration (G)
Upper Boundary Coordinates	A	0	2
	B	15	15
	C	50	0
Lower Boundary Coordinates	D	6	0
	E	15	8
	F	37	0

Table 5 — Coordinates for the Biomechanical Response Requirements for Various Lateral Impact Conditions

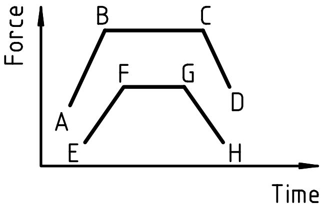


		Shoulder Test 1 4,5 m/s Pendulum		Thorax Test 3 1 m Rigid Drop		Thorax Test 4 2 m Padded Drop	
		Time (ms)	Pendulum Force (kN)	Time (ms)	Thorax Plate Force (kN)	Time (ms)	Thorax Plate Force (kN)
Upper Boundary Coordinates	A	0	1,6	0	2,0	0	4.0
	B	6	2,8	10	9,0	18	9.0
	C	26	2,8	31	9,0	50	9.0
	D	57	1,0	45	2,0	65	2.0
Lower Boundary Coordinates	E	0	0	5	0	0	0
	F	13	1,7	20	4,8	32	4.8
	G	42	0,6	30	2,0	45	2.0

		Thorax Test 5 6,8 m/s Rigid Sled		Abdomen Test 1 1 m Rigid Drop		Abdomen Test 2 2 m Rigid Drop	
		Time (ms)	Thorax Plate Force (kN)	Time (ms)	Armrest Force (kN)	Time (ms)	Armrest Force (kN)
Upper Boundary Coordinates	A	0	2	0	1,0	0	1.3
	B	10	17	13	4,5	8	6.1
	C	16	17	19	4,5	16	6.1
	D	50	2,5	38	1,0	38	0.5
Lower Boundary Coordinates	E	14	0	2	0	0	0
	F	20	5	17	2,5	13	4.1
	G	30	0	32	0,5	27	0.5

		Abdomen Test 3 6,8 m/s Rigid Sled		Pelvic Test 10 6, m/s Rigid Sled		Pelvic Test 11 8,9 m/s Rigid Sled	
		Time (ms)	Abdominal Plate Force (kN)	Time (ms)	Pelvic Plate Force (kN)	Time (ms)	Pelvic Plate Force (kN)
Upper Boundary Coordinates	A	0	0,5	0	1,0	0	4
	B	5	3,5	10	7,5	5	13
	C	30	3,5	20	7,5	10	13
	D	45	1,0	30	3,0	15	7
Lower Boundary Coordinates	E	0	0	5	0	2	0
	F	18	2,0	15	5,5	7.5	10
	G	38	1,0	30	0	15	4

Table 6 — Coordinates for the Biomechanical Response Requirements for Various Lateral Impact Conditions

		Shoulder Test 4 & Thorax Test 6 8.9 m/s Padded Sled		Thorax Test 1 4.3 m/s Pendulum		Thorax Test 2 6.7 m/s Pendulum	
		Time (ms)	Shoulder + Thoracic Plate Force (kN)	Time (ms)	Pendulum Force (kN)	Time (ms)	Pendulum Force (kN)
Upper Boundary Coordinates	A	0	2,0	0	1,7	0	1.2
	B	5	9,4	10	3,7	5	5.2
	C	30	9,4	30	3,7	25	5.2
	D	45	5,0	45	2,0	45	2.5
Lower Boundary Coordinates	E	0	0	0	0	0	0
	F	8	6,0	10	1,7	15	3.2
	G	30	6,0	30	1,7	25	3.2
	H	35	5,0	40	0	45	0

		Abdomen Test 4 8.9 m/s Rigid Sled		Abdomen Test 5 8.9 m/s Padded Sled		Pelvic Test 13 8.9 m/s Padded Sled	
		Time (ms)	Abdominal Plate Force (kN)	Time (ms)	Abdominal Plate Force (kN)	Time (ms)	Pelvic Plate Force (kN)
Upper Boundary Coordinates	A	0	0,5	0	0,5	0	2.0
	B	2	5,5	2	5,5	5	7.0
	C	20	5,5	25	5,5	35	7.0
	D	38	2,0	40	2,0	45	3.0
Lower Boundary Coordinates	E	0	0	0	0	2	0
	F	5	3,5	10	2,5	5	3.0
	G	20	3,5	20	2,5	30	3.0
	H	28	2,0	25	2,0	35	2.0

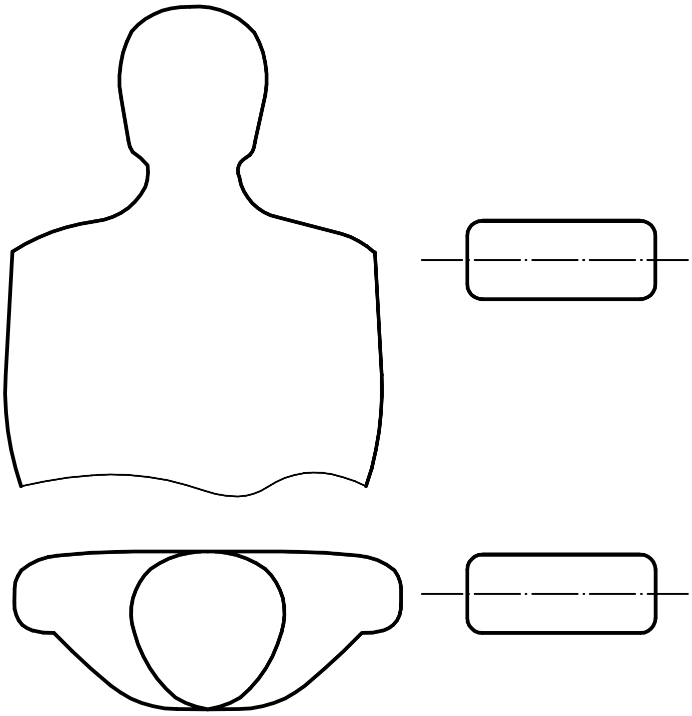


Figure 1 — Test Configuration for the Shoulder Test 1

Dimensions in millimetres

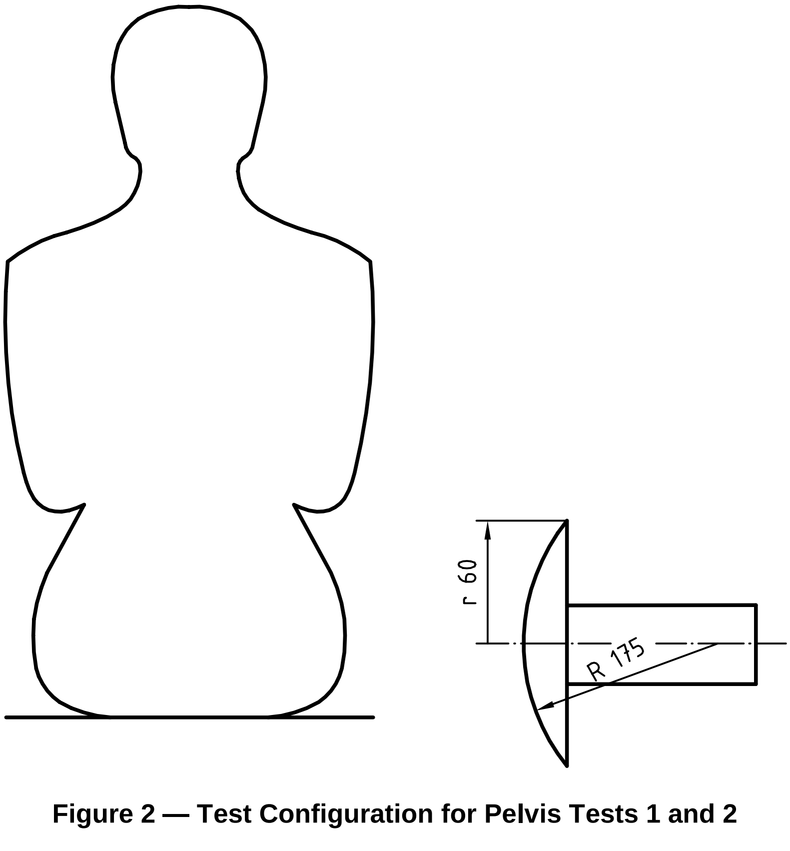


Figure 2 — Test Configuration for Pelvis Tests 1 and 2

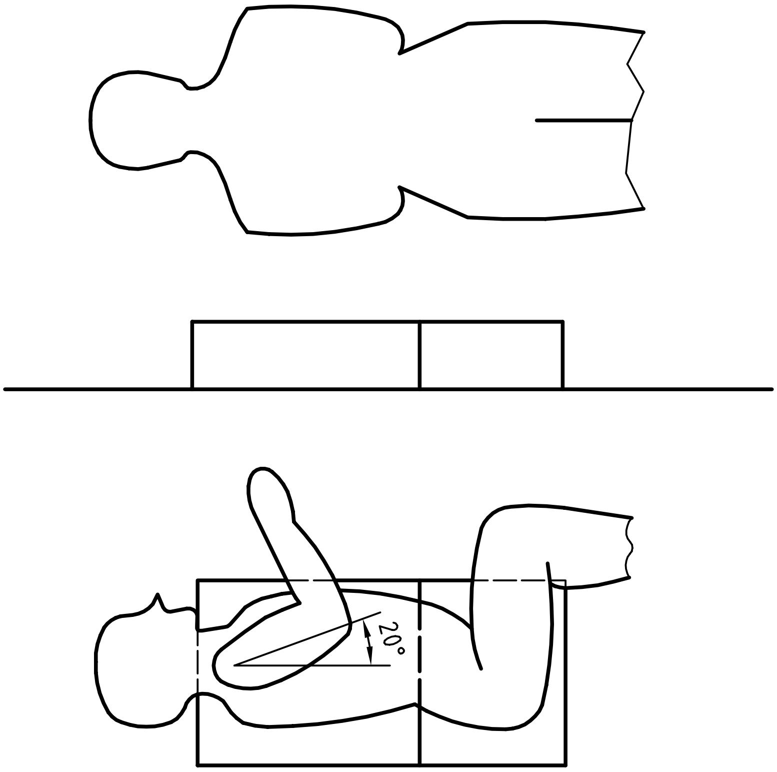


Figure 3 — Test Configuration for Thorax Test 3 and Pelvis Tests 3 and 4

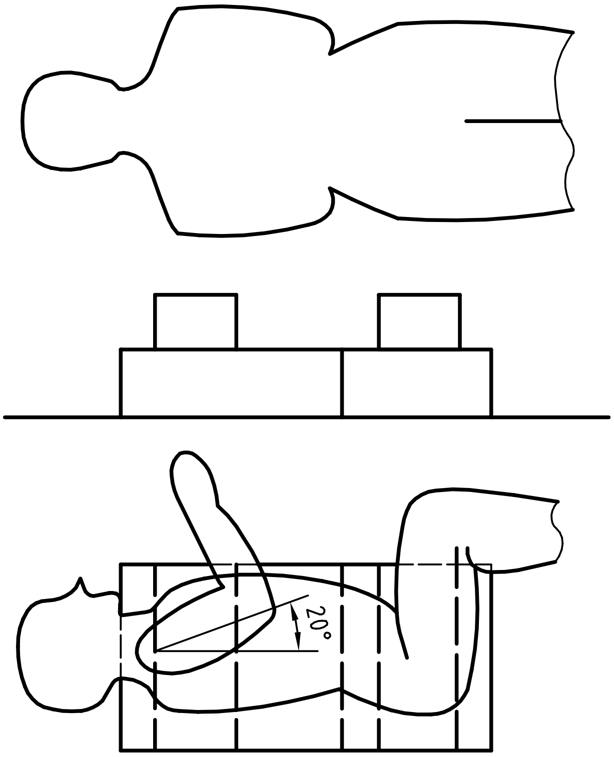


Figure 4 — Test Configuration for Thorax Test 4, and Pelvis Tests 5 and 6

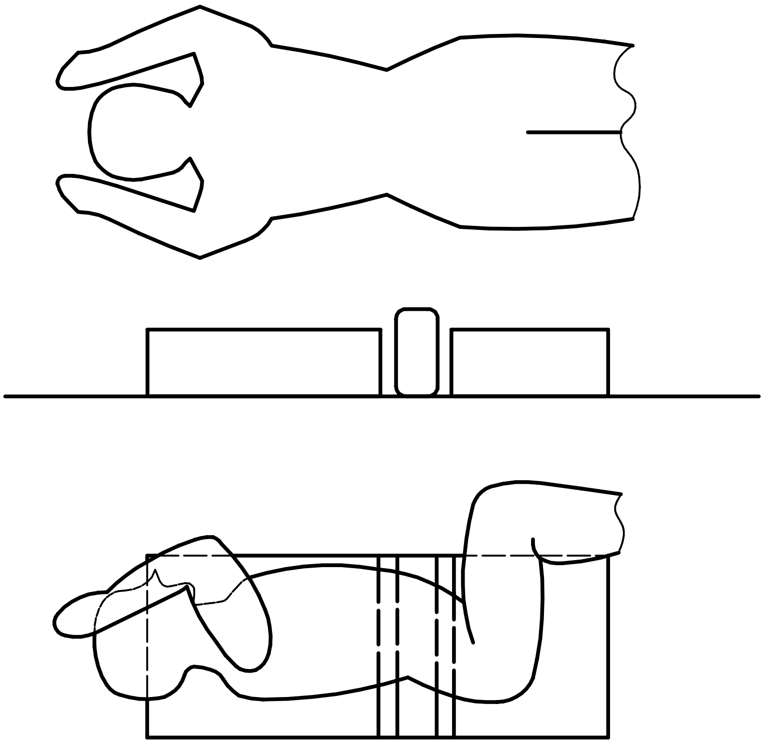


Figure 5 — Test Configuration for Abdomen Tests 1 and 2

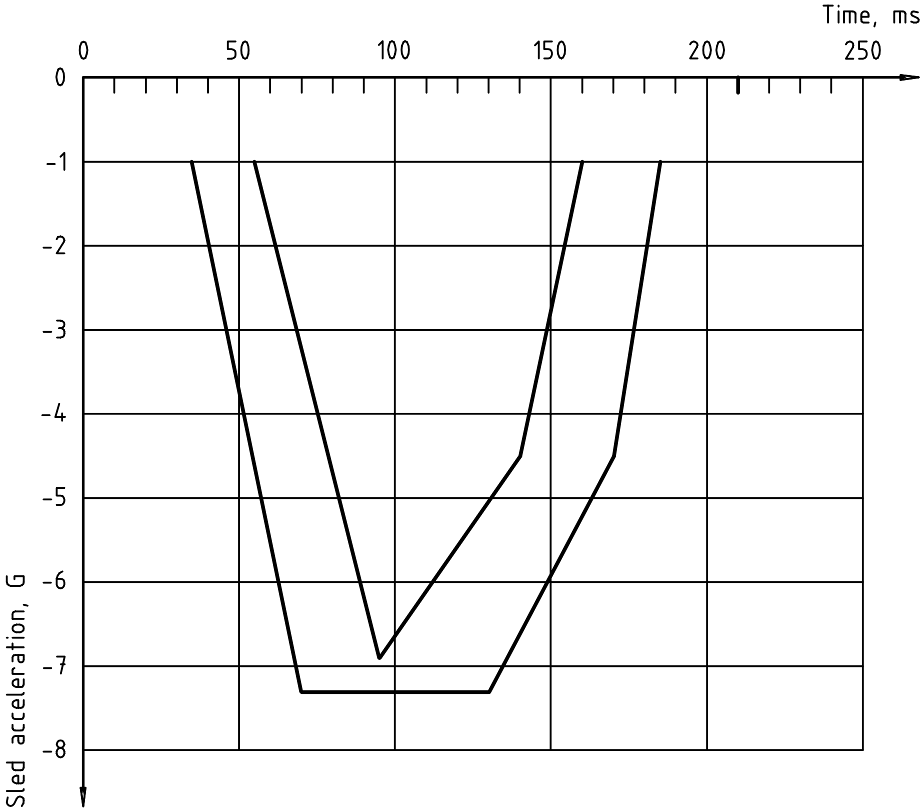


Figure 6 — Sled Pulse for Neck Test 1 and Shoulder Test 2

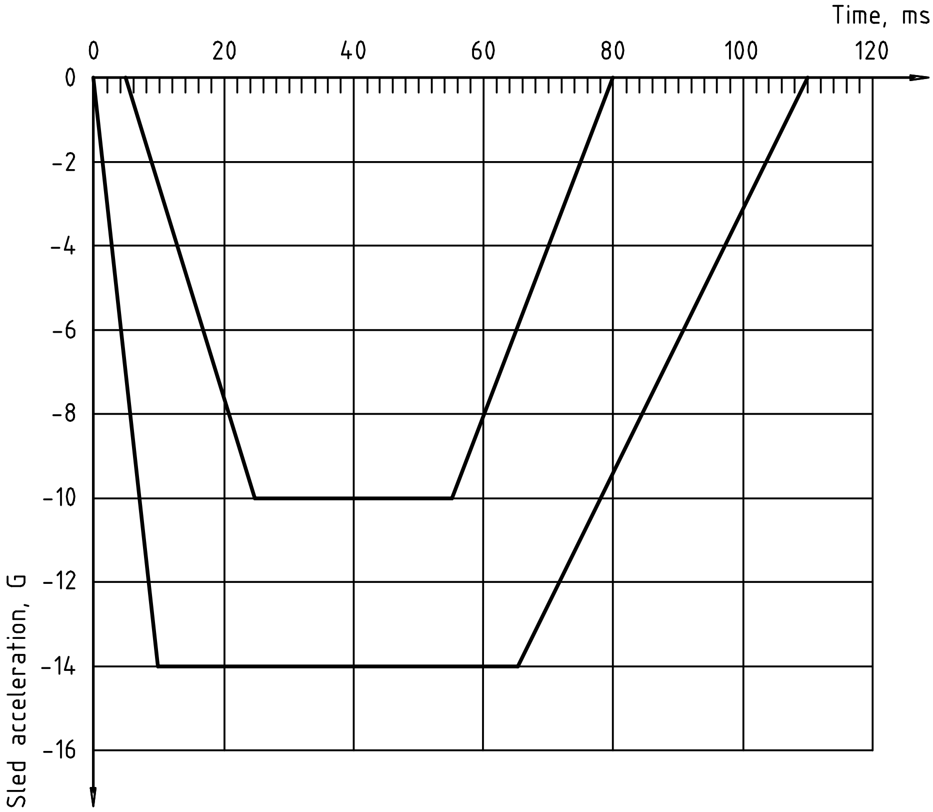


Figure 7 —Sled Pulse for Neck Test 3 and Shoulder Test 3

Dimensions in millimetres

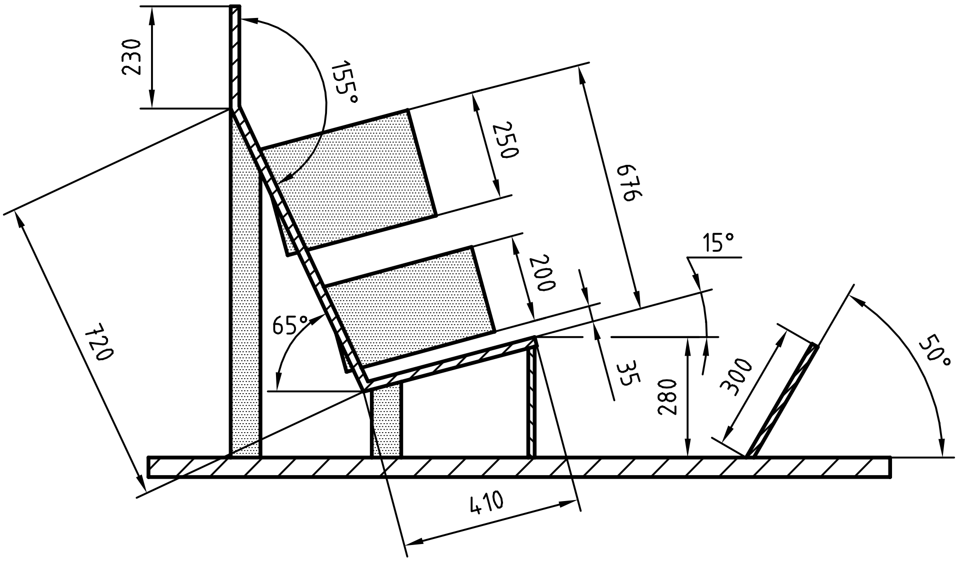
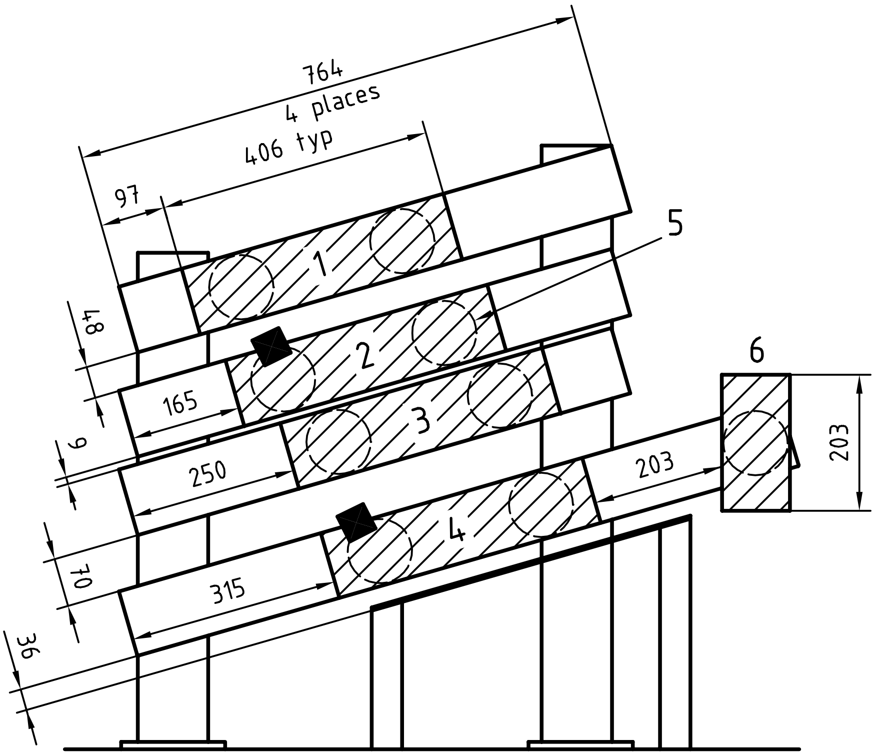


Figure 8 — Impact Surface Configuration for Thorax Test 5 and Pelvis Tests 7 - 9 (23)

Dimensions in millimetres



Key

1 Shoulder beam

2 Thorax beam

3 Abdomen beam

4 Pelvis beam

5 Load cell 9 places

6 Knee beam

Figure 9 — Impact Surface Configuration for Shoulder Test 4, Thorax Test 6, Abdomen Tests 3 - 5 and Pelvis Tests 10 - 13 (15)

Annex A

Analysis of Association PEUGEOT-RENAULT lateral shoulder impact

This annex describes the application of the normalization techniques of Mertz (17) to the lateral shoulder impact data provided by the Association Peugeot-Renault (14).

A.1 Original Data

Researchers of the Association Peugeot-Renault subjected 4 cadavers to lateral impacts delivered to the shoulder by the flat end of a 23 kg rigid cylinder (D=150 mm). Each cadaver was seated on a hardwood horizontal surface with a vertical backrest. The cadaver's hands were placed on its lap and the arm on the impacted side was suspended as if supported by an armrest. The impact was delivered laterally to the shoulder for Tests MS 201, MS 202, and MS 203. The impact for Test MS 204 was delivered at an angle of 15° forward of lateral, as defined in Figure A.1. The force and acceleration of the impactor, the acceleration of the thoracic spine and the deflection of the shoulder relative to the thoracic spine were measured for each test. Following each test, the cadaver was autopsied for fractures of the ribs, clavicle, or scapula.

Table A.1 provides a summary of the weights and thoracic depths of the cadavers. The impact angle defined in Figure A.1, the impact velocity and the maximum deflection of the shoulder relative to the thoracic spine are also given. The force versus time histories for the loads applied to the cadaver's shoulders are shown in Figure A.2. Acceleration versus time histories are not shown since they were not provided.

A.2 Normalized data

The force versus time histories of the impactor were digitized. The characteristic features of each curve were represented by approximately 50 points. The areas under the force versus time histories were calculated using the trapezoidal method of integration and the results were given in Table A.1 under the heading of "Impulse." The acceleration versus time histories and changes in velocity were not available. The impact velocity was used as an approximation of the change in velocity. The effective mass was estimated by,

$$M_e = \left[\int_0^T F dt\right] \Big/ (V_0) \tag{A.1}$$

where $\int_0^T F dt$ is the area under the force versus time history and V_0 is the impact velocity. The effective mass and percent of body mass for each cadaver are given in Table A.1.

The average percent of body mass is 27,0%. The effective mass of a 50th percentile adult male was obtained by multiplying its body mass of 76 kg by 27,0%, giving an effective mass of 20,5 kg.

The mass ratio, R_m, is defined as,

$$R_m = M_s / M_i \tag{A.2}$$

where M_s is the effective mass of the standard subject (50th percentile adult male) and M_i is the effective mass of the i-th subject. For the data discussed here, Equation A.2 becomes,

$$R_m = 20.5\,\text{kg} / M_i \tag{A.3}$$

The mass ratios for the cadavers are given in Table A.1.

The stiffness ratio, R_k, is defined as,

$$R_k = K_s / K_i \tag{A.4}$$

where K_s is the stiffness of the standard subject and K_i is the stiffness of the i-th subject. Mertz (17) has shown that for geometrically similar structures with the same elastic modulus the stiffness is proportional to the characteristic length. Thus, the stiffness ratio can be expressed as,

$$R_k = L_s / L_i \tag{A.5}$$

The characteristic length for the shoulder was chosen as the depth of the thorax. The thoracic depth of a 50th percentile male is 236 mm. Using $L_s = 236\,\mathrm{mm}$, Equation A.5 becomes,

$$R_k = 236\,\mathrm{mm} / L_i \tag{A.6}$$

The stiffness ratios for the cadavers are given in Table A.1.

The normalizing factors for force, R_f, time, R_t, and displacement, R_x, are given by,

$$R_f = \left(R_m R_k\right)^{1/2} \tag{A.7}$$

$$R_t = \left(R_m / R_k\right)^{1/2} \tag{A.8}$$

$$R_x = \left(R_m / R_k\right)^{1/2} \tag{A.9}$$

The normalizing factors calculated for the cadaver impacts are listed in Table A.1. The force and time factors were used to normalize the force versus time histories shown in Figure A.2. For a given impact, each force value was multiplied by its force normalizing factor and each time value was multiplied by its time normalizing factor. The resulting normalized force versus time histories are shown in Figure A.3.

A.3 Force versus time response requirements

The normalized force versus time histories of the cadaver subjects should map onto a single curve representing the response of a standard subject. Comparing the normalized force versus time histories of Figure A.3 it is noted that the curve for Test MS 201 has a considerably different shape and impulse value than those of the other tests. For this reason, Test MS 201 was considered an outlier and was not used in the development of a response corridor. The remaining three normalized force versus time histories and a proposed response corridor for a shoulder impact delivered by a 23 kg rigid cylinder are shown in Figure A.4. Note that the 15° impact angle used in Test MS 204 had very little effect on the resulting force versus time history of the cadaver.

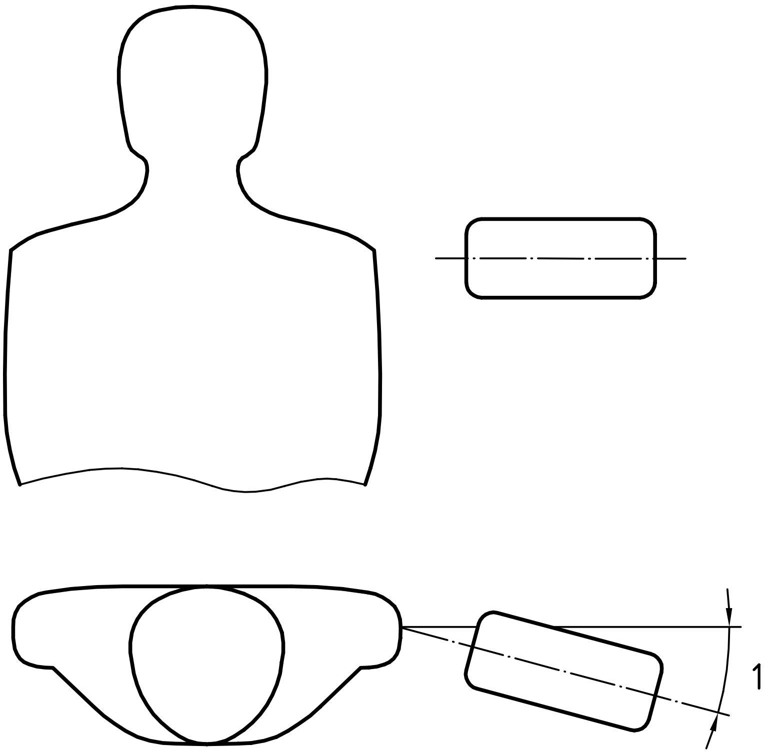
A.4 Maximum deflection response requirement

The maximum shoulder deflections relative to the thoracic spine for Tests MS 202 and MS 203 were normalized by multiplying these values by their corresponding deflection normalizing factor. The results were averaged, giving a value of 37,5 mm. Allowing a plus or minus 10 percent deviation from this value gives a reasonable range of 34 to 41 mm for the maximum shoulder to thoracic spine response requirement.

Table A.1 — Cadaver Data, Test conditions, and test results from the shoulder impact tests performed by the Association PEUGEOT-RENAULT (14); and effective mass, characteristic ratios, and normalizing factors for these data

Test Number	Cadaver Data		Test Conditions		Test Results		Effective Mass		Characteristic Ratios		Normalizing Factors		
	Body Mass (kg)	Thoracic Depth (mm)	Impact Angle (°)	Impact Velocity (m/s)	Defl. (mm)	Impulse (Ns)	M_e (kg)	Body mass (%)	Mass R_m	Stiffness R_k	Force R_f	Time R_t	Defl. R_x
MS 202	52	185	0	4,2	34	74,6	17.8	34,2	1.15	1,28	1.21	0.95	0.95
MS 203	49	180	0	4,5	37	53,7	11.9	24,3	1.72	1,31	1.50	1.15	1.15
MS 204	56	185	15	4,5	[a]	82,1	18.2	32,5	1.13	1,28	1.20	0.94	[a]
MS 201	48	180	0	4,6	37	37,1	8.1	16,9	2.53	1,31	1.82	1.39	1.39

[a] The deflection data for MS 204 were not available.



Key

1 Angle of impact

Figure A.1 — Test Configuration for Shoulder Impact Test MS 204

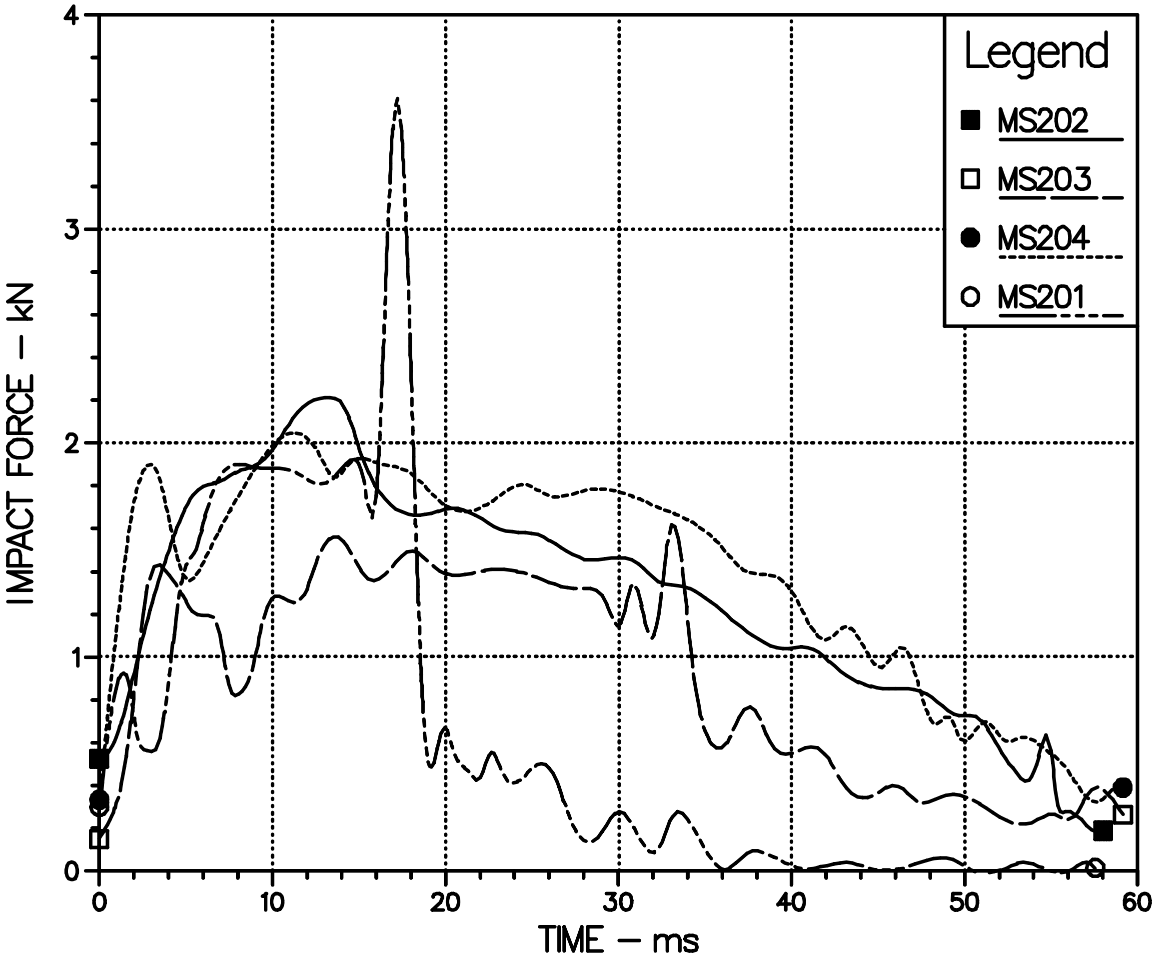


Figure A.2 — Force versus time histories of a 23 kg Rigid Pendulum Used to Impact the Shoulder of Cadavers

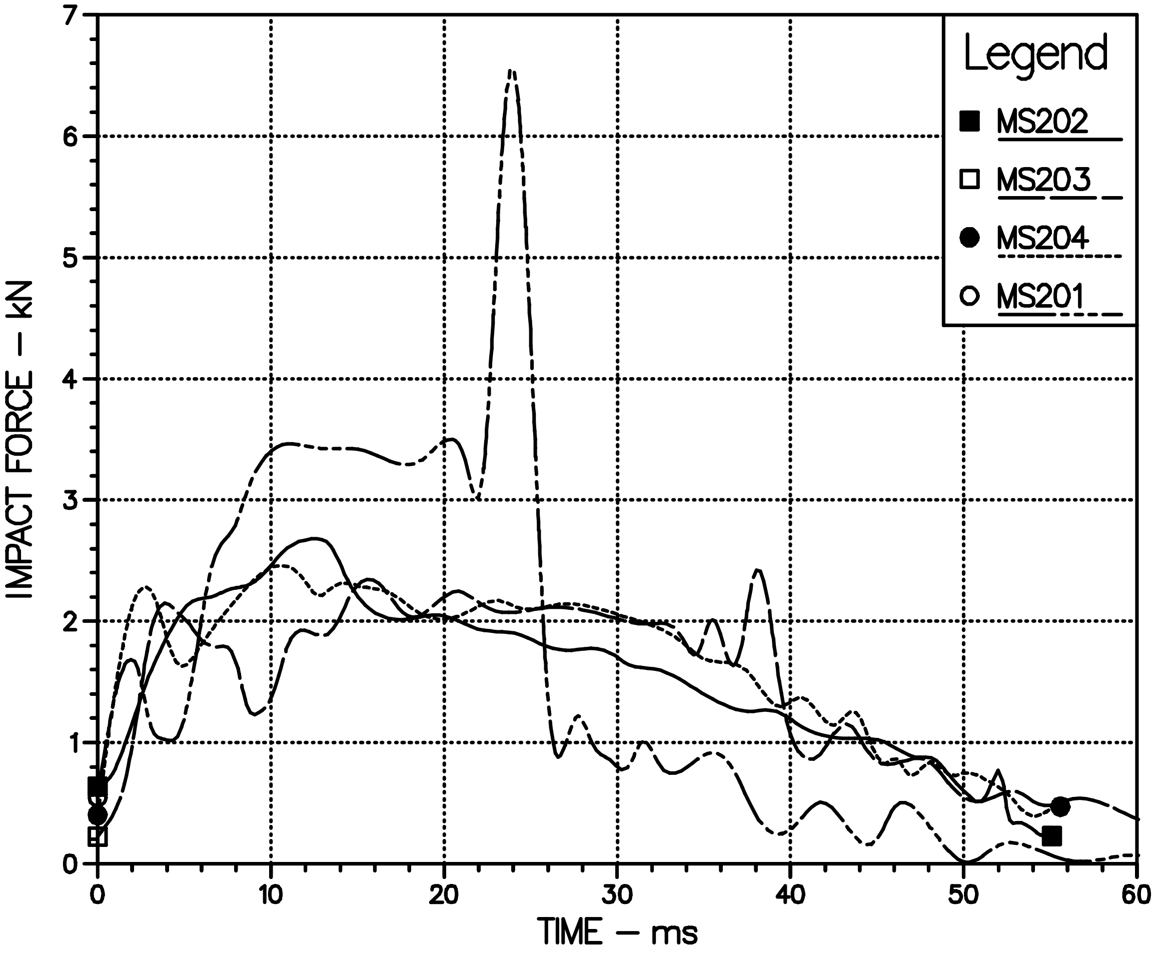


Figure A.3 — Normalized Force Versus Time Histories of a 23 kg Rigid Pendulum Used to Impact the Shoulder of Cadavers

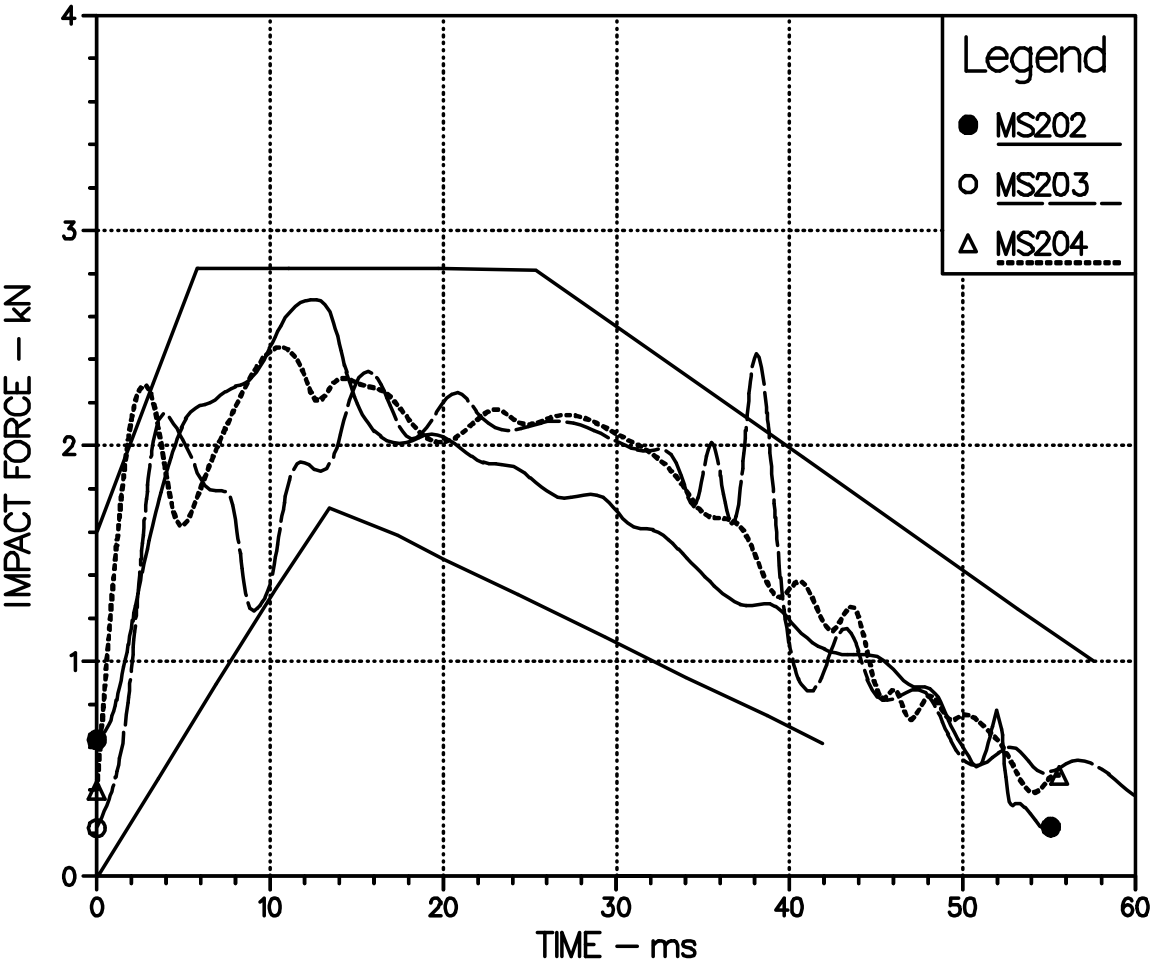


Figure A.4 — Normalized Force Versus Time Histories and Proposed Corridor for a 23 kg Rigid Pendulum Used to Impact the Shoulder

Annex B

Analysis of HSRI lateral thoracic impact data

This annex describes the application of the normalization techniques of Mertz (17) to the lateral thoracic impact data provided by the HSRI (18). Biomechanical impact response requirements based on the normalized HSRI data and the WSU/GMR data (19) are defined in annex C.

B.1 Original Data

A series of cadaver impact tests was conducted by the HSRI (18). The cadavers were seated upright with one arm raised so that the lateral aspect of the chest could be impacted. The impactor had a flat, rigid impact surface which was 150 mm in diameter and its mass was 23,4 kg. The impact velocity was 4,3 m/s. Impactor deceleration versus time histories are shown in Figure B.1. The corresponding lateral acceleration versus time histories of the cadavers' first thoracic vertebrae are shown in Figure B.2. These curves were obtained using a 100 Hz Finite Impulse Response (FIR) filter (18). Similar filtering must be done to the dummy data since the FIR filter may have significantly distorted the amplitude and phase of the cadaver data. The mass of each cadaver and the number of rib fractures are summarized in Table B.1.

B.2 Normalized data

The acceleration versus time histories shown in Figures B.1 and B.2 were normalized to represent characteristic curves for a 50th percentile adult male interacting with a 23,4 kg impactor using an extension of Mertz's technique (17) that was developed by Lowne (24) for a two mass system. The normalizing factors for a two mass system can be defined as follows:

— Impactor Acceleration Factor

$$\left(R_a\right)_p = \left(R_k \cdot R_m\right)^{1/2}\left(23{,}4\,\text{kg} + M_c\right)^{1/2}\left(23{,}4\,\text{kg} + M_s\right)^{-1/2} \qquad \text{(B.1)}$$

— Thoracic Acceleration Factor

$$\left(R_a\right)_T = \left(R_k / R_m\right)^{1/2}\left(23{,}4\,\text{kg} + M_c\right)^{1/2}\left(23{,}4\,\text{kg} + M_s\right)^{-1/2} \qquad \text{(B.2)}$$

a) Time Factor

$$R_t = \left(R_m / R_k\right)^{1/2}\left(23{,}4\,\text{kg} + M_c\right)^{1/2}\left(23{,}4\,\text{kg} + M_s\right)^{-1/2} \qquad \text{(B.3)}$$

where the thoracic mass ratio, R_m, and the thoracic stiffness ratio, R_k, are defined as;

$$R_m = M_s / M_c \qquad \text{(B.4)}$$

$$R_k = K_s / K_c \qquad \text{(B.5)}$$

Note in equations B.4 and B.5, M represents the thoracic mass and K represents the thoracic stiffness. The subscripts in the above equations are defined as follows.

a	Acceleration
k	Stiffness
m	Mass
p	Impactor
c	Cadaver
s	Standard Subject
t	Time
T	Thorax

Mertz (17) has shown that for geometrically similar subjects, the thoracic stiffness ratio is equal to the ratio of characteristic lengths, or,

$$R_k = L_s / L_c \tag{B.6}$$

Unfortunately, no length dimensions are given for the cadavers. Only their total body masses are given. If we extend the assumption of geometric similitude to the total body, then an estimate of the thoracic stiffness ratio can be obtained from the cube root of the body mass, M_B, ratio, or,

$$R_k = \sqrt[3]{(M_B)_s / (M_B)_c} \tag{B.7}$$

The thoracic stiffness ratio for each cadaver is given in Table B.1.

The thoracic cadaver mass, M_c, can be calculated by dividing the thoracic impulse by its change in velocity, or,

$$M_c = \left[\int_\tau M_p a_p dt \right] \Big/ \left[\int_\tau a_T dt \right] \tag{B.8}$$

where

a_P Acceleration versus time history of the impactor

a_T Lateral acceleration versus time history of the thorax

τ Impact duration for $\Delta V = V_0$

The effective mass of the thorax for each cadaver test is given in Table B.1 as well as the ratio of the effective mass to the cadaver's total body mass. The effective mass of the thorax for the standard subject, M_s, subjected to a 4,3 m/s pendulum impact is given in annex C as 20,8 kg. The thoracic mass ratio, R_m, was calculated for each cadaver test and is given in Table B.1. Using the values given in Table B.1, the normalizing factors given in Table B.1 for the impactor acceleration, $(R_a)_p$, thoracic acceleration, $(R_a)_T$, and time, R_t, were calculated from Equations B.1, B.2 and B.3. The curves of Figures B.1 and B.2 were multiplied by the appropriate factors to give the normalized curves of Figures B.3 and B.4, respectively.

The normalized impactor force versus time curve was obtained from the normalized impactor deceleration pulse by multiplying each acceleration value by the impactor mass (23,4 kg) and dividing by the acceleration of gravity, or,

$$F_p = a_p \left(23{,}4\,\text{kg} \Big/ 9{,}8\,\frac{\text{m}}{\text{s}^2} \right) \tag{B.9}$$

where F_p represents the impactor force. The normalized impactor force versus time curves are shown in Figure B.5.

B.3 Response requirements

The average of the normalized cadaver responses is the best estimate of the normalized response of a 50th percentile male. One response requirement for a side impact test device consists of a corridor around the normalized T1 lateral acceleration versus time curves. Figure B.6 shows the lateral T1 acceleration versus time response corridor for the 4,3 m/s lateral impact from a 23,4 kg impactor. The normalized acceleration versus time history of the side impact dummies should lie within the corridor. The response requirement for the impactor force is given in annex C.

Table B.1 — Cadaver Data from the Lateral Thoracic Impact Tests Performed by the HSRI (18); and Effective Mass, Characteristic Ratios, and Normalizing Factors for These Data

Test No.	Cadaver Data		Effective Mass		Characteristic Ratios		Normalizing Factors		
	Body Mass (kg)	Number of Rib Fractures	M_e (kg)	Body mass (%)	Mass R_m	Stiffness R_k	Impactor Accel. $(R_a)_p$	Thorax Accel. $(R_a)_T$	Time R_t
76T062	50.1	7	18.3	36.5	1.14	1.15	1.11	0.98	0.97
77T071	80.7	0	36.0	44.6	0.58	0.98	0.87	1.51	0.89
77T072	54.0	2	25.9	48.0	0.80	1.12	1.00	1.25	0.89

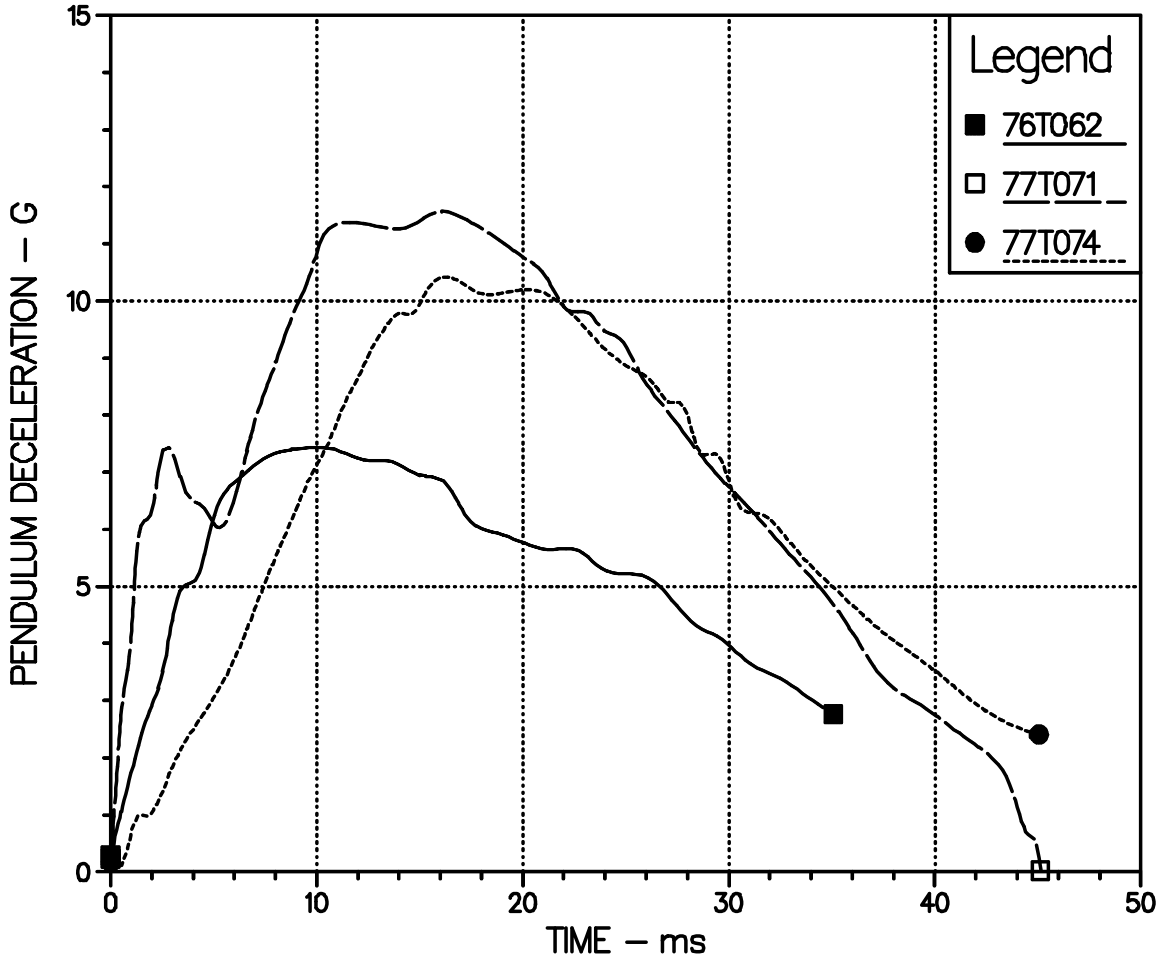


Figure B.1 — Acceleration Versus Time Histories of a 23,4 kg Rigid Pendulum Used to Impact the Lateral Thorax of Cadavers

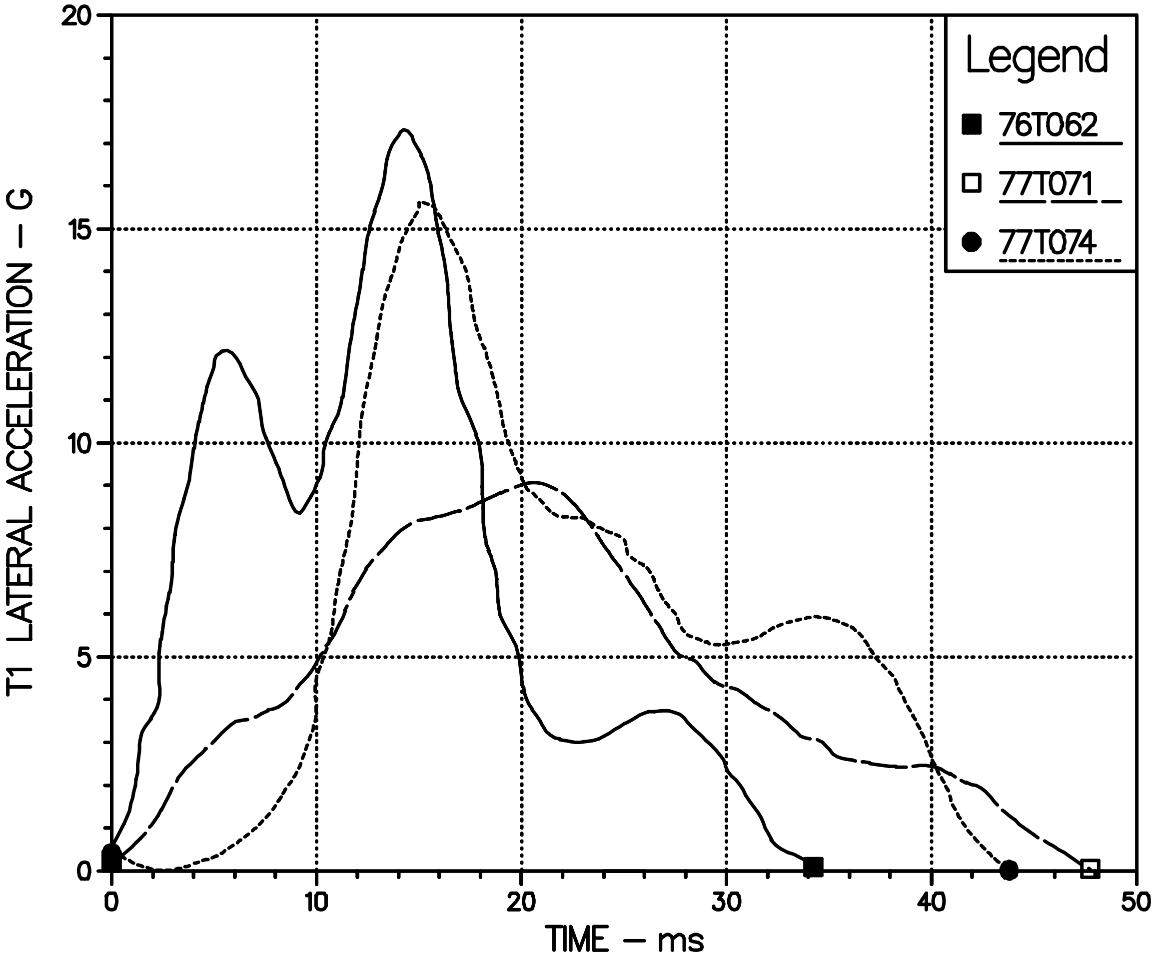


Figure B.2 — Lateral Acceleration Versus Time Histories of T1 for Cadavers Subjected to Thoracic Impacts at 4,3 m/s From a 23 kg Rigid Pendulum

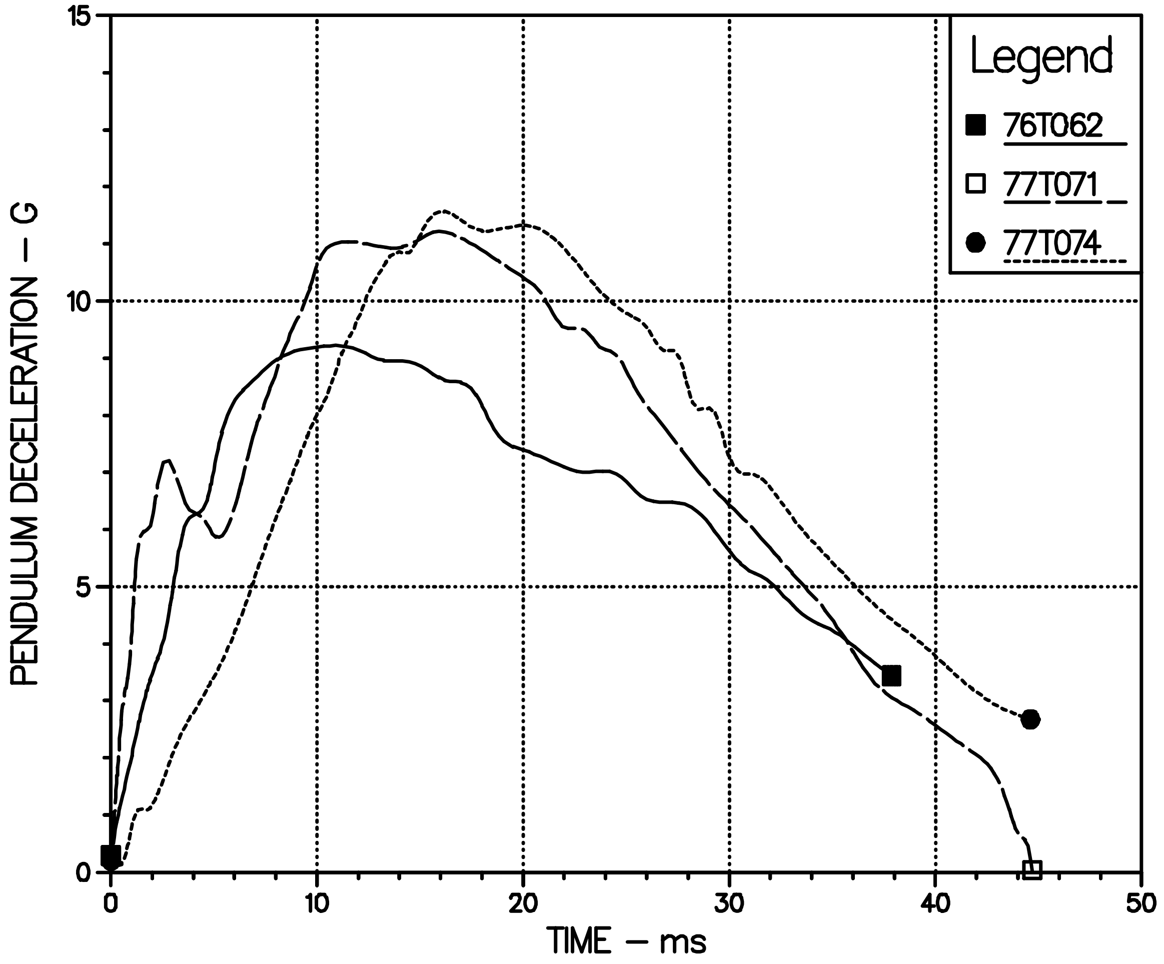


Figure B.3 — Normalized Acceleration Versus Time Histories of a 23,4 kg Rigid Pendulum Used to Impact the Lateral Thorax of Cadavers

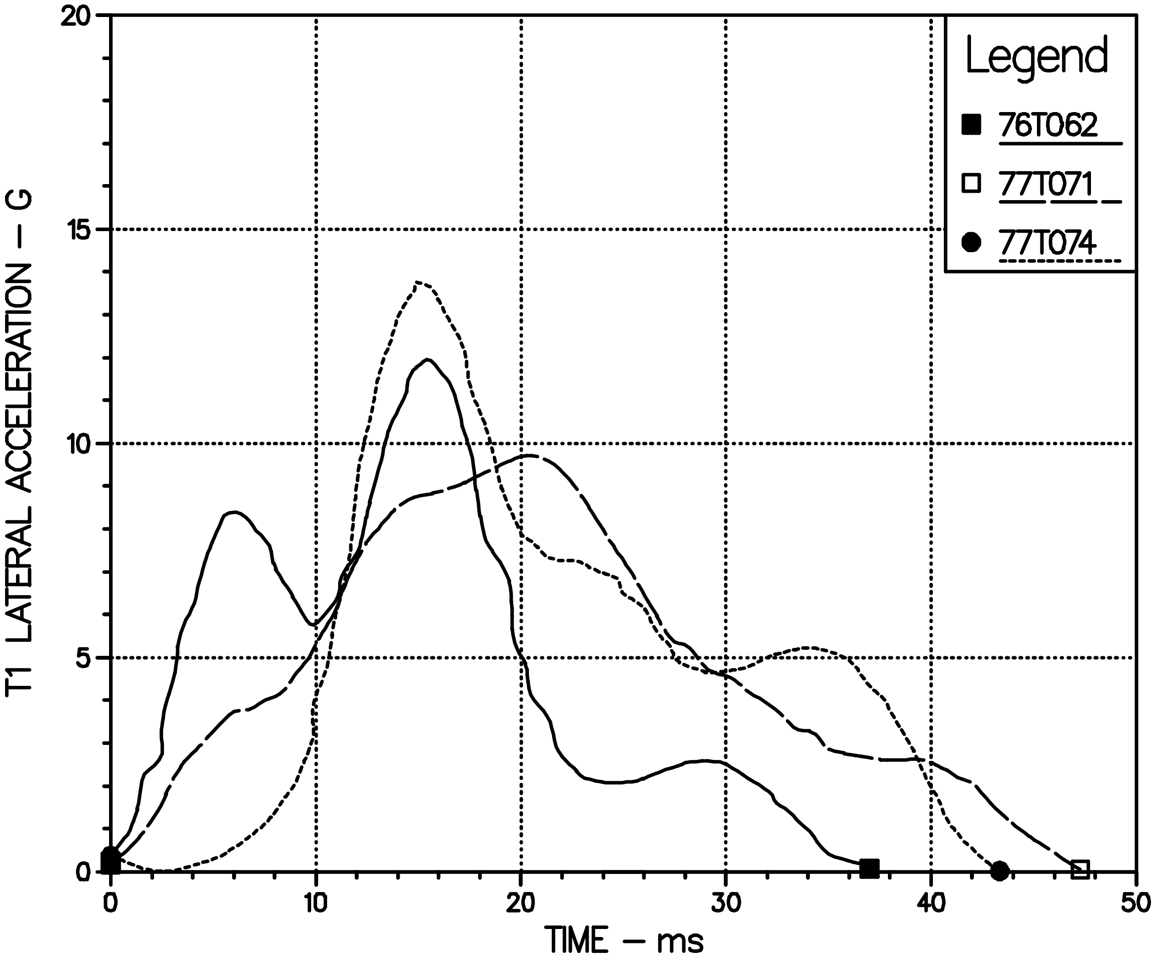


Figure B.4 — Normalized Lateral Acceleration Versus Time Histories of T1 for Cadavers Subjected to Thoracic Impacts at 4,3 m/s From a 23 kg Rigid Pendulum

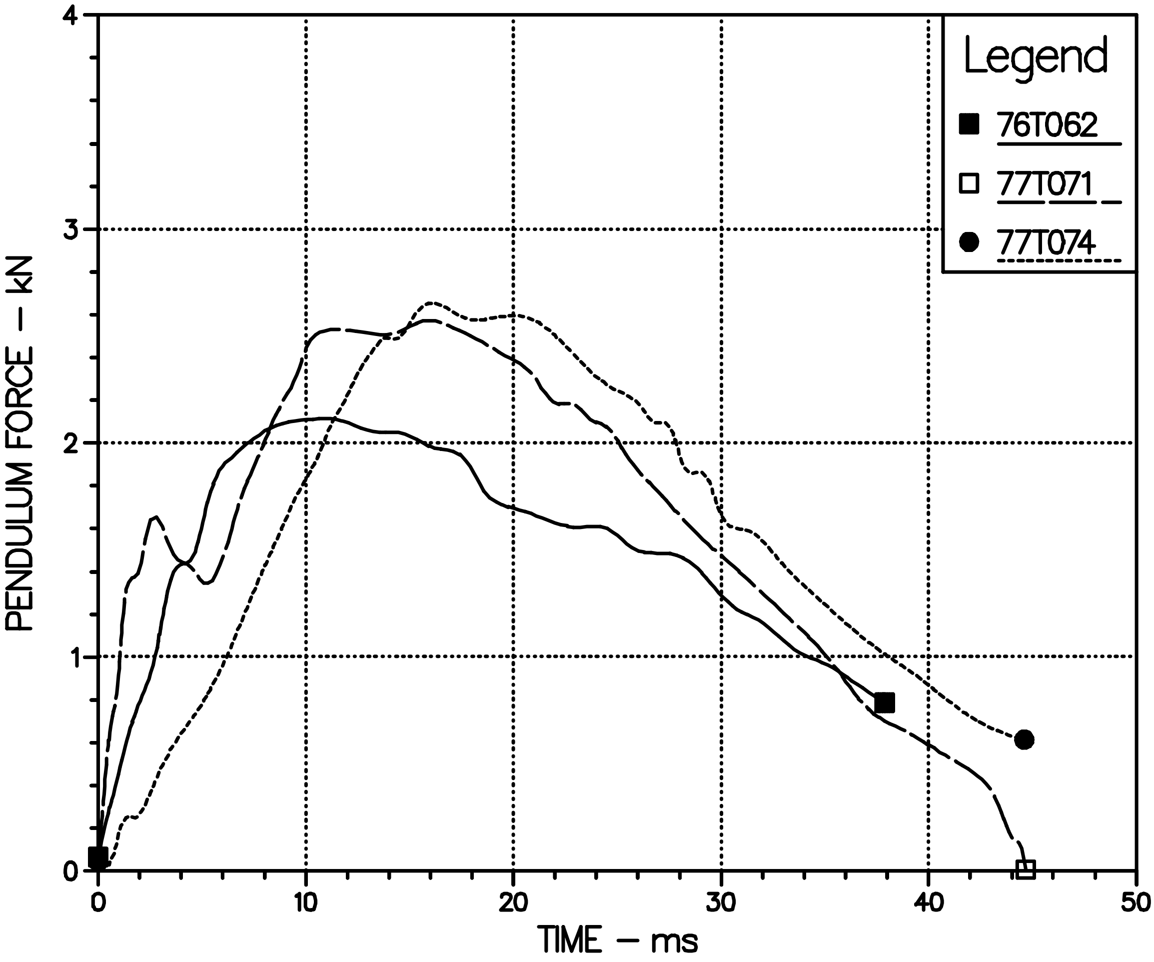


Figure B.5 — Normalized Pendulum Force Versus Time Histories of a 23,4 kg Rigid Pendulum used to Impact the Lateral Thorax of Cadavers

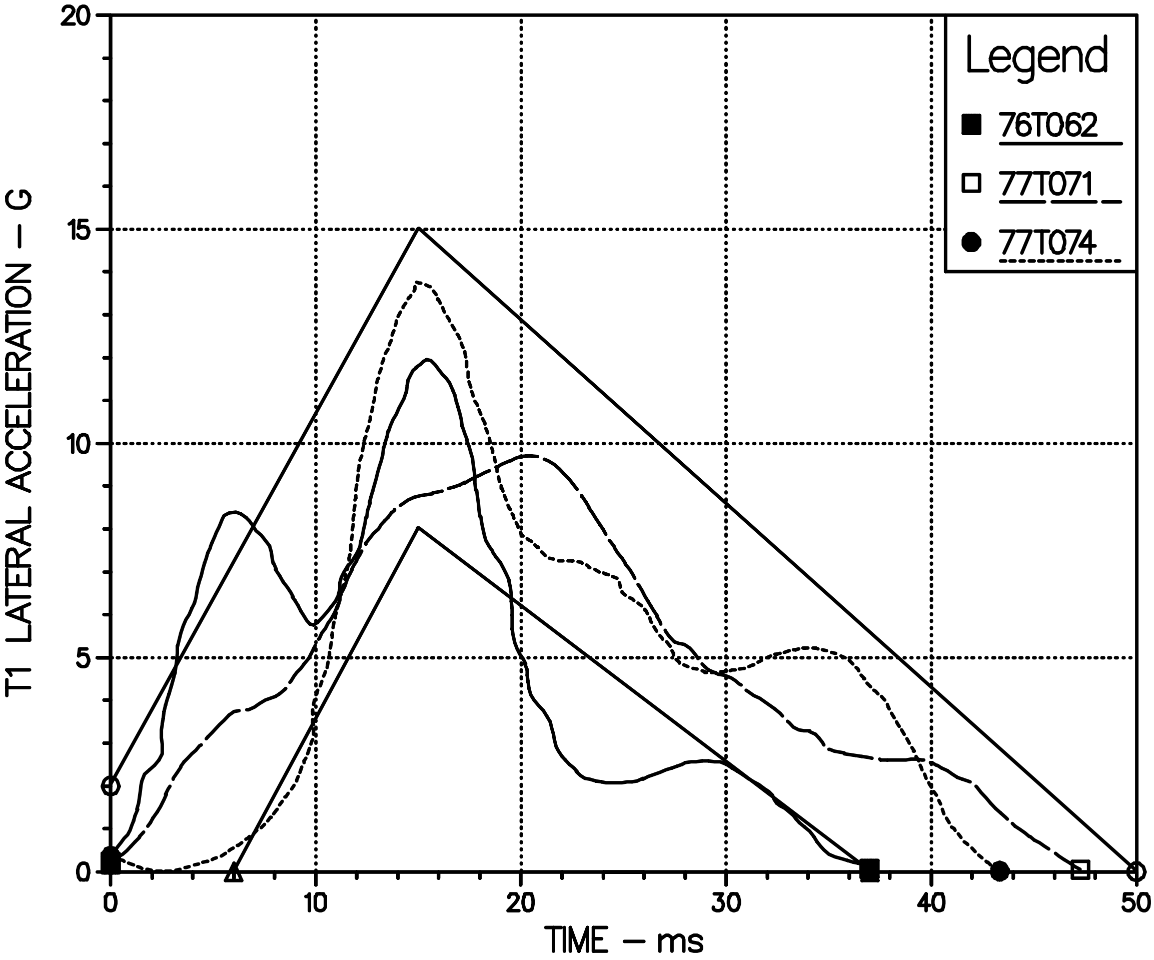


Figure B.6 — Normalized Lateral Acceleration Versus Time Histories of T1 and Proposed Corridor for a 23 kg Rigid Pendulum Impact to the Lateral Thorax

Annex C

Analysis of WSU/GMR oblique lateral thoracic impact data

This annex describes the application of the normalization techniques of Mertz (17) to the oblique lateral thoracic impact data collected by researchers of Wayne State University (19). Data from these tests were provided by the General Motors Research Laboratories who funded the studies and performed the data analysis. This annex also defines the biomechanical impact response requirements based on the normalized WSU/GMR data and the normalized HSRI data (18) presented in annex B.

C.1 Original Data

Unembalmed cadavers were used in a series of impactor tests of the thorax. Each cadaver was instrumented with triaxial accelerometers mounted to the 1st, 8th, and 12th thoracic vertebrae and the 2nd sacral vertebra. The cadavers' lungs and arterial systems were pressurized prior to the tests.

The rigid impact pendulum had a mass of 23,4 kg and a flat circular face of 150 mm diameter. A uniaxial accelerometer was attached to the pendulum. The impact force versus time history was obtained by multiplying the pendulum accelerations by the pendulum mass.

Prior to the impact, the cadavers were suspended upright with their arms overhead. The arms were released at impact. The center of the pendulum impacted a point at the level of the xiphoid process and 60° lateral from the midsagittal plane. Impacts were conducted at velocities ranging from 3,62 to 10,20 m/s. The response data were grouped according to pendulum impact velocity. The cadavers subjected to the highest impact velocities experienced extensive structural damage and were not used to set response requirements.

C.2 Normalized data

The impactor force versus time histories were obtained from the impactor deceleration pulse by multiplying each acceleration value by the impactor mass of 23,4 kg. The force versus time histories shown in Figures C.1 and C.2 were then normalized to represent the characteristic curves for a 50th percentile adult male impacted by a 23,4 kg pendulum at standard velocities of 4,3 and 6,7 m/s (19). The curves were normalized using an extension of Mertz's technique (17) that was developed by Lowne (24) for a two mass system. The normalizing factors for a two mass system can be defined as follows:

— Impactor Force Factor, R_f

$$R_f = (V_s/V_c)(R_k \cdot R_m)^{1/2}(23{,}4\,\mathrm{kg} + M_c)^{1/2}(23{,}4\,\mathrm{kg} + M_s)^{-1/2} \qquad \text{(C.1)}$$

where V_s is the standard impact velocity and V_c is the cadaver impact velocity.

— Time Factor, R_t

$$R_t = (R_m/R_k)^{1/2}(23{,}4\,\mathrm{kg} + M_c)^{1/2}(23{,}4\,\mathrm{kg} + M_s)^{-1/2} \qquad \text{(C.2)}$$

The subscripts used in the previous equations are defined as

f	Force
k	Stiffness
m	Mass
p	Impactor
c	Cadaver
s	Standard Subject
t	Time

The characteristic ratios for mass, R_m, and the thoracic stiffness, R_k, are defined respectively as;

$$R_m = M_s / M_c \tag{C.3}$$

$$R_k = K_s / K_c \tag{C.4}$$

In the equations above, M represents the effective mass of the thorax and K represents the thoracic stiffness. For geometrically similar structures with the same elastic modulus, the stiffness is proportional to the characteristic length (17). The characteristic length chosen was the chest breadth. The chest breadth of the 50th percentile adult male is 349 mm. The thoracic stiffness ratio was calculated using,

$$R_k = 349\,\text{mm}/L \tag{C.5}$$

where L is the chest breadth of the cadaver whose data is being analyzed. The thoracic stiffness ratio for each cadaver is given in Table C.1.

The cadaver's thoracic mass, M_c, can be calculated by dividing the thoracic impulse by its change in velocity, or,

$$M_c = \left[\int_\tau M_p a_p dt\right] \Big/ \left[\int_\tau a_T dt\right] \tag{C.6}$$

where

a_P Acceleration versus time history of the impactor

a_T Resultant of the lateral and longitudinal components of the acceleration versus time history of T8

τ Impact duration for $\Delta V = V_0$

The effective mass of the thorax and the ratio of the effective mass to the cadaver's body mass for each cadaver are given in Table C.1. The averages of the ratios are 0,274 for the 4,3 m/s impacts and 0,200 for the 6,7 m/s impacts. The thoracic mass for the standard subject impacted at 4,3 m/s and 6,7 m/s were obtained by multiplying the body mass of the 50th percentile adult male by the appropriate average ratio, or,

M_S = (0,274) (76 kg) = 20,8 kg for the 4,3 m/s impacts (C.7)

M_S = (0,200) (76 kg) = 15,2 kg for the 6,7 m/s impacts (C.8)

The thoracic mass ratio, R_m, was calculated for each cadaver test and is given in Table C.1. Using the values given in Table C.1, the normalizing factors for impactor force, R_f, and time, R_t, were calculated from equations C.1 and C.2, respectively. The resulting normalizing factors are given in Table C.1.

The force versus time histories were normalized for cadaver size and initial impactor velocity by multiplying each value of force by R_f and each value of time by R_t for that cadaver. Figures C.3 and C.4 show the normalized force versus time curves for the 4,3 and 6,7 m/s oblique lateral impacts, respectively.

C.3 Comparison of lateral and oblique lateral test results

Three lateral impact tests were conducted with initial impactor velocities near 6,7 m/s (34). The cadaver data and test conditions for these tests are given in Table C.2. These tests were normalized as described in clause C.2 Normalized Data, using a standard effective mass of the thorax equal to 15,2 kg. The effective thoracic masses of the cadavers and the resulting normalizing factors are given in Table C.2. Figure C.5 shows the normalized force versus time histories of the lateral and oblique lateral impacts at 6,7 m/s.

The normalized force versus time histories for the lateral and oblique lateral impacts are similar. The peak normalized force values for the lateral impacts lie within the range of normalized peak values for the oblique lateral impacts. The pulse durations of the two test conditions are also similar. Therefore, the normalized force versus time histories for the 4,3 and 6,7 m/s oblique lateral impacts can be used to set impact response requirements for dummies subjected to pure lateral impacts at 4,3 and 6,7 m/s, respectively.

C.4 Comparison of oblique lateral results to HSRI lateral results

Figure C.6 shows the normalized force versus time histories of the HSRI lateral and the WSU/GMR oblique lateral impacts at 4,3 m/s. The peak normalized force values for the HSRI lateral impacts lie within the range of normalized peak values for the WSU/GMR oblique lateral impacts. However, the pulse durations of the HSRI lateral impacts are considerably shorter than the WSU/GMR results.

C.5 Elimination of massively damaged cadavers

Tables B.1, C.1 and C.2 give the number of rib fractures sustained by each cadaver used in the HSRI and WSU/GMR test series. The response requirements were established from cadavers which sustained less than 6 fractures to the ribs. This cutoff level was chosen arbitrarily. If this cutoff level were set lower, too little data remained to define the responses of the thorax.

C.6 Response requirements

The average of the normalized cadaver responses is the best estimate of the normalized response of the 50th percentile male. Response requirements for the side impact test device consist of corridors drawn around the normalized impactor force versus time histories for the 4,3 and 6,7 m/s pendulum impacts.

C.6.1 Normalized Impactor Force Versus Time Corridor for 4,3 m/s Impacts

The force versus time response corridor was constructed around the normalized cadaver curves and then shifted 700 N upward to account for muscle tone. Figure C.7 shows the force versus time response corridor and the normalized HSRI and WSU/GMR cadaver curves for the 4,3 m/s lateral impact from a 23,4 kg impactor. The normalized force versus time curves of the side impact dummies should lie within the corridor.

C.6.2 Normalized Impactor Force Versus Time Corridor for 6,7 m/s Impacts

The force versus time response corridor was constructed around the normalized cadaver curves and then shifted 700 N upward to account for muscle tone. Figure C.8 shows the force versus time response corridor and the normalized lateral and oblique lateral cadaver curves for the 6,7 m/s impact from a 23,4 kg impactor. The normalized force versus time curves of the side impact dummies should lie within the corridor.

Table C.1 — Cadaver Data and Test Conditions from the Oblique Lateral Thoracic Impact Tests Performed by WSU (19); and Effective Mass, Characteristic Ratios, and Normalizing Factors for These Data

Test No.	Cadaver Data				Test Conditions	Effective Mass		Characteristic Ratios			Normalizing Factors	
	Body Mass	Chest Breadth	No. of Rib Fractures		Impactor Velocity	M_e	Body mass	Mass	Stiff.	Impactor Velocity	Force	Time
	(kg)	(mm)	L	R	(m/s)	(kg)	(%)	R_m	R_k	V_s/V_i	R_f	R_t
17	70,3	300	0	0	5,50	16,7	23,8	1,247	1,163	0,782	0,897	0,986
29	53,1	285	0	0	5,20	18,9	35,6	1,103	1,225	0,827	0,940	0,928
36	67,6	305	0	0	4,00	16,4	24,2	1,271	1,144	1,075	1,230	1,000
40	75,8	335	0	2	3,62	19,2	25,4	1,085	1,042	1,188	1,240	1,002
41	75,8	335	0	0	3,80	21,3	28,1	0,979	1,042	1,132	1,150	0,975
4	69,9	280	7	0	5,99	10,1	14,5	1,504	1,246	1,119	1,427	1,023
5	56,3	290	3	0	6,48	9,3	16,6	1,631	1,203	1,034	1,333	1,072
7	56,3	270	5	1	6,73	12,9	23,0	1,175	1,293	0,996	1,191	0,925
9	61,7	280	2	3	6,71	15,6	25,3	0,972	1,246	0,999	1,105	0,888
11	76,2	295	5	0	6,71	15,7	20,6	0,967	1,183	0,999	1,075	0,910

Table C.2 — Cadaver Data and Test Conditions from the Lateral Thoracic Impact Tests Performed by WSU (34); and Effective Mass, Characteristic Ratios, and Normalizing Factors for These Data

Test No.	Cadaver Data				Test Conditions	Effective Mass		Characteristic Ratios			Normalizing Factors	
	Body Mass	Chest Breadth	No. of Rib Fractures		Impactor Velocity	M_e	Body mass	Mass	Stiff.	Impactor Velocity	Force	Time
	(kg)	(mm)	L	R	(m/s)	(kg)	(%)	R_m	R_k	V_s/V_i	R_f	R_t
47[a]	70,3	350	14	2	6,48	14,9	21,1	1,020	0,997	1,034	1,039	1,007
52[a]	92,1	320	7	5	6,44	19,8	21,5	0,768	1,091	1,040	1,007	0,888
58	66,7	270	8	5	6,50	13,2	19,7	1,152	1,293	1,031	1,225	0,919

[a] These cadavers were subjected to an impact at 4,3 m/s on the right side of the thorax, followed by an impact at 6,7 m/s on the left side of the thorax. The number of rib fractures given here represents the total after both impacts.

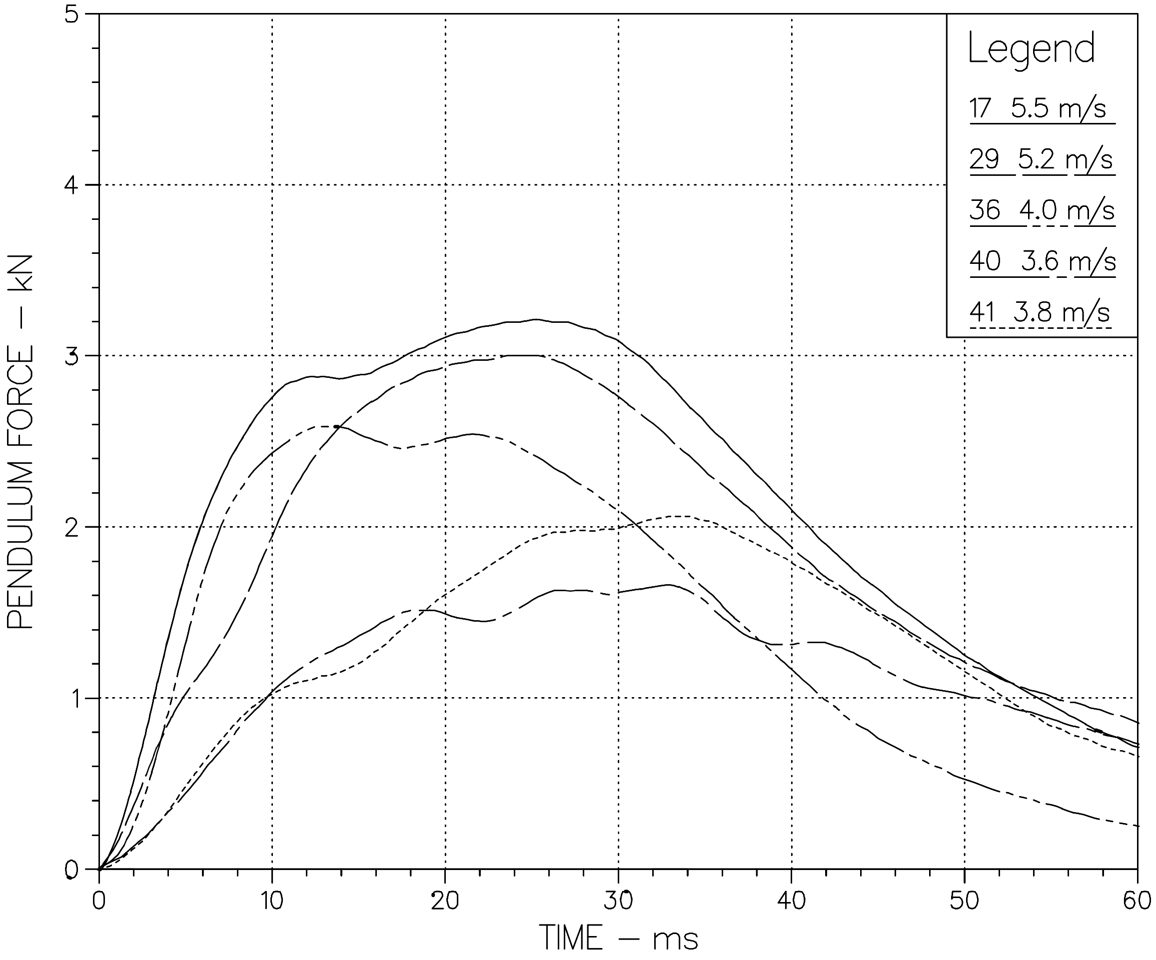


Figure C.1 — Force versus time histories of a 23,4 rigid pendulum used to impact the oblique lateral thorax of cadavers at 4,3 m/s

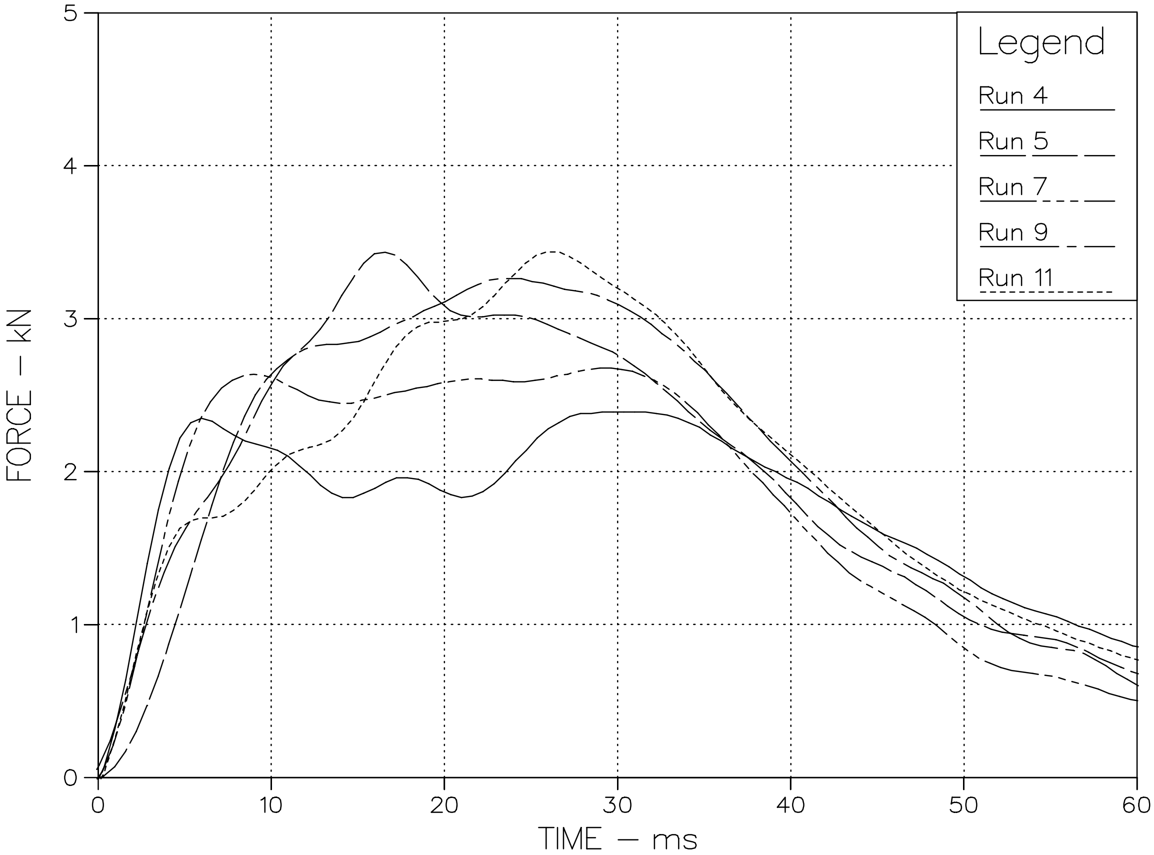


Figure C.2 — Force versus time histories of a 23,4 rigid pendulum used to impact the oblique lateral thorax of cadavers at 6,7 m/s

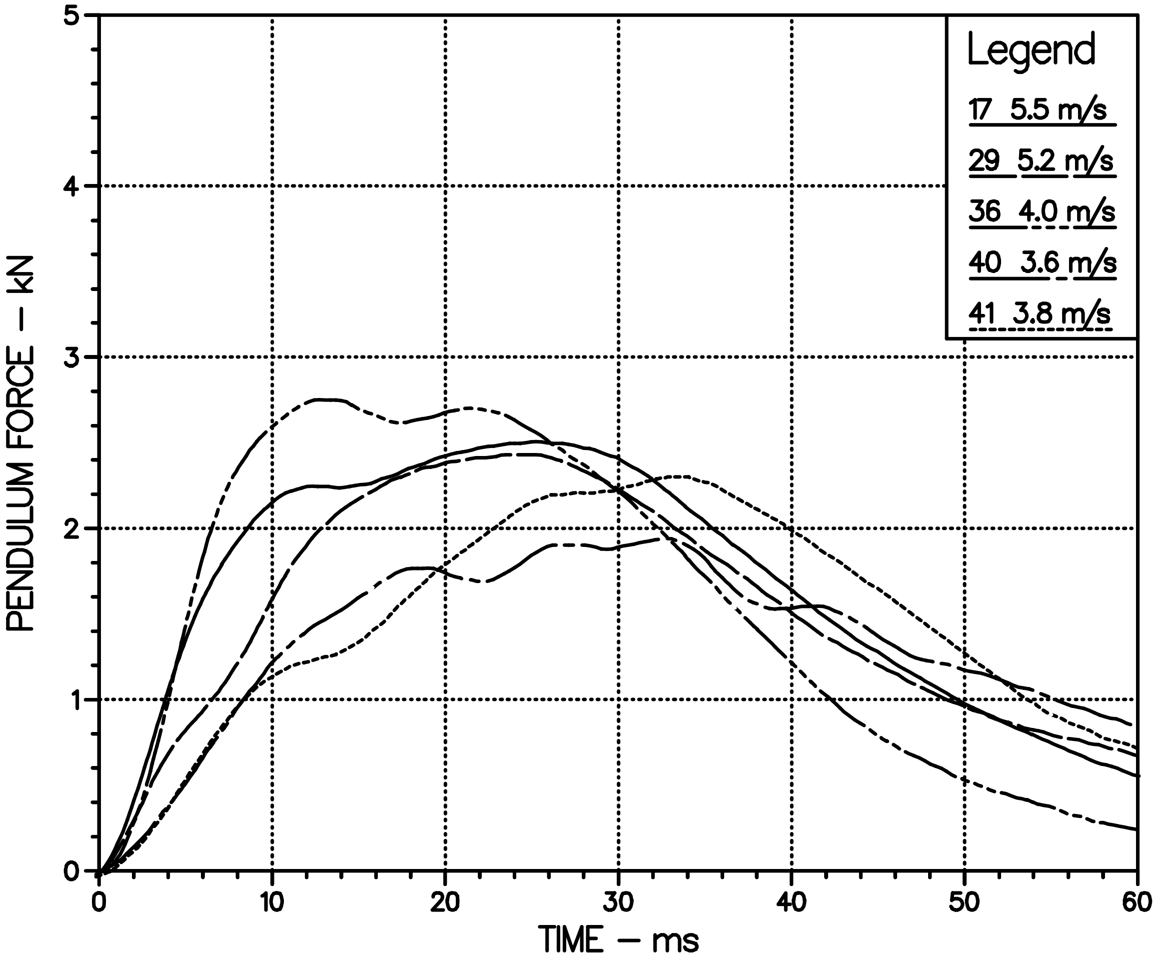


Figure C.3 – Normalized force versus time histories of a 23,4 rigid pendulum used to impact the oblique lateral thorax of cadavers at 4,3 m/s

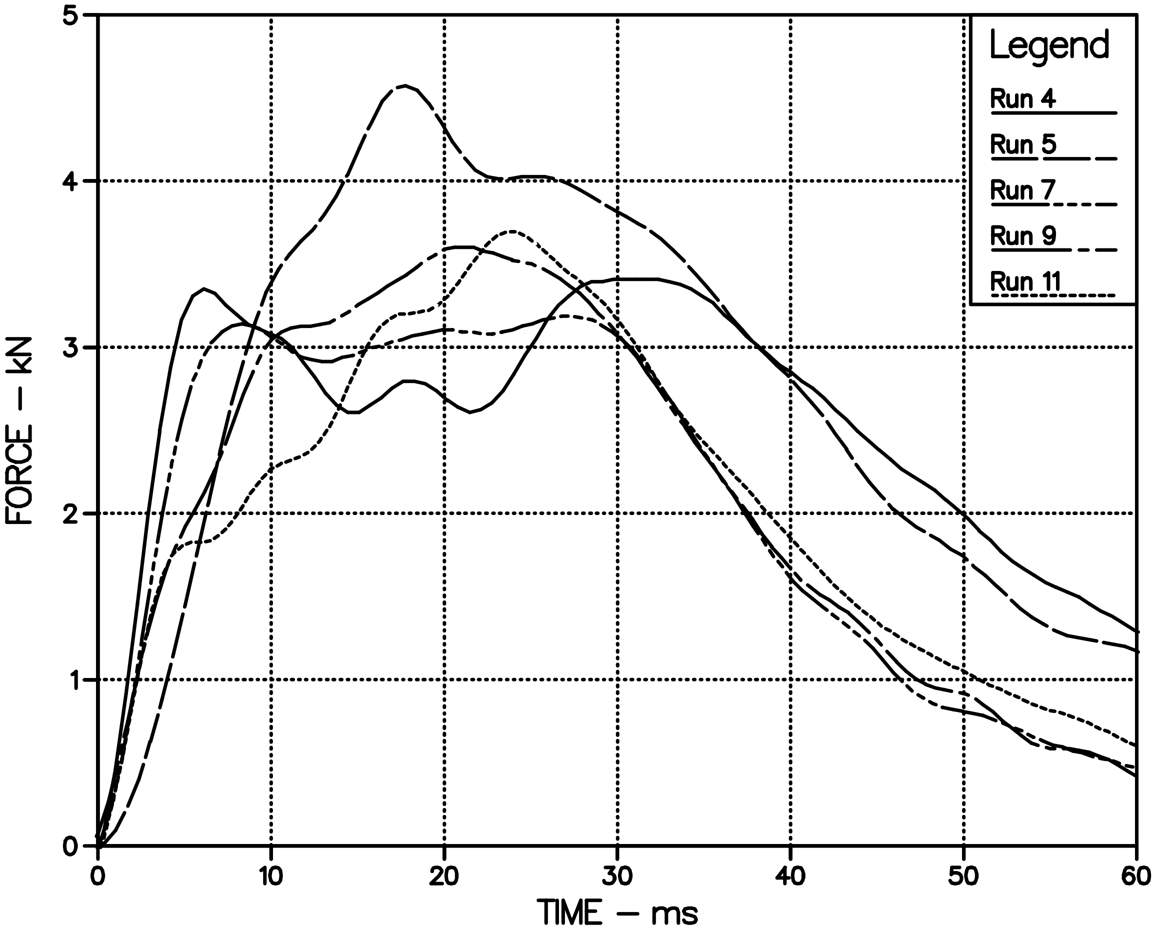


Figure C.4 – Normalized force versus time histories of a 23,4 rigid pendulum used to impact the oblique lateral thorax of cadavers at 6,7 m/s

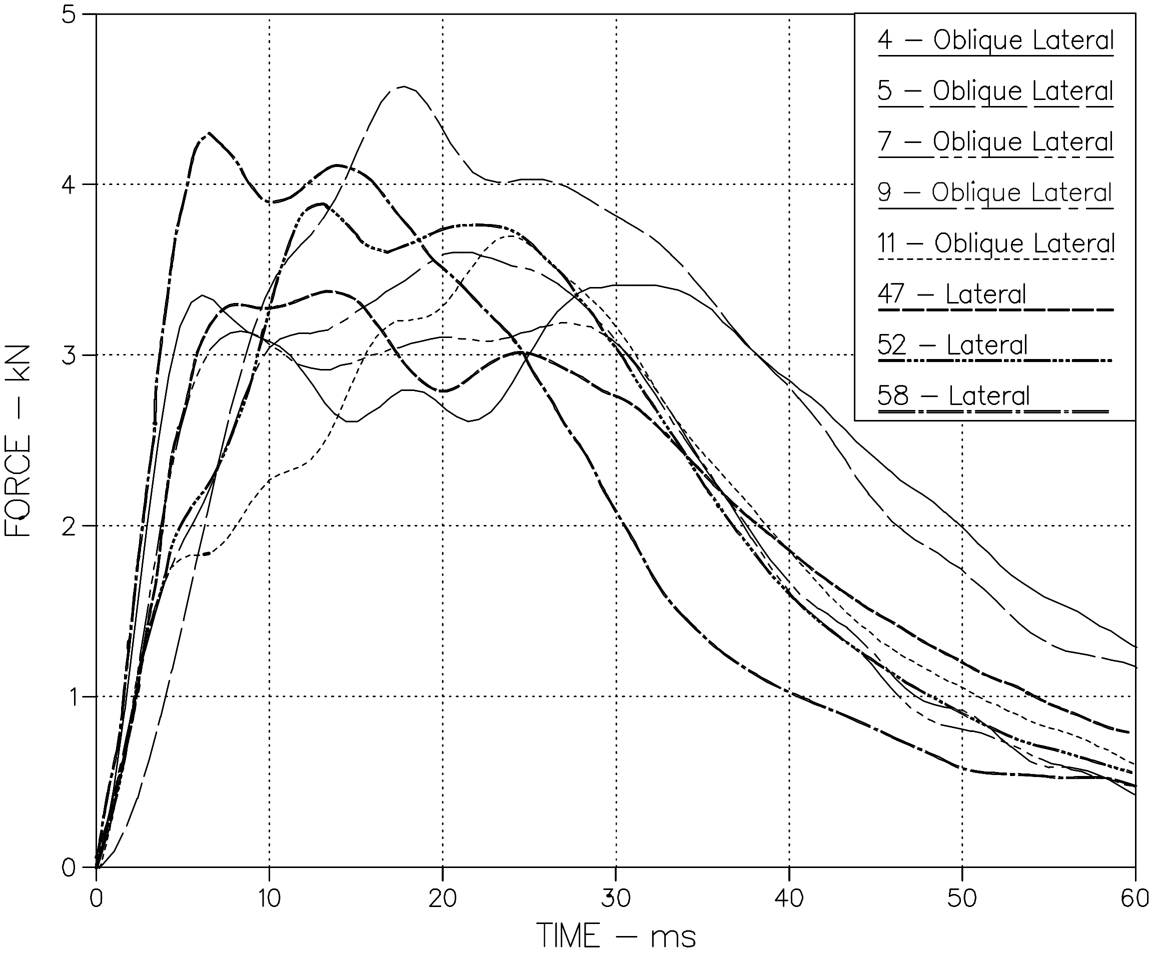


Figure C.5 — Normalized Force Versus Time Histories of a 23,4 kg Rigid Pendulum Used to Impact the Lateral or Oblique Lateral Thorax of Cadavers at 6,7 m/s

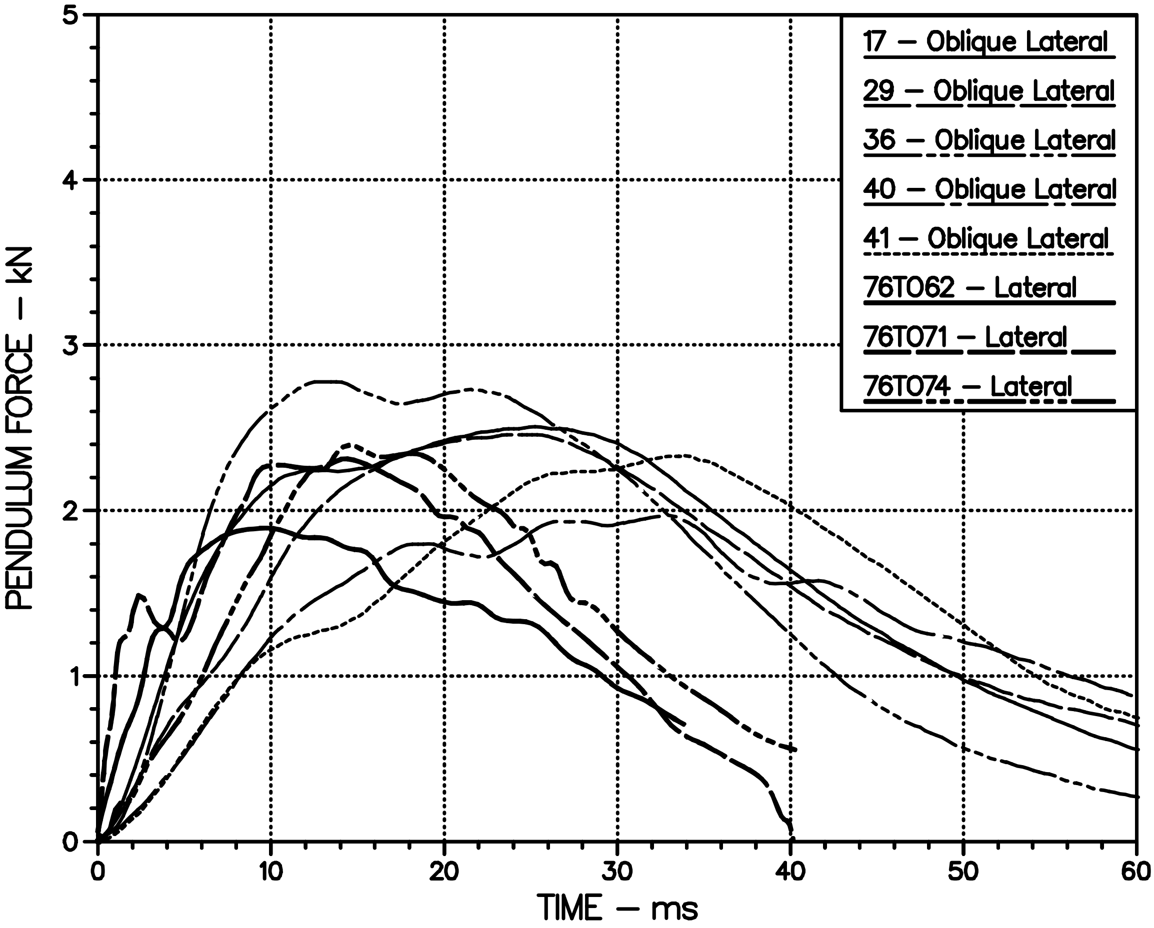


Figure C.6 — Normalized Force Versus Time Histories of a 23,4 kg Rigid Pendulum Used to Impact the Lateral or Oblique Lateral Thorax of Cadavers at 4,3 m/s

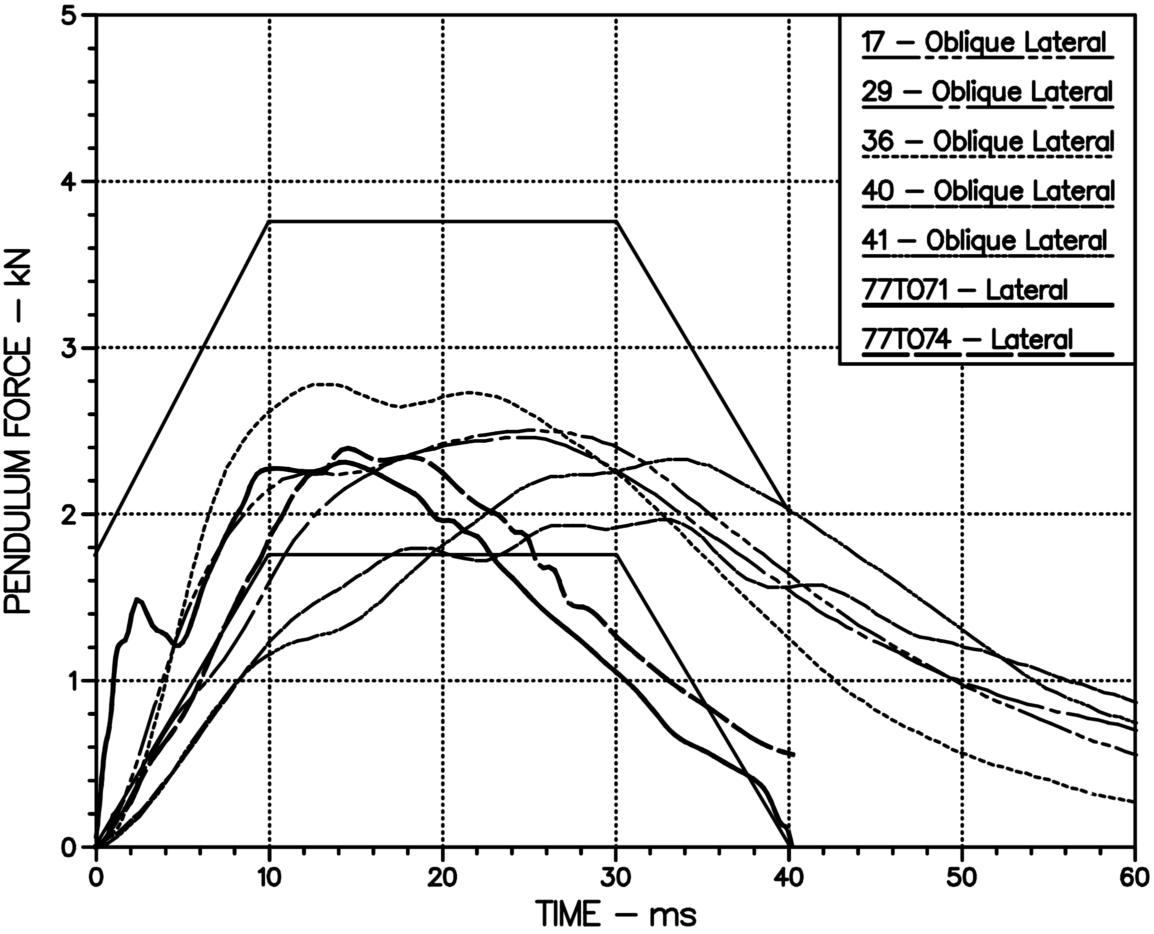


Figure C.7 — Normalized Force Versus Time Histories and Proposed Corridor for a 23,4 kg Rigid Pendulum Impact to the Lateral Thorax at 4,3 m/s

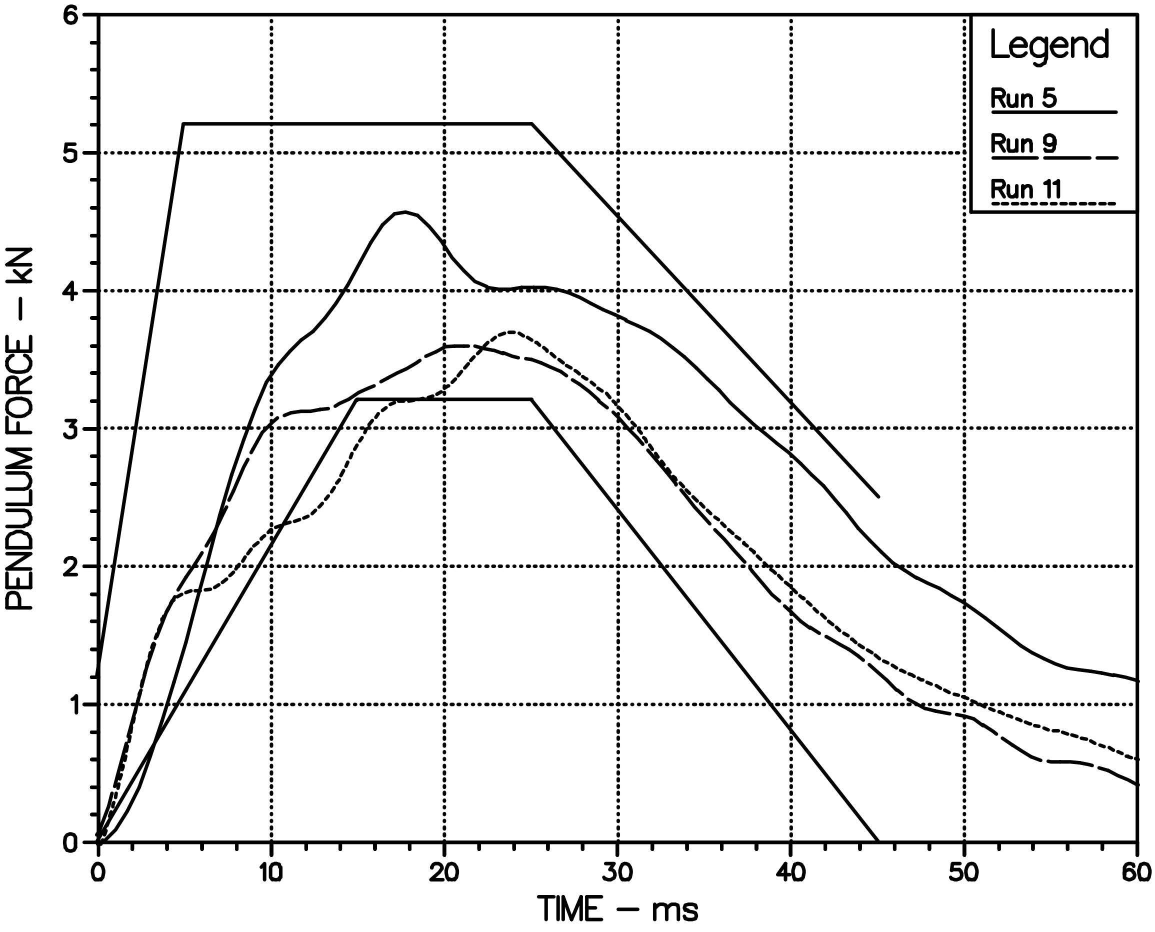


Figure C.8 — Normalized Force Versus Time Histories and Proposed Corridor for a 23,4 kg Rigid Pendulum Impact to the Lateral Thorax at 6,7 m/s

Annex D

Analysis of onser lateral pelvic impact data

This annex describes the application of the normalization techniques of Mertz (17) to the lateral pelvic impact data provided by ONSER (26, 27 and 28).

D.1 Original Data

Researchers of ONSER studied the responses of 22 unembalmed cadavers to lateral impacts delivered to the greater trochanter. Pelvic strains were measured by 3 strain gages on the internal face of the ileal wing and 1 strain gage on the ileo-pubic ramus (28). Pelvic acceleration was measured by an accelerometer attached to the posterior of the sacrum. The cadavers were seated without lateral support, as shown in Figure D.1. Lateral impacts were delivered at known speeds by a 17,3 kg rigid or padded impactor. The impact surface of the rigid impactor was a segment of a sphere (R=175 mm, r=60 mm). The padded surface was a polyurethane block. Forces and accelerations of the impactor were measured. Each cadaver was impacted at increasing speeds until pelvic fracture was diagnosed by X-ray or external examination (27).

The mass and height of cadavers struck by the rigid impactor are summarized in Table D.1. The impact velocity, peck force, and impulse of the first impact to each cadaver are also given. Only results where data for the first impact were given and the cadavers had acceptable bone condition were analyzed.

D.2 Normalized data

For the case where the impulse direction is horizontal, Mertz (17) defines the effective mass of the pelvis as,

$$M_e = \left[\int_0^T F dt\right] \Big/ (\Delta V) \qquad (D.1)$$

where $\int_0^T F dt$ is the impulse and ΔV is the change in velocity. The impact velocity was used as an estimate of the change in velocity since data were not available to calculate it. The effective mass of the pelvis and the ratio of the effective mass to the total body mass for the first impact of each cadaver are given in Table D.1. The average percent of body mass is 19,1%.

The effective mass of a 50th percentile adult male was obtained by multiplying its body mass of 76 kg by 19,1%, giving an effective mass of 14,5 kg for the pelvis.

The mass ratio, R_m, as defined by Mertz (17) is,

$$R_m = M_s / M_i \qquad (D.2)$$

where M_S is the effective mass of the standard subject and M_i is the effective mass of the i-th subject. For the data discussed here, Equation D.2 becomes,

$$R_m = 14.5\,\mathrm{kg} / M_i \qquad (D.3)$$

The mass ratios for the cadavers are given in Table D.1.

The stiffness ratio, R_k, is defined as,

$$R_k = K_s / K_i \qquad (D.4)$$

where K_S is the stiffness of the standard subject and K_i is the stiffness of the i-th subject. Mertz (17) has shown that for geometrically similar structures with the same elastic modulus, the stiffness is proportional to the characteristic length. For such structures the stiffness ratio can be expressed as,

$$R_k = L_s / L_i \qquad (D.5)$$

where L_S and L_i are characteristic lengths of the standard and i-th subjects, respectively.

A characteristic length of the pelvis was not available. The standing height was used as the characteristic length. The standing height of each cadaver is given in Table D.1. This measurement is 1,74 m for the 50th percentile adult male. Using this value, Equation D.5 can be written as,

$$R_k = 174\,m/L_i \tag{D.6}$$

The stiffness ratios for the cadavers are given in Table D.1.

The normalizing factor for force as defined by Mertz (17) is,

$$R_f = \left(R_m R_k\right)^{1/2} \tag{D.7}$$

The force normalizing factors for the cadaver impacts are given in Table D.1. The normalized peak forces were obtained by multiplying the measured peak forces by their force normalizing factors. The resulting normalized peak forces are given in Table D.1. A plot of normalized peak force versus impact velocity is shown in Figure D.2.

D.3 Peak impactor force response requirements

The force normalizing factors map the peak impact forces of the cadaver subjects onto the peak forces of a 50th percentile adult male. The normalizing factors do not correct for the variability of the impact surface material. Test number I.1 appears to be an outlier and was not used in the selection of a response corridor.

Linear regression analysis was performed to determine the relationship between impact velocity and normalized peak force for the rigid impactor data given in Table D.1. The computed relationship, with a sample correlation of 0,71, is given by,

$$F = 0,71 + 0,83V \tag{D.8}$$

where F is the normalized peak force and V is the impact velocity. A response corridor was drawn to allow reasonable deviation from the impact velocity and peak force relationship. Figure D.3 shows the scatter plot of impact velocity versus the normalized peak force, the relationship given by Equation D.8, and the response corridor for impacts delivered by a 17,3 kg rigid impactor. For dummy impacts between 6 m/s and 10 m/s, the normalized peak impactor force should lie within the corridor shown in Figure D.3.

Response requirements are not proposed for tests with a padded impactor because the results of the first impact were available for only one cadaver subject.

Table D.1 — Cadaver Data, Test Conditions and Test Results of the ONSER Lateral Pelvic Impact Tests (26, 27, 28); and Characteristic Ratios, Normalizing Factors, and Normalized Test Results for These Data

	Cadaver Data		Test Conditions		Test Results		Effective Mass		Characteristic Ratios		Normalizing Factors	Norm. Results
Test No.	**Body Mass** (kg)	**Height** (m)	**Impact Velocity** (m/s)	**Impact Surface**	**Peak Force** (kN)	**Impulse** (Ns)	M_e (kg)	**Body Mass** (%)	**Mass** R_m	**Stiff-ness** R_k	**Force** R_f	**Peak Force** (kN)
A1	58	1,67	5,83	Rigid	4,17	63	10,8	18,6	1,34	1,04	1,18	4,92
B1	70	154	5,83	Rigid	5,10	71	12,2	17,4	1,19	1,13	1,16	5,92
C1	78	1,73	7,11	Rigid	5,62	113	15,9	20,4	0,91	1,01	0,96	5,40
D1	52	1,60	6,94	Rigid	4,41	88	11,3	24,2	1,28	1,09	1,18	5,20
E1	60	1,56	7,00	Rigid	5,52	88	12,6	21,0	1,15	1,12	1,13	6,24
F1	55	1,52	7,86	Rigid	5,61	89	11,3	20,5	1,28	1,14	1,21	6,79
H1	86	1,75	7,08	Rigid	6,62	82	11,6	13,5	1,25	0,99	1,11	7,35
I1	63	1,81	7,08	Rigid	10,21	77	10,9	17,3	1,33	0,96	1,13	11,54
J1	63	1,77	7,08	Rigid	7,73	79	11,2	17,8	1,29	0,98	1,12	8,66
K1	55	1,71	6,94	Rigid	5,52	73	10,5	19,1	1,38	1,02	1,19	6,57
L1	85	1,75	8,25	Rigid	8,33	118	14,3	16,8	1,01	0,99	1,00	8,33
R1	82	1,80	10,14	Rigid	9,44	163	16,1	19,6	0,9	0,97	0,93	8,78
Z1	58	1,67	12,64	Padded	7,36	158	12,5	21,6	1,16	1,04	1,10	8,10

Dimensions in millimetres

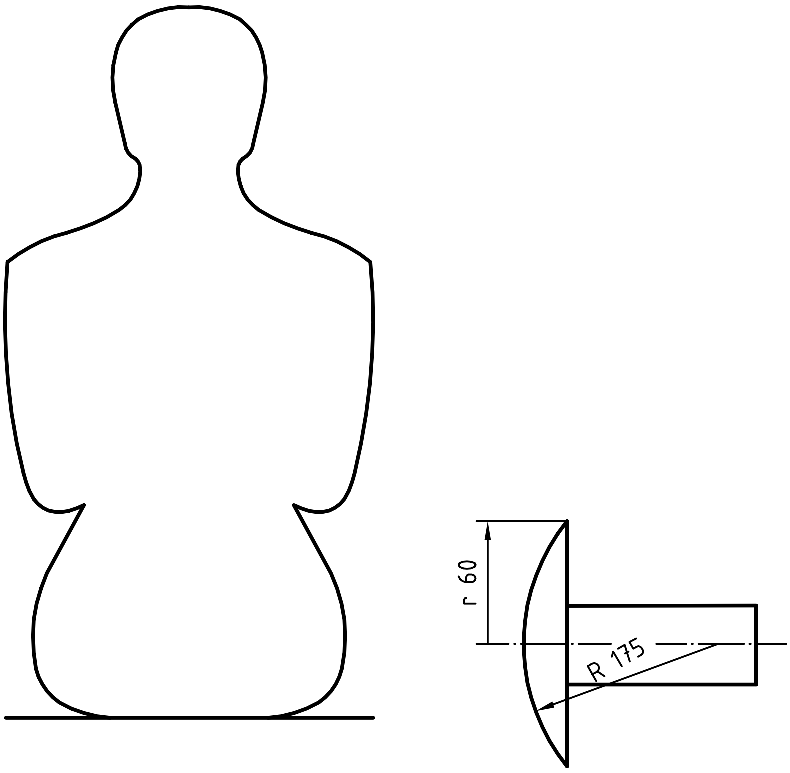


Figure D.1 — Test Configuration for the Pelvic Impact Test

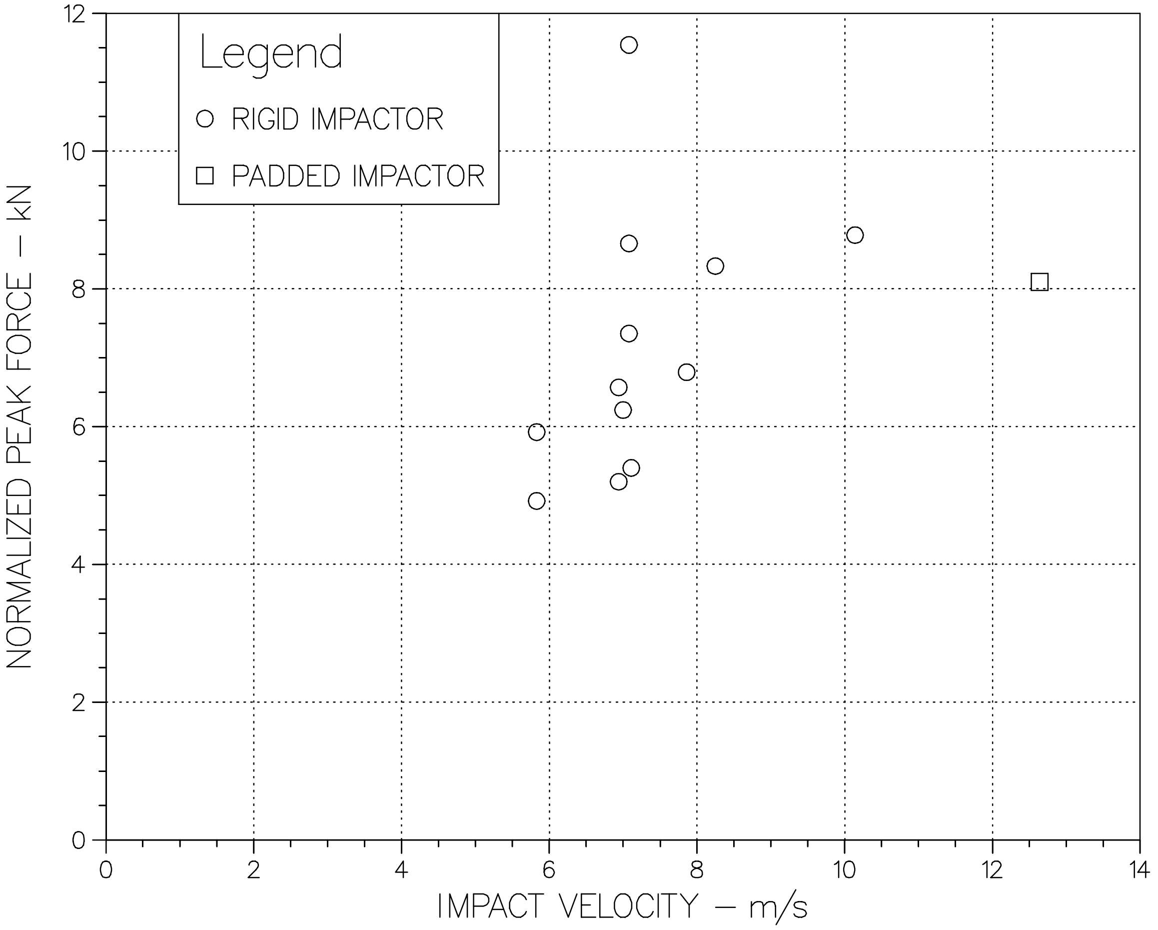


Figure D.2 — Peak Normalized Force Versus Impact Velocity from the Lateral Pelvic Impacts with a 17,3 kg Pendulum

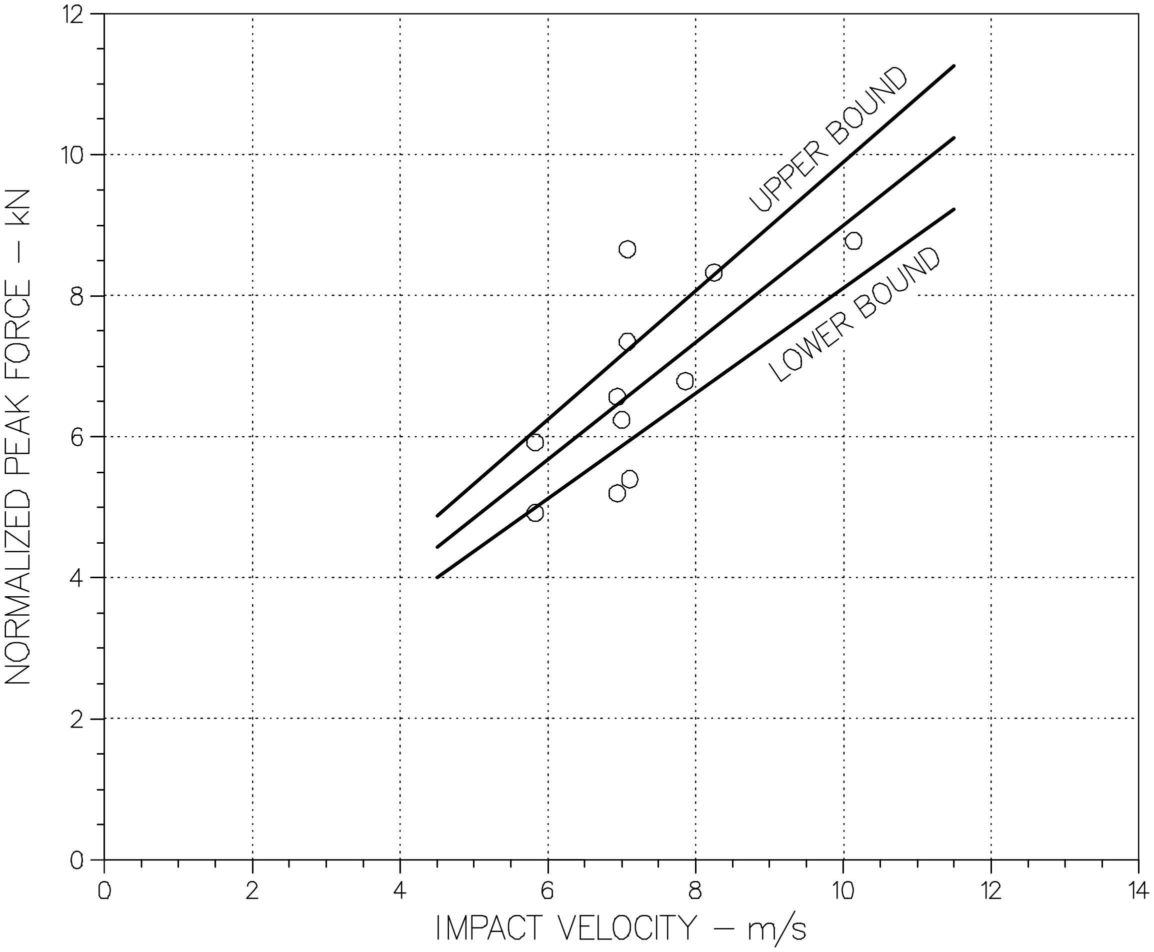


Figure D.3 — Response Corridor for the Peak Force Versus Impact Velocity for Lateral Pelvic Impacts with a 17,3 kg Pendulum

Annex E

Analysis of HODGSON and THOMAS lateral head impact data

This annex describes the lateral head impact data of Hodgson and Thomas (1) and the biomechanical impact response requirements based on the data.

E.1 Original data

Hodgson and Thomas (1) conducted a series of non-fracture, cadaver head impact tests. In these tests, the cadavers were strapped on their sides to a pallet that was free to pivot about one end. The cadaver's head and neck were allowed to extend over the free end of the pallet. The pallet was rotated upwards to achieve a prescribed distance between the head and the impact surface. Then the pallet was released producing the desired head impact. Rigid surface impact data for seven embalmed cadavers are summarized in Table E.1. Listed in Table E.1 are the cadaver identifications, the head impact velocities, the equivalent free-fall drop heights and the peak resultant accelerations measured on the side of the head opposite the impact site.

E.2 Response requirement

Figure E.1 is a plot of the Hodgson and Thomas (1) data in terms of the peak resultant head acceleration versus head impact velocity. For a linear spring-mass system dropped onto a rigid surface, the peak acceleration of the mass is directly proportional to the impact velocity. Assuming the head responds in a similar fashion, a corridor was drawn as indicated by the lines shown in Figure E.1. Note that all the data points lie within the boundaries. Based on these data, a reasonable response requirement is that the peak resultant head acceleration of a point on the non-impacted side of the head should be between 100 and 150 G for a 200 mm free fall drop onto a flat, rigid surface. This drop height will produce an impact velocity of 2 m/s.

Table E.1 — Summary of the Rigid Surface Lateral Head Impact Data of Hodgson and Thomas (1)

Cadaver ID	Impact Velocity (m/s)	Equivalent Free Fall Drop Height (mm)	Peak Resultant Acceleration at a point on the Non-impacted Side of the Head (G)
2864	1,92	188	107
2953	1,74	154	108
3030	1,92	188	135
3042	1,92	188	118
3083	1,92	188	96
3116	1,65	139	121
3184	1,74	154	101

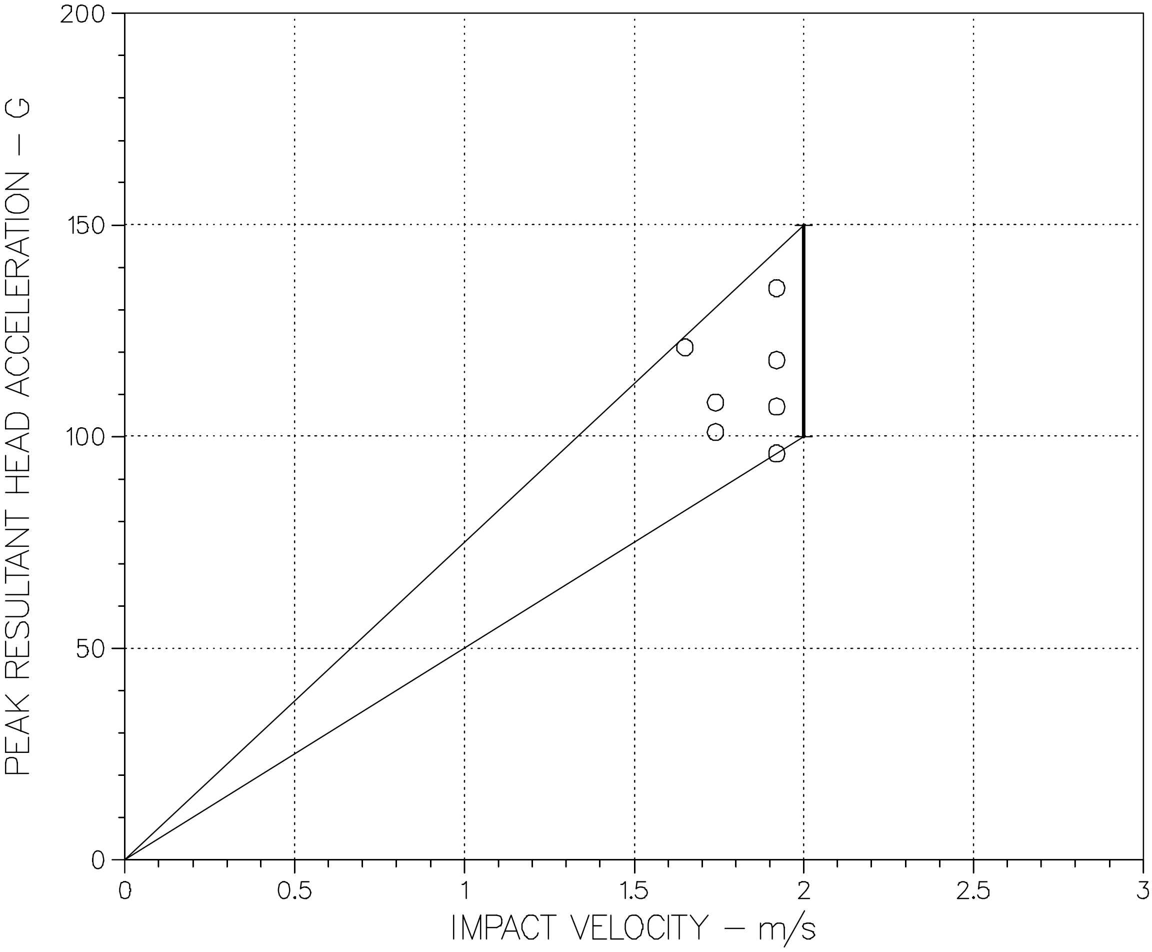


Figure E.1 — Peak resultant head acceleration responses for rigid surface lateral impacts compared to the corridor

Annex F

Analysis of Association PEUGEOT-RENAULT lateral head impact data

This annex describes the lateral head impact data of the APR (2) and the biomechanical impact response requirements based on the data.

F.1 Original data

The APR (2) conducted a series of lateral head impact tests involving five cadavers. The first test involved dropping a cadaver 300 mm onto a rigid impact surface. No data were given for this test. The remaining four cadavers were dropped from a height of 1200 mm onto a rigid surface covered by a 5 mm thick rubber pad with the following characteristics:

- Shore A Hardness = 50
- Rupture Strength = 14 Mpa
- Tear Strength = 15 kN/m

Two of the cadavers received skull fractures. Table F.1 gives the peak resultant head accelerations for the two cadavers without skull fractures. Sufficient accelerometers (3-3-3 combination) were used to calculate the acceleration of the center of gravity of the head which are given in Table F.1. All acceleration data were filtered at channel frequency class 1000 Hz, according to the requirements of SAE Recommended Practice J211. The padded surface data are compared to the rigid surface data of annex E in Figure F.1. The padding that was used produced about a 20% reduction in peak head acceleration.

F.2 Response requirement

The average of the peak resultant head accelerations given in Table F.1 is 241 G.Allowing a ± 15 % deviation from the average gives a range of 205 G to 277 G for a 1200 mm drop onto the padded surface.

Table F.1 — Summary of the padded surface lateral head impact data of the APR (2)

Cadaver ID	Impact velocity (m/s)	Drop Height (mm)	Peak Resultant Acceleration at the Center of Gravity of the Head (G)
3	4,85	1200	230
4	4,85	1200	253

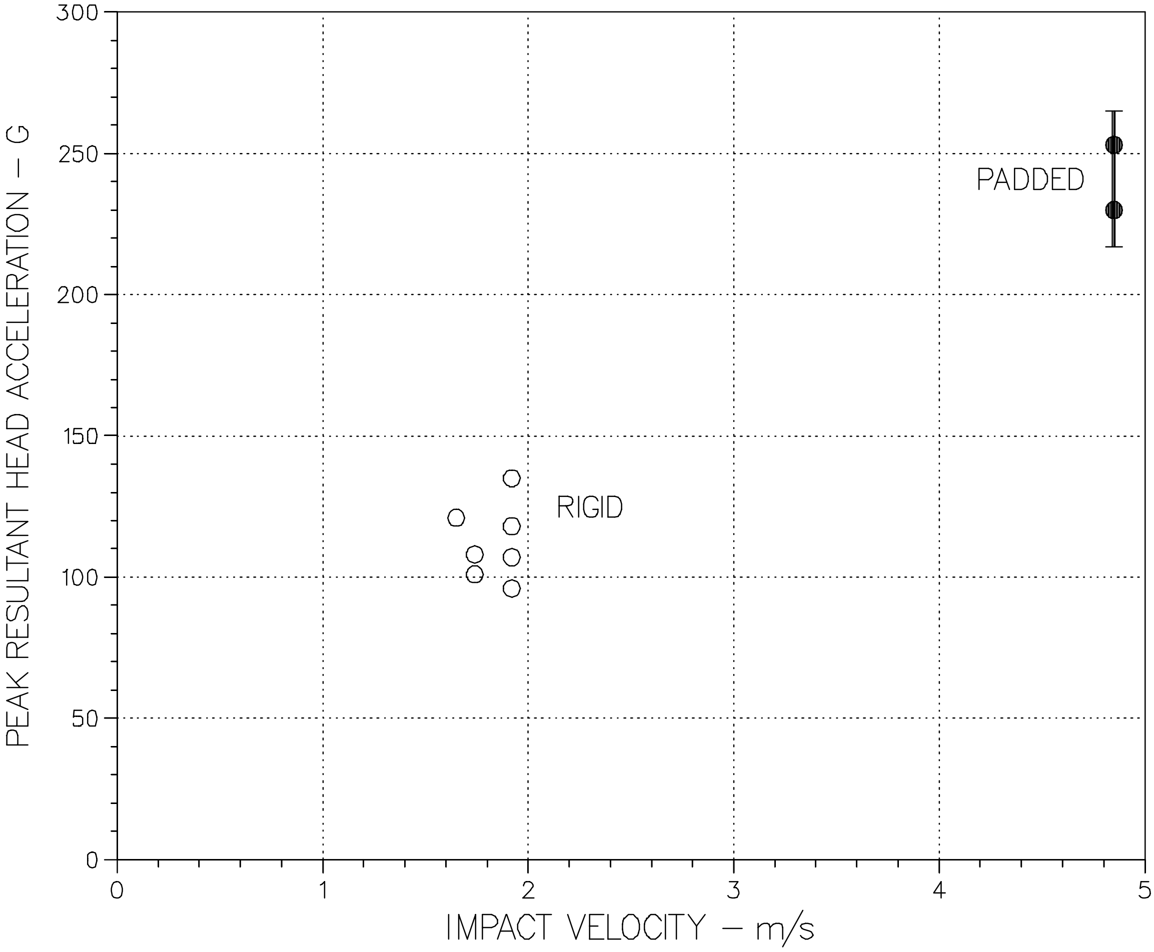


Figure F.1 — Peak resultant head acceleration responses for rigid and padded surface lateral impacts compared to the corridor for the padded impact

Annex G

Analysis of Association PEUGEOT-RENAULT lateral thoracic impact data

This annex describes the application of the normalization techniques of Mertz (17) to the lateral thoracic impact data collected by researchers of the Association Peugeot-Renault (20, 21, 22). Biomechanical impact response requirements are defined, based on the normalized data.

G.1 Original Data

Researchers of the Association Peugeot-Renault subjected unembalmed cadavers to lateral free falls from heights of either 1 or 2 m. The thoracic and pelvic impact surfaces were rigid for the 1 m drops and padded for the 2 m drops. The padding used for the thoracic impact surface was either a block of polyurethane (referred to as APR pad), or a block of phenespan embedded in polyurethane. Characteristics of the phenespan/polyurethane padding are not available. These data were not included in the analysis. Figures G.1, G.2 and G.3 show the thoracic and pelvic impact surfaces for two rigid impact configurations and the APR padded tests, respectively. The thoracic impact surfaces were instrumented with load cells to measure the impact force.

Some of the 1 m drops were conducted with the cadavers' arms rotated forward and upward. This configuration is shown in Figure G.1. The remaining 1 m drops and all of the 2 m drops were conducted with the arms rotated forward such that an angle of 20° was formed between the upper arm and the thoracic spine. This arm position is shown in Figures G.2 and G.3. A triaxial accelerometer was screwed to T4 to measure thoracic acceleration. Rib cage compression was measured from high speed movies of the impact.

Table G.1 summarizes the drop height, impact surface, arm position and cadaver data for the rigid and padded impacts. The lateral thoracic force versus time histories for the 1 m rigid impacts without arm involvement and with arm involvement are shown, respectively, in Figures G.4 and G.5. Figure G.6 gives the lateral thoracic force versus time histories for the 2 m drops onto the APR padded surfaces.

G.2 Normalized data

The technique described by Mertz (17) was used to normalize the force versus time histories to represent the response characteristics of a 50th percentile adult male. If the normalization procedure was exact, then for each impact configuration, every normalized cadaver curve would map onto a single curve. This curve would be the force versus time history of the standard size subject.

The effective thoracic mass was calculated from the lateral thoracic acceleration versus time histories and the force versus time histories of the thoracic impact surface. The duration of the impact, τ, was chosen as the period of time from initial contact until the change in velocity equaled the initial velocity, or the τ for which,

$$\int_{\tau} \mathrm{adt} = \mathrm{V}_0 \tag{G.1}$$

where a is the lateral acceleration of the thorax and V_0 is the initial impact velocity.

The effective mass of the thorax, M_e, was calculated from the following equation,

$$\mathrm{M_e} = \left[\int_{\tau} \mathrm{Fdt} \right] \Big/ \left(\tau \mathrm{g} + \mathrm{V}_0 \right) \tag{G.2}$$

where F is the thoracic impact surface force and g is the acceleration of gravity. The effective thoracic masses for the 1 m rigid and 2 m padded drop tests are given in Table G.1. An effective thoracic mass of 38 kg was chosen for the standard subject. This is 50% of the total body mass of a 50th percentile adult male and is within the range of the percent body mass for the effective masses of the cadavers.

The mass ratio, R_m, was calculated from the following equation,

$$R_m = 38\,\mathrm{kg}/M_e \tag{G.3}$$

The mass ratios for the APR cadaver drop tests are given in Table G.1.

The stiffness ratio, R_k, is defined as,

$$R_k = K_s/K_i \tag{G.4}$$

where K_s is the stiffness of the standard subject and K_i is the stiffness of the i-th subject. Mertz (17) has shown that for geometrically similar structures with the same elastic modulus, the stiffness is proportional to the characteristic length. The thoracic depth was the characteristic length chosen for the normalization of the APR data. For the 50th percentile adult male, this length is 236 mm. The characteristic ratio for the thoracic stiffness, R_k, was calculated by,

$$R_k = 236\,\mathrm{mm}/L_i \tag{G.5}$$

where L is the chest depth of the cadaver whose data were to be normalized. The stiffness ratios for the cadavers are given in Table G.1.

The normalizing factors for force, R_f, time, R_t, and displacement, R_x, were calculated from the equations given by Mertz (17),

$$R_f = \left(R_m R_k\right)^{1/2} \tag{G.6}$$

$$R_t = \left(R_m/R_k\right)^{1/2} \tag{G.7}$$

$$R_x = \left(R_m/R_k\right)^{1/2} \tag{G.8}$$

The characteristic ratios and normalizing factors for the APR cadaver impacts are given in Table G.1. The normalized force versus time histories were obtained by multiplying each value of force by its force normalizing factor and each value of time by its time normalizing factor. Figures G.7, G.8 and G.9 give the normalized force versus time histories for the various test conditions. The normalized peak rib deflection for each cadaver was obtained by multiplying the peak measured deflection by the deflection normalizing factor for that cadaver. The normalized peak rib deflections for the 1 m rigid and 2 m padded drops are given in Table G.1.

G.3 Elimination of massively damaged cadavers

Table G.1 gives the number of rib fractures sustained by each cadaver used in the APR drop tests. The response requirements were established from cadavers which sustained less than 6 fractures to the ribs. This cutoff level was chosen arbitrarily. If this cutoff level were set lower, too little data remained to define the responses of the thorax.

G.4 Response requirements

The best estimate of the response of the 50th percentile male to the APR impact conditions is the average of the normalized cadaver responses for each impact configuration. Response requirements for the side impact test device consist of corridors constructed around the normalized cadaver force versus time histories and ranges for the normalized peak rib deflections.

Normalized Force Versus Time Corridors - The normalized force versus time histories for the 1 m rigid drops are shown in Figure G.10. Figure G.10 also shows the corridor for the history of thoracic force versus time for the 1 m drop onto a rigid surface. It should be noted that the corridor is in good agreement with one developed using linear regression analysis on the same data (33). The normalized force versus time history of any side impact dummy should lie within the corridor for a drop of 1 m onto a rigid impact surface.

Figure G.11 shows the normalized force versus time histories and the corridor for the force versus time history for the 2 m drop onto APR padded surfaces. The normalized force versus time history for the side impact dummy should lie within this corridor for a drop of 2 m onto APR padding.

Normalized Peak Deflection - Cadavers with multiple rib fractures were not used to define the normalized rib deflection requirements. Only test 155, a 1 m rigid drop, and test 122, a 2 m padded drop produced no rib fractures. These cadavers experienced normalized rib to spine deflections of 32 and 33 mm, respectively. Because of the sparsity of the data, a deviation of ±20% was chosen. This gives a normalized rib to spine deflection requirement of 26 to 38 mm for the 1 m rigid impact and 26 to 40 mm for the 2 m padded drop.

Table G.1 — Cadaver Data, Test Conditions and Test Results of the APR Lateral Drop Tests (20, 21, 22); and Effective Mass, Characteristic Ratios, Normalizing Factors, and Normalized Test Results for These Data

	Cadaver Data			**Test Conditions**				**Test Results**	**Effective Mass**		**Character-istic Ratios**		**Normalizing Factors**			**Norm. Results**
Test No.	**Body Mass** (kg)	**Chest Depth** (mm)	**No. of Rib** Fx	**Drop Height** (m)	**Impact Velocity** (m/s)	**Impact Surface**	**Arm Posi-tion**	**Peak Rib Defl.** (mm)	M_e (kg)	**Body Mass** (%)	**Mass** R_m	**Stiff.** R_k	**Force** R_f	**Time** R_t	**Defl.** R_x	**Peak Rib Defl.** (mm)
104	59	200	14	1	4,4	rigid	up	52	21,8	37	1,74	1,18	1,43	1,21	1,21	63
105	54	200	13	1	4,4	rigid	up	66	25,9	48	1,47	1,18	1,32	1,12	1,12	74
111	53	210	5	1	4,4	rigid	20° fwd	30	26,0	49	1,46	1,12	1,28	1,14	1,14	34
155	69	200	0	1	4,4	rigid	20° fwd	34	36,6	53	1,04	1,18	1,11	0,94	0,94	32
120	70	230	13	2	6,3	APR pad	20° fwd	79	52,5	75	0,72	1,03	0,86	0,84	0,84	66
121	75	230	4	2	6,3	APR pad	20° fwd	44	58,2	78	0,65	1,03	0,82	0,79	0,79	35
122	45	160	0	2	6,3	APR pad	20° fwd	36	30,7	68	1,24	1,48	1,35	0,92	0,92	33

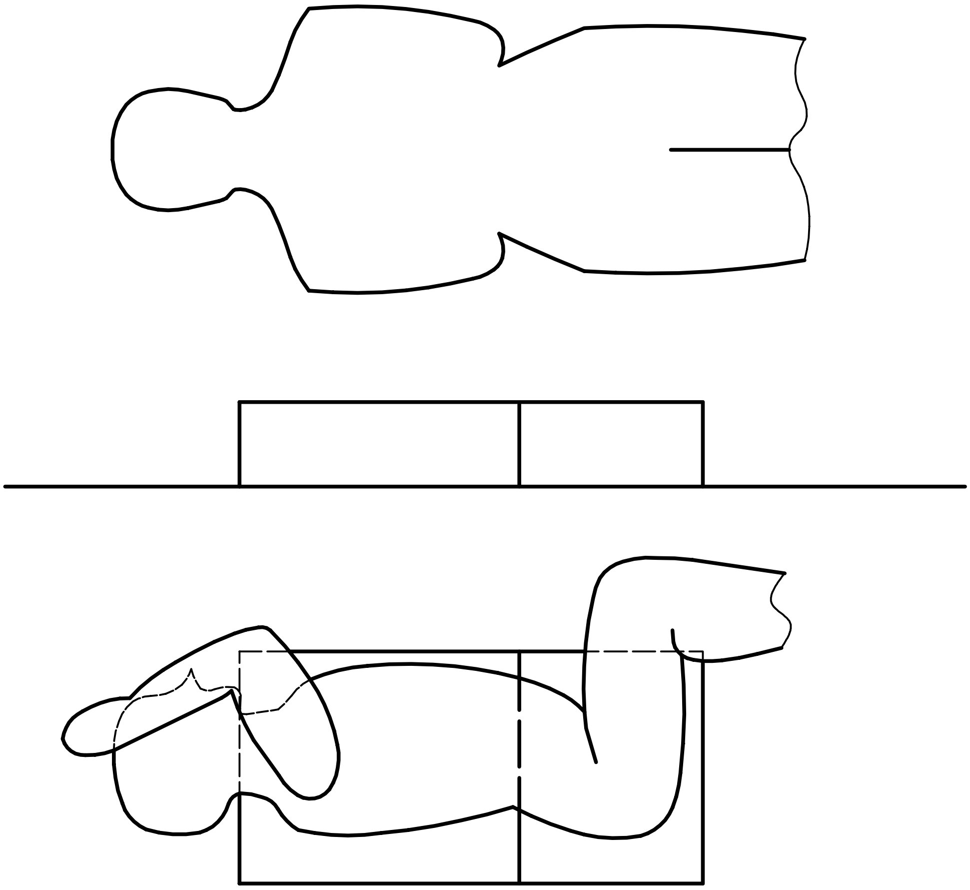


Figure G.1 — Lateral Thoracic Impact Test Configuration for the 1 m Drop onto a Rigid Surface Without Arm Involvement

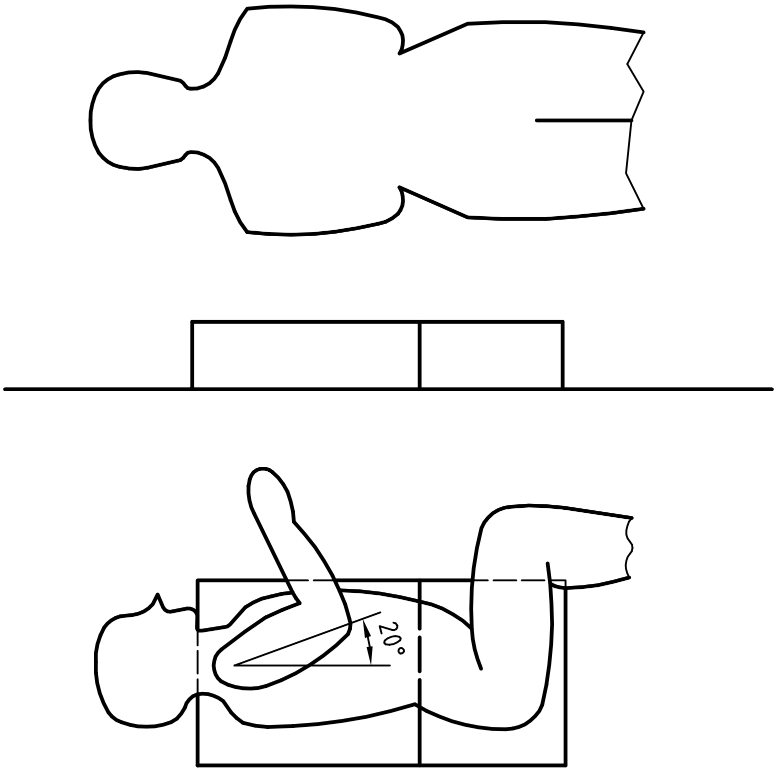


Figure G.2 — Lateral Thoracic Impact Test Configuration for the 1 m Drop onto a Rigid Surface With Arm Involvement

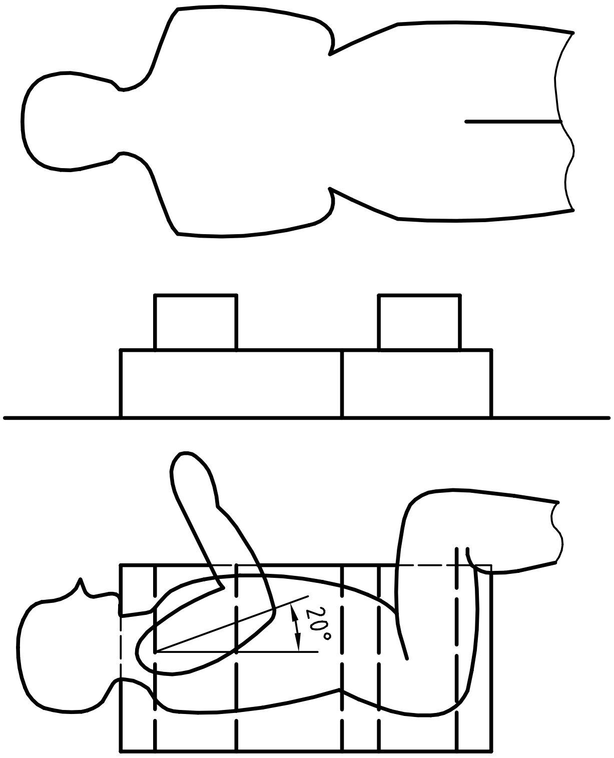


Figure G.3 — Lateral Thoracic Impact Test Configuration for the 2 m Drop onto an APR Padded Surface With Arm Involvement

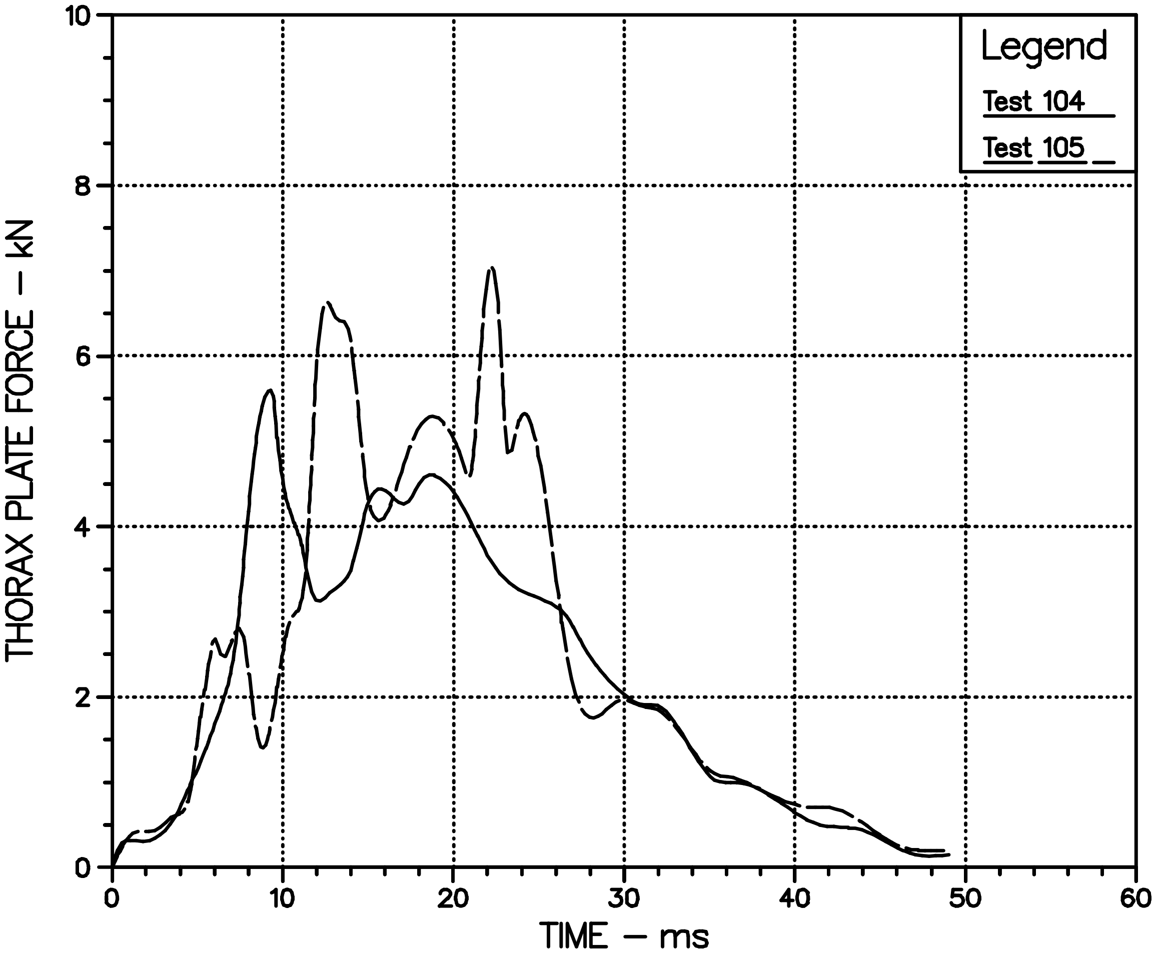


Figure G.4 — Lateral Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to 1 m Drops onto a Rigid Surface Without Arm Involvement

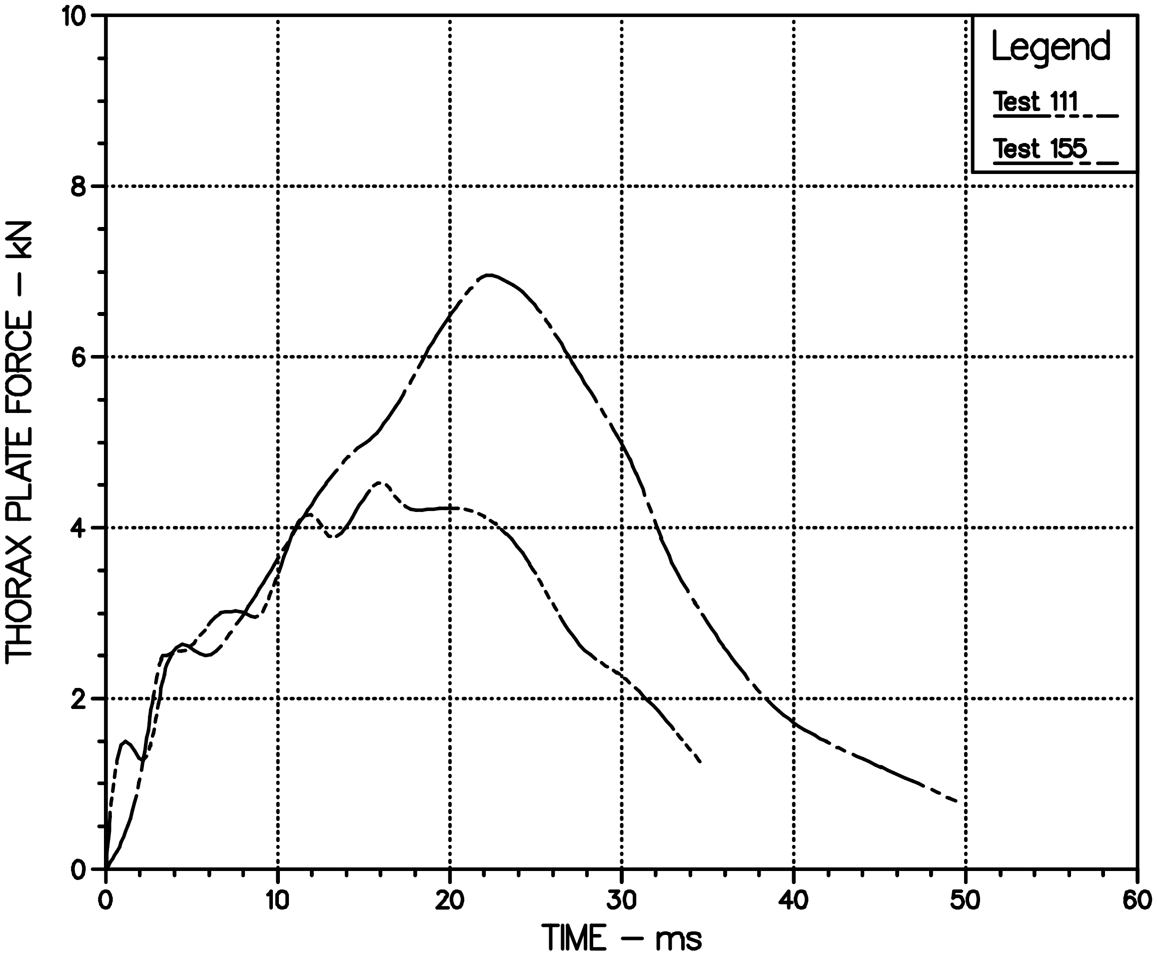


Figure G.5 — Lateral Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to 1 m Drops onto a Rigid Surface With Arm Involvement

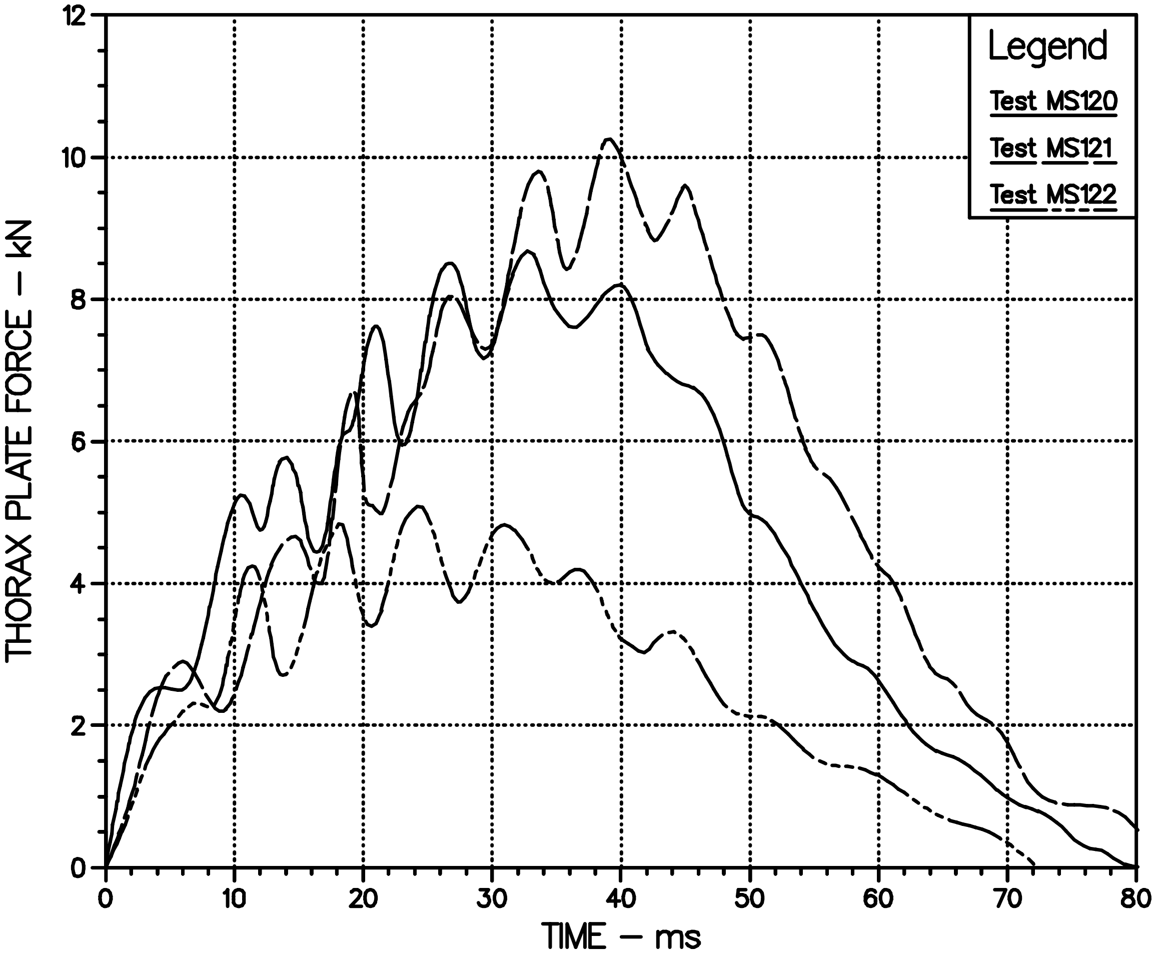


Figure G.6 — Lateral Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to 2 m Drops onto an APR Padded Surface With Arm Involvement

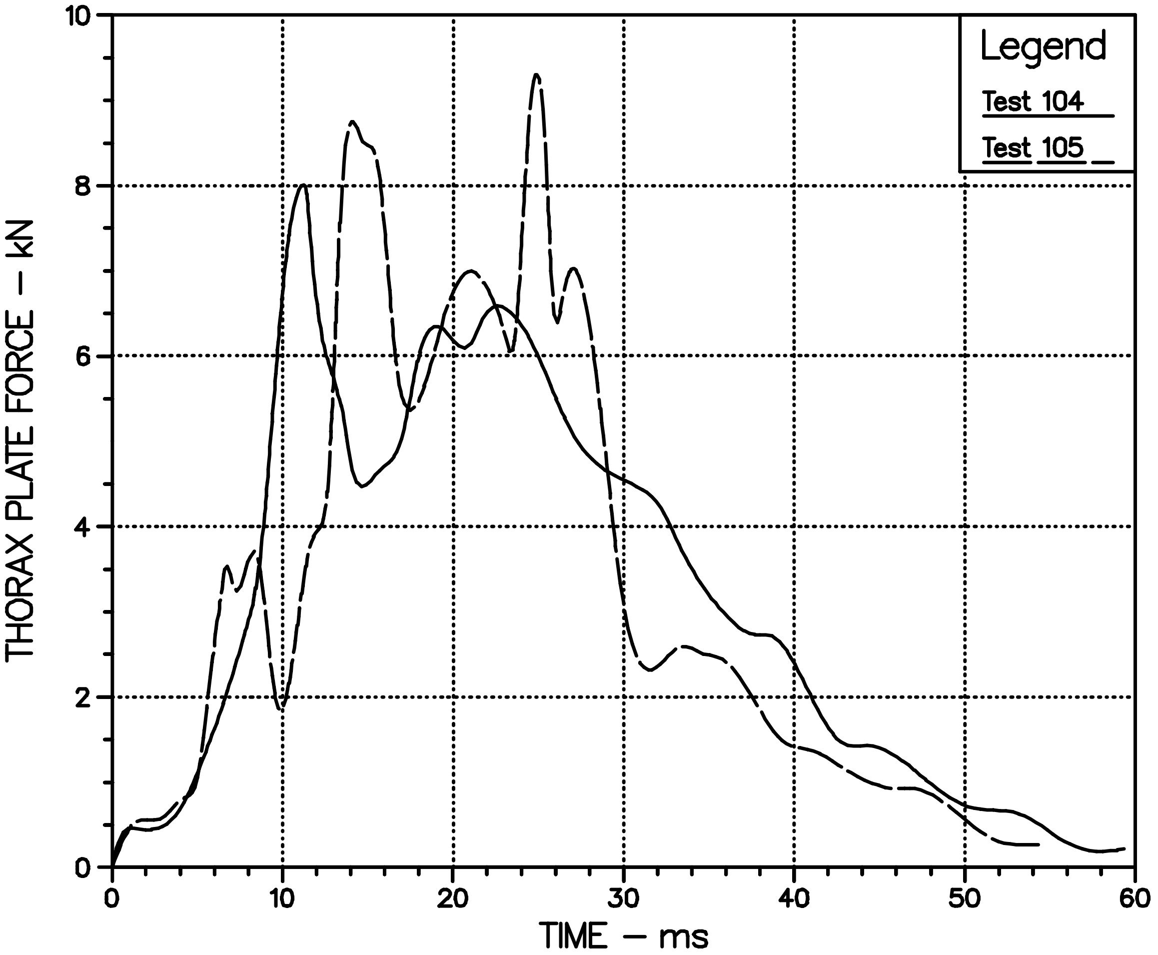


Figure G.7 — Normalized Lateral Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to 1 m Drops onto a Rigid Surface Without Arm Involvement

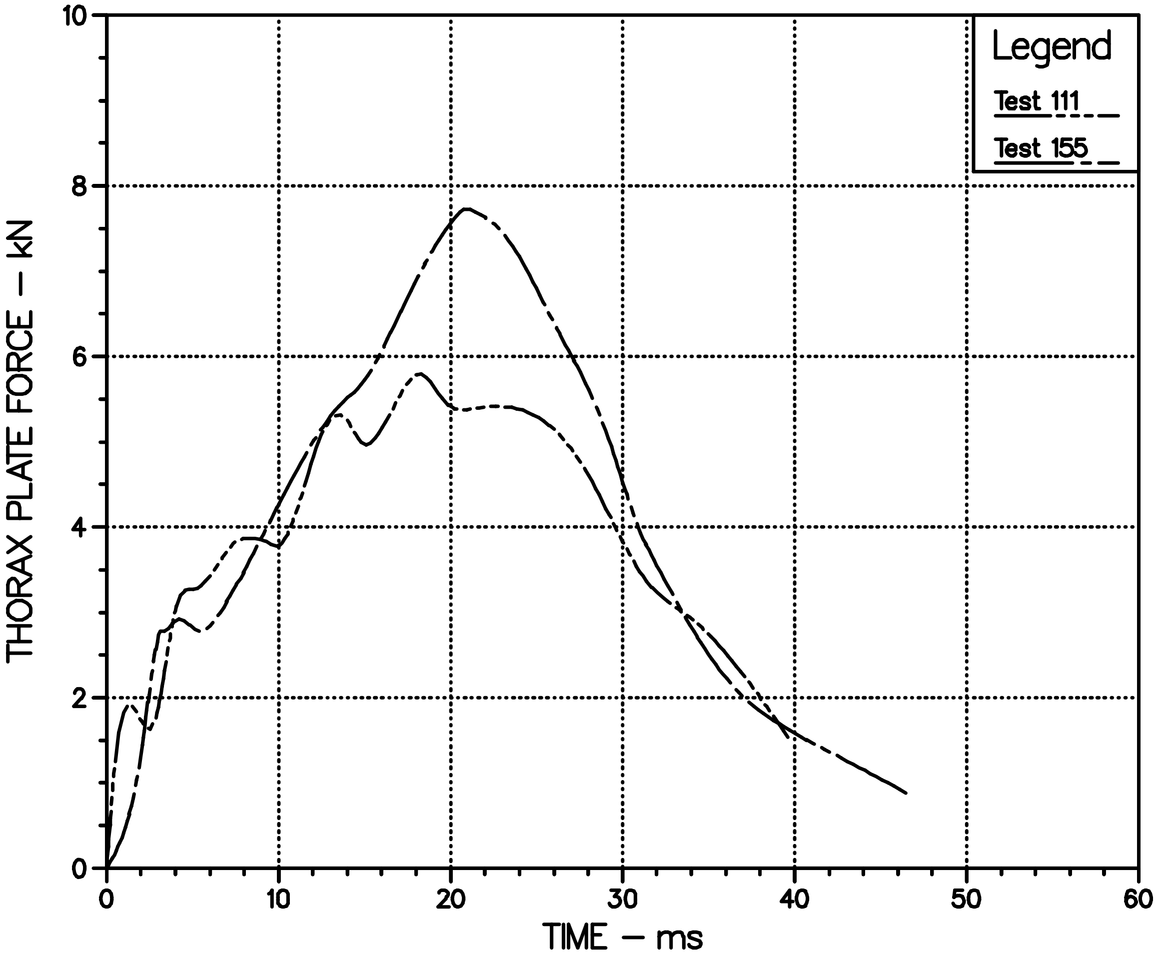


Figure G.8 — Normalized Lateral Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to 1 m Drops onto a Rigid Surface With Arm Involvement

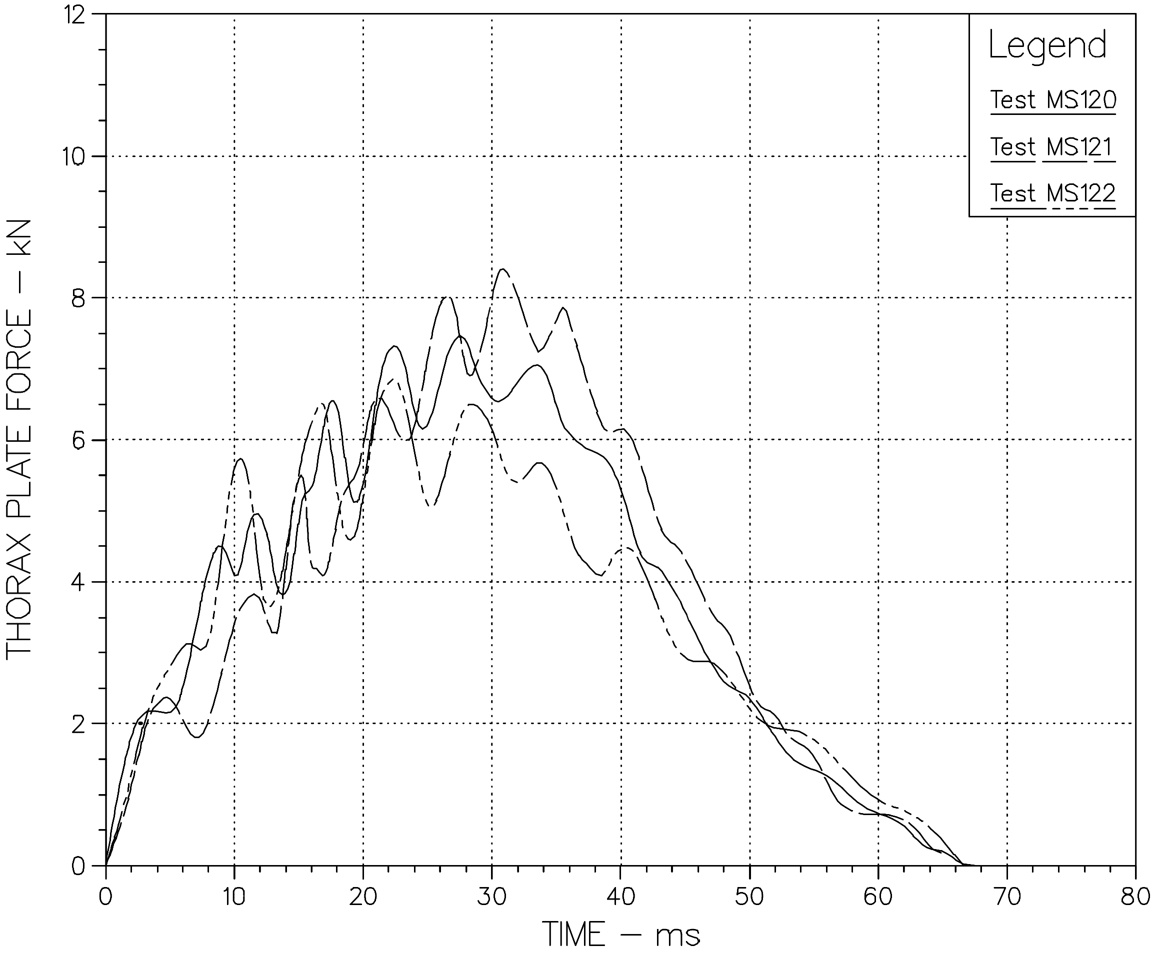


Figure G.9 — Normalized Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to 2 m Drops onto an APR Padded Surface With Arm Involvement

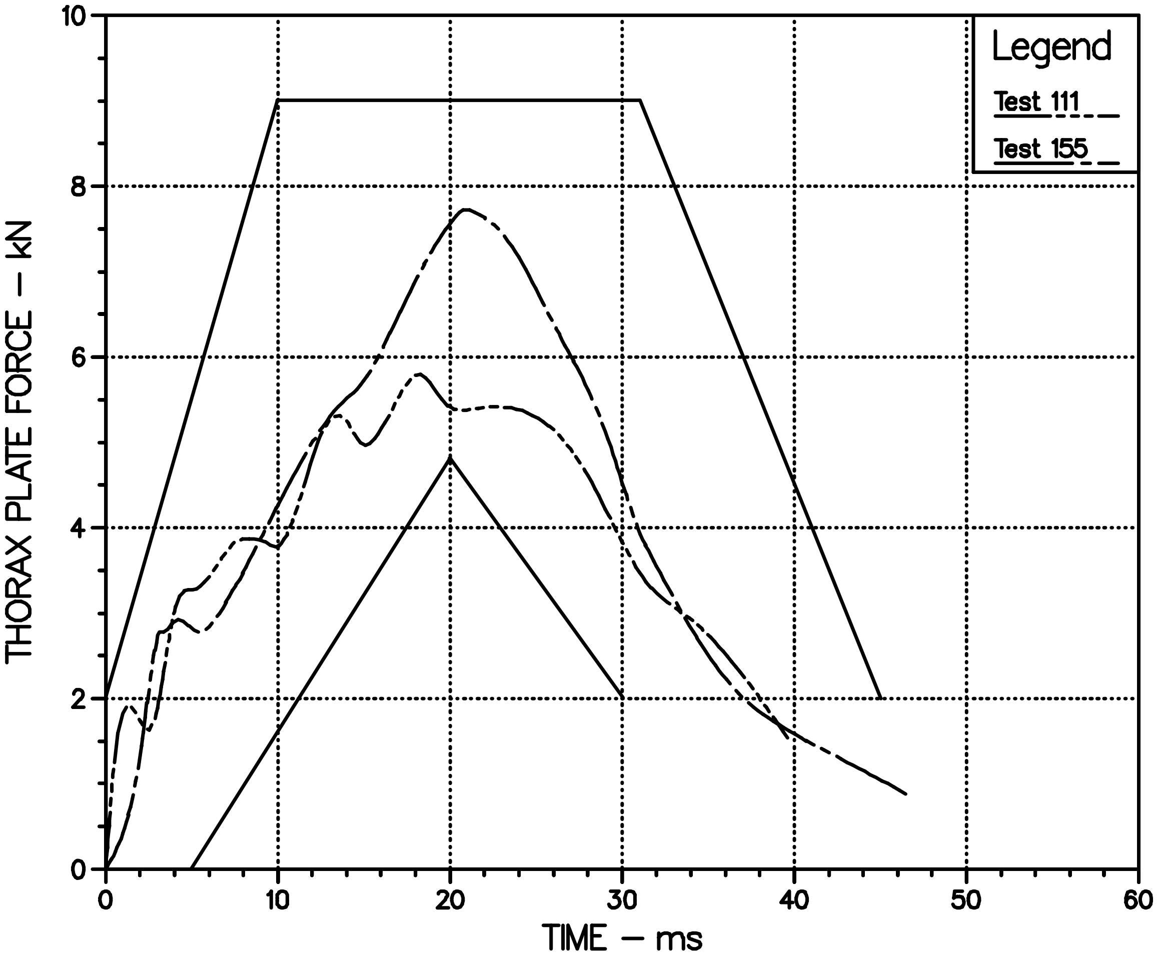


Figure G.10 — Normalized Thoracic Impact Surface Force Versus Time Histories and Response Corridor for a 1 m Drop onto a Rigid Surface With Arm Involvement

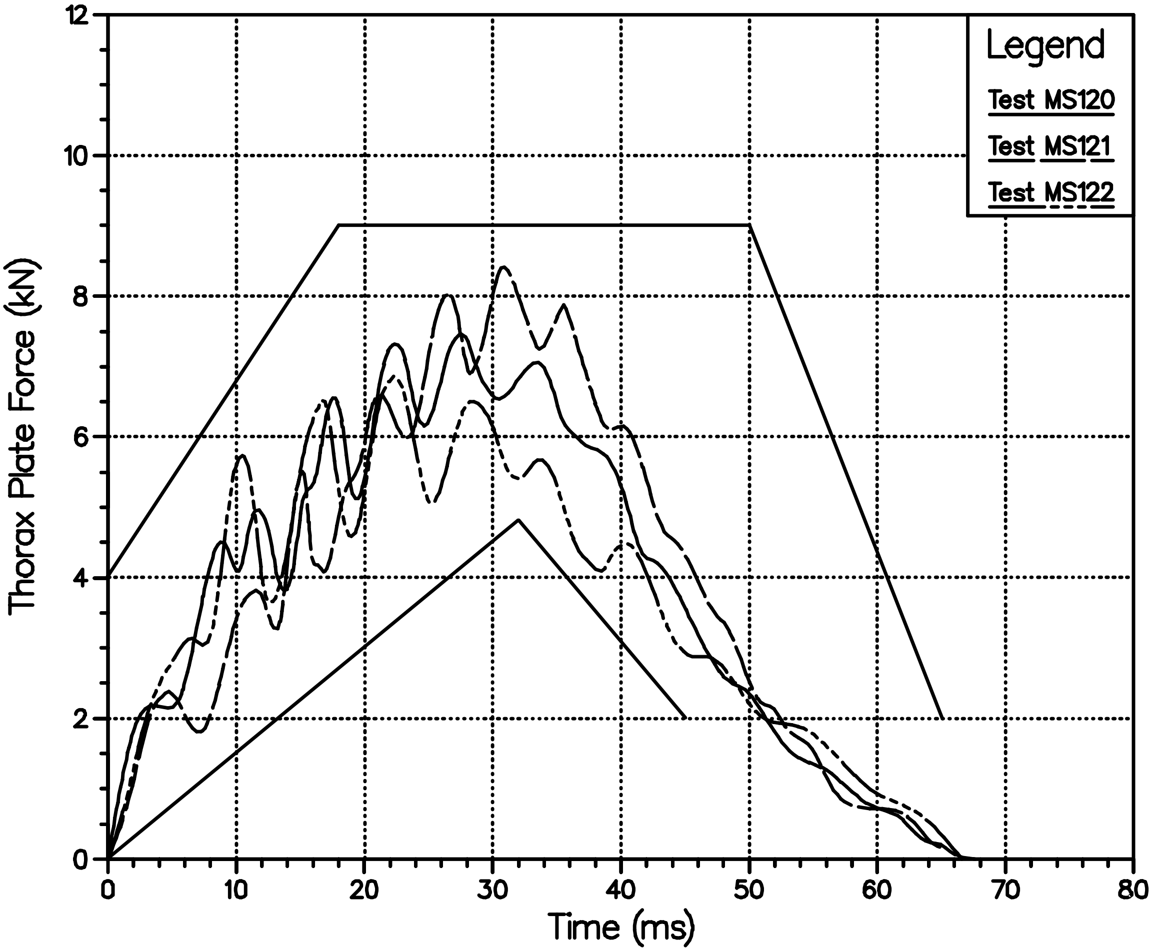


Figure G.11 — Normalized Thoracic Impact Surface Force Versus Time Histories and Proposed Response Corridor for a 2 m Drop onto an APR Padded Surface With Arm Involvement

Annex H

Analysis of Association Peugeot-Renault lateral pelvic impact data

This annex describes the application of the normalization techniques of Mertz (17) to the lateral pelvic impact data collected by researchers of the Association Peugeot-Renault (29).

H.1 Original Data

Researchers of the APR subjected 26 unembalmed cadavers to lateral free falls onto either rigid or padded impact surfaces. Accelerometers were attached to T4 and the sacrum. The impact surfaces were positioned to impact with the thorax and pelvis, as shown in Figures H.1 and H.2. The padded, pelvic impact surfaces were polyurethane foam. The cadavers were dropped from heights ranging from 0,5 to 3,0 m. Following each test, the cadaver was autopsied for thoracic and pelvic fractures.

Table H.1 summarizes the body mass and thoracic depths of the cadavers for the rigid and padded impacts. The drop height, impact surface configuration, and pelvic acceleration are also given for each test.

H.2 Normalized data

The force versus time and acceleration versus time histories were not available for these data. Consequently, the mass ratio, R_m, was calculated using the total body mass or,

$$R_m = 76\,\mathrm{kg}/M_i \qquad \text{(H.1)}$$

where 76 kg is the total body mass of the 50th percentile adult male and M_i is the total body mass of the i-th subject. The mass ratios for the cadavers are given in Table H.1.

The stiffness ratio can be defined (17) in terms of characteristic lengths for geometrically similar structures with the same elastic modulus, or,

$$R_k = L_s/L_i \qquad \text{(H.2)}$$

Using the thoracic depth as the characteristic length, Equation H.2 becomes,

$$R_k = 236\,\mathrm{mm}/L_i \qquad \text{(H.3)}$$

where 236 mm is the thoracic depth for a 50th percentile adult male. The stiffness ratios for the cadavers are given in Table H.1.

The normalizing factor for acceleration, R_a, is defined as,

$$R_a = (R_k/R_m)^{1/2} \qquad \text{(H.4)}$$

The acceleration normalizing factors for the cadaver impacts are listed in Table H.1. For each test, the peak pelvic acceleration was multiplied by its normalizing factor, and the resulting normalized peak pelvic accelerations are given in Table H.1.

H.3 Peak acceleration response requirements

The acceleration normalizing factors adjust the peak pelvic acceleration values of the available subjects to a standard cadaver subject. The data in Table H.1 were grouped by impact surface stiffness and drop height. Average normalized peak accelerations were calculated and are given in Table H.2. Tests 101 and 105 were not included in the analysis since these peak pelvic accelerations appear to be outliers. Consequently, the peak normalized pelvic acceleration bounds for the 2,0 m drop onto APR pad were based on a single test. Upper and lower bounds for the peak normalized dummy pelvis accelerations for each impact configuration are given in Table H.2 as well.

Table H.1 — Cadaver Data, Test Conditions, and Test Results from the APR Lateral Drop Tests (29); and Characteristic Ratios, Normalizing Factors and Normalized Test Results for These Data

	Cadaver Data		**Test Conditions**			**Test Results**	**Character. Ratios**		**Normalizing Factors**	**Normalized Results**
Test No.	**Body Mass** (kg)	**Thoracic Depth** (mm)	**Drop Height** (m)	**Config.**	**Impact Surface**	**Pk. Pelvic Accel.** (G)	**Mass** R_m	**Stiff-ness** R_k	**Accel.** R_a	**Pk. Pelvic Accel.** (G)
118	49	200	0,5	Bb	rigid	62	1,55	1,18	0,87	54
119	41	200	0,5	Bb	rigid	34	1,85	1,18	0,80	27
104	59	200	1,0	Aa	rigid	55	1,29	1,18	0,96	53
105	54	200	1,0	Aa	rigid	153	1,41	1,18	0,91	139
111	53	210	1,0	Ab	rigid	89	1,43	1,12	0,88	78
155	69	200	1,0	Ab	rigid	75	1,10	1,18	1,04	78
156	57	170	1,0	Ab	rigid	69	1,33	1,39	1,02	70
100	56	180	2,0	Fb	APR pad	44	1,36	1,31	0,98	43
101	52	200	2,0	Fb	APR pad	110	1,46	1,18	0,90	99
102	53	210	3,0	Eb	APR pad	62	1,43	0,87	0,78	48
107	42	170	3,0	Eb	APR pad	77	1,81	0,91	0,71	55
108	50	190	3,0	Eb	APR pad	74	1,52	0,87	0,76	56
120	70	230	2,0	Cb	improved pad [a]	37	1,09	1,03	0,97	36
121	75	230	2,0	Cb	improved pad	32	1,01	1,03	1,01	32
122	45	160	2,0	Cb	improved pad	34	1,69	1,48	0,94	32
128	50	200	2,0	Db	improved pad	48	1,52	1,18	0,88	42
129	44	210	2,0	Db	improved pad	48	1,73	1,12	0,80	38
131	45	210	2,0	Db	improved pad	50	1,69	1,12	0,81	41
132	44	200	2,0	Db	improved pad	60	1,73	1,18	0,83	50
133	61	230	2,0	Db	improved pad	84	1,25	1,03	0,91	76

[a] A description of the characteristics of the "improved pad" is not available. These data will not be used in defining performance requirements.

Table H.2 — Pelvic Response Requirements for the Lateral Pelvic Drop Tests Determined from the Response Data of Tarriere et al. (29)

Test Conditions		**Average of the Peak Normalized Pelvic Accelerations** (G)	**Response Requirements for Peak Pelvic Acceleration**	
Drop Height (m)	**Impact Surface**		**Lower Bound** (G)	**Upper Bound** (G)
0,5	rigid	41	37	45
1,0	rigid	70	63	77
2,0	APR pad	43	39	47
3,0	APR pad	53	48	58

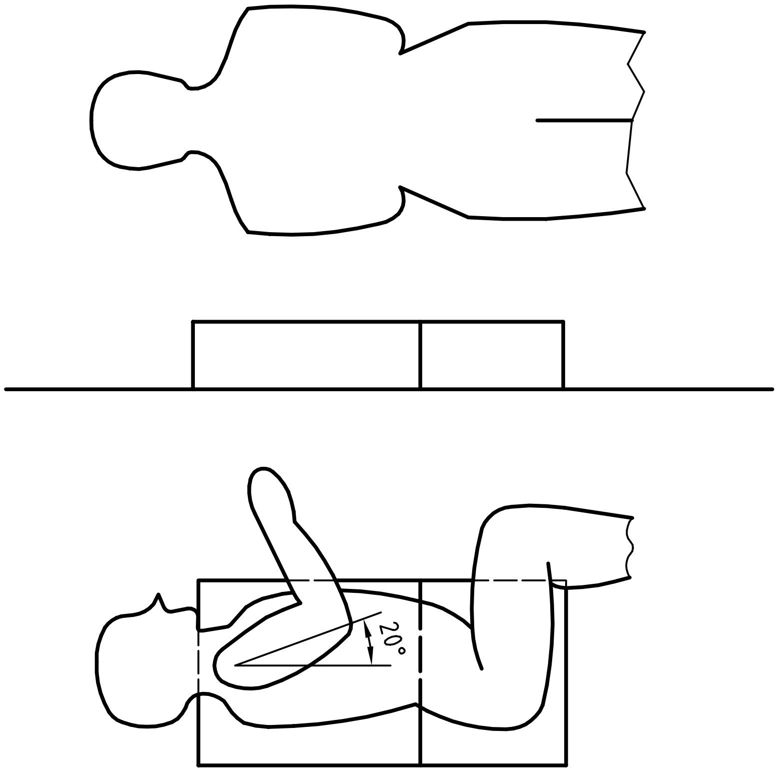


Figure H.1 — Lateral Pelvic Impact Test Configuration for the 0,5 and 1 m Drops onto Rigid Surfaces

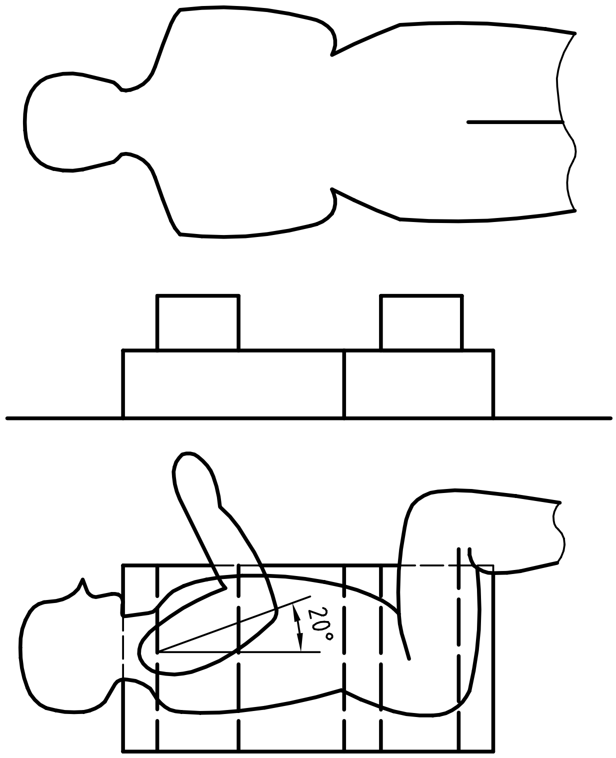


Figure H.2 — Lateral Thoracic Impact Test Configuration for the 2 and 3 m Drops onto an APR Padded Surfaces

Annex I

Characteristics of APR padding

The APR padding is a rectangular parallelepiped with dimensions of 140 mm × 140 mm × 420 mm. It is made of polyurethane open cell foam with a density range of 135 to 150 g/l. Quasi-static (100 mm/min) loading rate) force versus deflection tests were conducted on two blocks. Figure I.1 depicts the resulting force versus deflection curves. The average static crush pressure was 51 kPa.

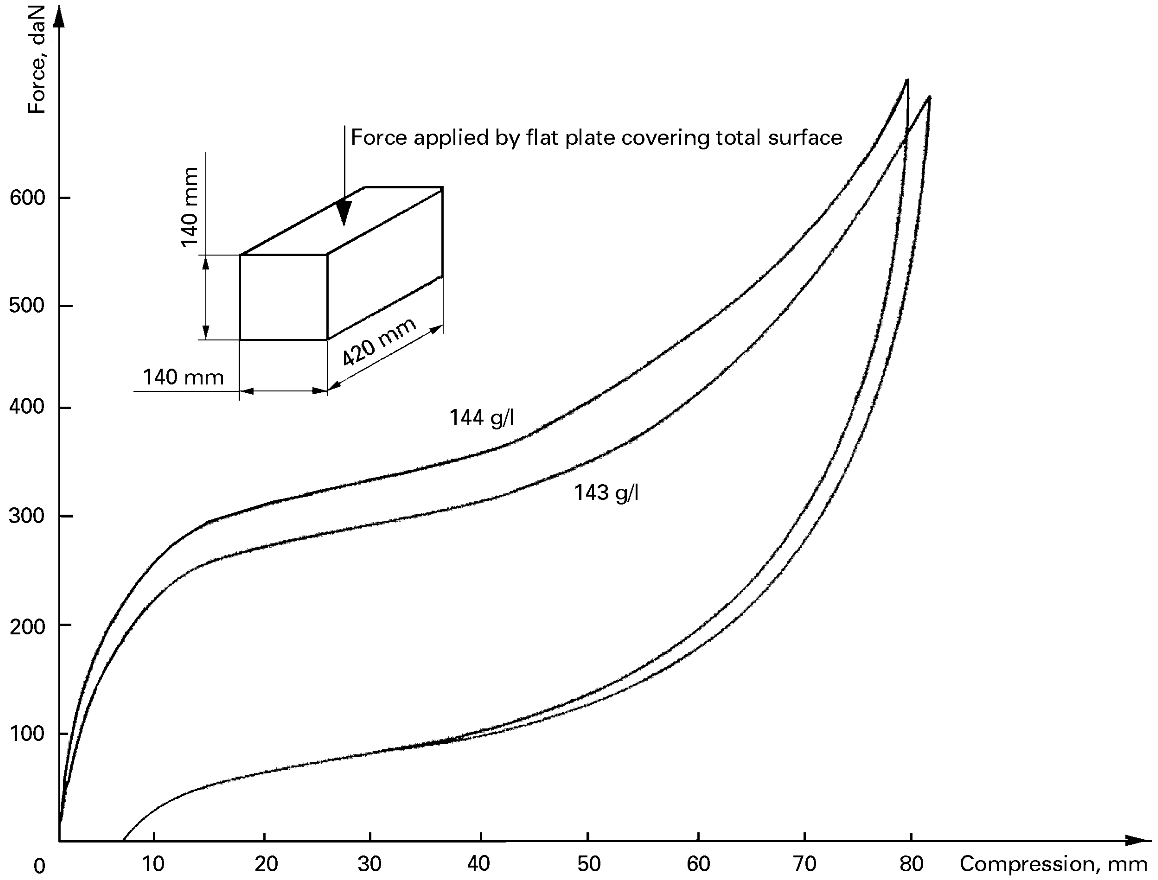


Figure I.1 — Force Versus Compression Curves of APR Blocks

Annex J

Analysis of Association Peugeot-Renault — Lateral abdominal impact data

This annex describes the application of the normalization techniques of Mertz (17) to the lateral abdominal impact data collected by researchers of the Association Peugeot-Renault (14).

J.1 Original Data

Researchers of the APR subjected 11 unembalmed cadavers to lateral free falls onto simulated armrests (25). Accelerometers were attached to T12 and the 9th rib on the left and right sides of the cadavers. The cadavers were perfused and at room temperature during the test. The simulated armrest consisted of a rigid hardwood impact surface secured to a supporting material. The hardwood section was 70 mm wide and 25 mm thick, with rounded edges. The supporting material was either rigid hardwood, polystyrene or phenespan. The thickness of the supporting material ranged from 6 to 30 mm. The armrest was secured to a piezoelectric load cell. Initially, the cadavers were suspended either 1 or 2 m above the top surface of the armrest, as shown in Figure J.1. The cadavers were positioned such that their right sides would impact the armrest at the level of their 9th ribs ensuring involvement of their livers. Their right arms were raised so as not to impact the armrest. Following each test, the cadaver was autopsied for rib fractures and injuries to the liver.

Table J.1 provides a summary of the weights of the cadavers and their abdominal widths measured at the level of the 9th rib. Also given are the total armrest height and type of supporting material used for each test. The force versus time histories for the load applied to the cadavers' abdomens by the simulated armrest are shown in Figures J.2 through J.5. The peak acceleration values of T12 and the 9th rib on the impacted side are given in Table J.2. Note that complete data necessary for the calculation of normalizing factors were available for only 9 of the 11 cadavers that were tested. The acceleration versus time histories for the 9th rib were available for only 8 of these cadavers.

J.2 Normalized data

The force versus time histories of the armrest and the lateral acceleration versus time histories of T12 were digitized for nine subjects. (Plots for the remaining two subjects were not available.) The characteristic features of each curve were represented by 50 to 100 points.

The effective mass of the abdomen, as defined by Mertz (17), was calculated by,

$$M_e = \left[\int_0^T F dt\right] \Big/ (Tg + \Delta V) \qquad (J.1)$$

where $\int_0^T F dt$ is the area under the force versus time history, T is the pulse duration, g is the acceleration of gravity and ΔV is the change in velocity during the impact which was obtained by integrating the time history of the lateral acceleration of T12. The areas under the curves were calculated using the trapezoidal method of integration and the results are given in Table J.2 under the headings of "Impulse" and "Change in Velocity." The effective mass of the abdomen and percent of body mass for each cadaver are also given in Table J.2. The average percent of body mass was 21,6%

The effective mass of a 50th percentile adult male was obtained by multiplying its body mass of 76 kg by 21,6% giving an effective mass of 16,4 kg.

The mass ratio, R_m, is defined as,

$$R_m = M_s / M_i \qquad (J.2)$$

where M_s is the effective mass of the standard subject and M_i is the effective mass of the i-th subject. For the data discussed here, Equation J.2 becomes,

$$R_m = 16{,}4\,\mathrm{kg} / M_e \qquad (J.3)$$

The mass ratios for the cadavers are given in Table J.2.

The stiffness ratio, R_k, is defined as,

$$R_k = K_s / K_i \tag{J.4}$$

where K_S is the stiffness of the standard subject and K_i is the stiffness of the i-th subject.

Mertz (17) has shown that for geometrically similar structures with the same elastic modulus, the stiffness is proportional to a characteristic length. This implies that the stiffness ratio can be expressed in terms of characteristic lengths, or,

$$R_k = L_s / L_i \tag{J.5}$$

The characteristic length for the abdomen was chosen as the abdominal depth at the level of the 9th rib. This measurement, for each test subject, is listed in Table J.1. The abdominal depth of a 50th percentile adult male was not available. A linear relationship was assumed between the body mass and the abdominal depth for the cadaver subjects. The computed relationship, with a sample correlation of 0,84, is given by,

$$L = 9{,}8 + 0{,}20\ M \tag{J.6}$$

where L is the abdominal depth and M is the total body mass. For a 76 kg, 50th percentile adult male, the calculated depth is 250 mm. This value is used as the characteristic length L_S in Equation J.5, or,

$$R_k = 250\,\mathrm{mm} / L_i \tag{J.7}$$

The stiffness ratios for the cadavers are given in Table J.2.

The normalizing factors for force, R_f, acceleration, R_a, and time, R_t, are defined by Mertz (17) as,

$$R_f = \left(R_m R_k\right)^{1/2} \tag{J.8}$$

$$R_a = \left(R_k / R_m\right)^{1/2} \tag{J.9}$$

$$R_t = \left(R_m / R_k\right)^{1/2} \tag{J.10}$$

The force, acceleration and time normalizing factors for each cadaver impact are listed in Table J.2. These factors were used to normalize the force versus time histories shown in Figures J.2 through J.5 and the peak acceleration values given in Table J.2. For a given impact, the normalized force versus time history was obtained by multiplying each force value by its force normalizing factor and each time value by its time normalizing factor. The normalized force versus time histories are shown in Figures J.6 through J.9. The peak normalized acceleration values were obtained by multiplying each acceleration value by its acceleration normalizing factor. The normalized peak acceleration values for T12 and the 9th rib on the impacted side are given in Table J.2.

J.3 Force versus time corridors

Mertz (17) described the use of response corridors to facilitate the design of crash test dummies. He proposed to average the normalized force versus time histories and define a response corridor containing the average curve. Unfortunately, average impact response curves cannot be obtained from the normalized APR data since replicate tests were not conducted. As an alternate approach, it was decided to define corridors that contain the normalized force versus time histories for different armrest heights, but with the same drop height. Such corridors for the 1 and 2 m rigid armrest tests are shown in Figures J.10 and J.11, respectively. It is proposed that these corridors be used to assess normalized dummy force versus time histories for a 41 mm rigid armrest. No corridors are proposed for the padded surface impacts because the material properties were not defined.

J.4 Peak T12 acceleration requirements

Ranges for the peak accelerations are proposed. The average magnitude of the peak normalized acceleration for a 1 m free fall onto a rigid surface is 32 G. The proposed range, allowing for a ±10% deviation from the average peak normalized acceleration, is 29 to 35 G for a 1 m free fall of the dummy onto a 41 mm rigid armrest. The average magnitude of the peak normalized acceleration for a 2 m free fall onto a rigid surface is 83 G. The proposed range, allowing for a ±10% deviation from the average peak normalized acceleration, is 75 to 91 G, for a 2 m free fall of a dummy onto a 41 mm rigid armrest. Response requirements are not proposed for free falls onto padded impact surfaces because the material properties of the padding were not available.

J.5 Peak acceleration requirements of the near side rib

Ranges for the peak acceleration are proposed for the 1 and 2 m free falls onto rigid impact surfaces. The average magnitude of the acceleration peak for a 1 m drop onto a rigid armrest is 113 G. The proposed range, allowing for a ±10% deviation from the average peak normalized acceleration, is 100 to 125 G for a 1 m free fall of a dummy onto a 41 mm rigid armrest. The peak normalized acceleration of the normalized 2 m free fall onto a rigid surface was 180 G. The proposed range, allowing for a ±10% deviation from the average peak normalized acceleration, is 160 to 200 G for a 2 m free fall of a dummy onto a 41 mm rigid armrest. Response requirements are not given for free falls onto padded impact surfaces because the material properties of the padding were not available.

J.6 Abdominal penetration

Abdominal penetration is defined as the vertical displacement of the thoracic spine (that portion directly over the armrest) relative to the top surface of the armrest measured from the time of first contact of the abdominal surface with the top surface of the armrest. For all the 1 m and 2 m rigid armrest impacts, the abdominal penetration was as least as great as the height of the armrest. Abdominal penetration for the padded armrest impacts is unknown since the crush of the armrest was not measured.

Table J.1 — Cadaver Data and Test Conditions from the APR Lateral Abdominal Drop Tests (14)

Test No.	Cadaver Data		Test Conditions		
	Body Mass (kg)	**Abdominal Depth** (mm)	**Drop Height** (m)	**Supporting Material**	**Armrest Height** (mm)
205	32	135	1	hardwood	31
219	52	185	1	hardwood	41
206	82	240	1	hardwood	51
215	53	205	2	hardwood	31
216	49	207	2	hardwood	51
210	71	263	1	polystyrene	51
211	43	185	1	phenespan	53
212	45	210	1	polystyrene	55
213	77	245	2	polystyrene	55

Table J.2 — Test Results from the APR Lateral Abdominal Drop Tests (14); and Effective Mass, Characteristic Ratios, and Normalizing Factors for These Data

Test No.	Test Results				Effective Mass		Characteristic Ratios		Normalizing Factors			Normalized Results	
	Peak T12 Accel. (G)	**Peak Rib Accel.** (G)	**Impulse** (Ns)	**Change in Velocity** (m/s)	M_e (kg)	**Body mass** (%)	**Mass** R_m	**Stiff-ness** R_k	**Time** R_t	**Force** R_f	**Accel.** R_a	**Peak T12 Accel.** (G)	**Peak Rib Accel.** (G)
205	35	111	29,9	4,7	6,36	19,9	2,58	1,85	1,18	2,18	0,85	30	94
219	28	123	52,3	4,4	11,89	22,9	1,38	1,35	1,01	1,36	0,99	28	122
206	33	108	107,4	5,1	21,02	25,6	0,78	1,04	0,87	0,90	1,15	38	124
215	78	-	98,9	6,4	15,55	29,3	1,05	1,22	0,93	1,13	1,08	84	-
216	87	194	77,6	6,6	11,82	24,1	1,39	1,21	1,07	1,30	0,93	81	180
210	49	137	77,2	5,0	15,56	21,9	1,05	0,95	1,05	1,00	0,95	47	130
211	38	98	52,3	6,3	8,30	19,3	1,98	1,35	1,21	1,63	0,83	32	81
212	31	131	41,4	5,4	7,70	17,1	2,13	1,19	1,34	1,59	0,75	23	98
213	68	159	91,3	8,5	10,75	14,0	1,53	1,02	1,22	1,25	0,82	56	130

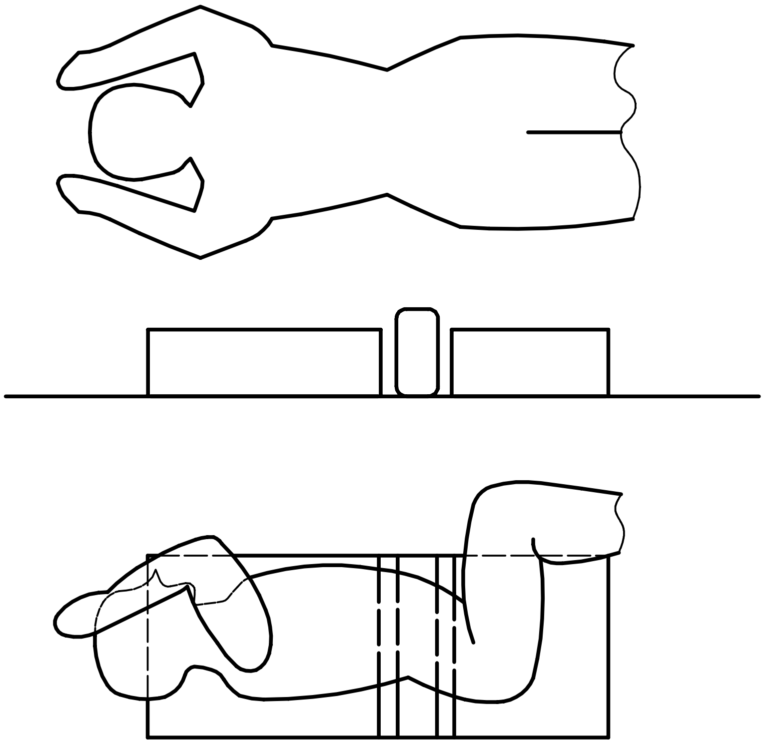


Figure J.1 – Lateral Abdominal impact test configuration

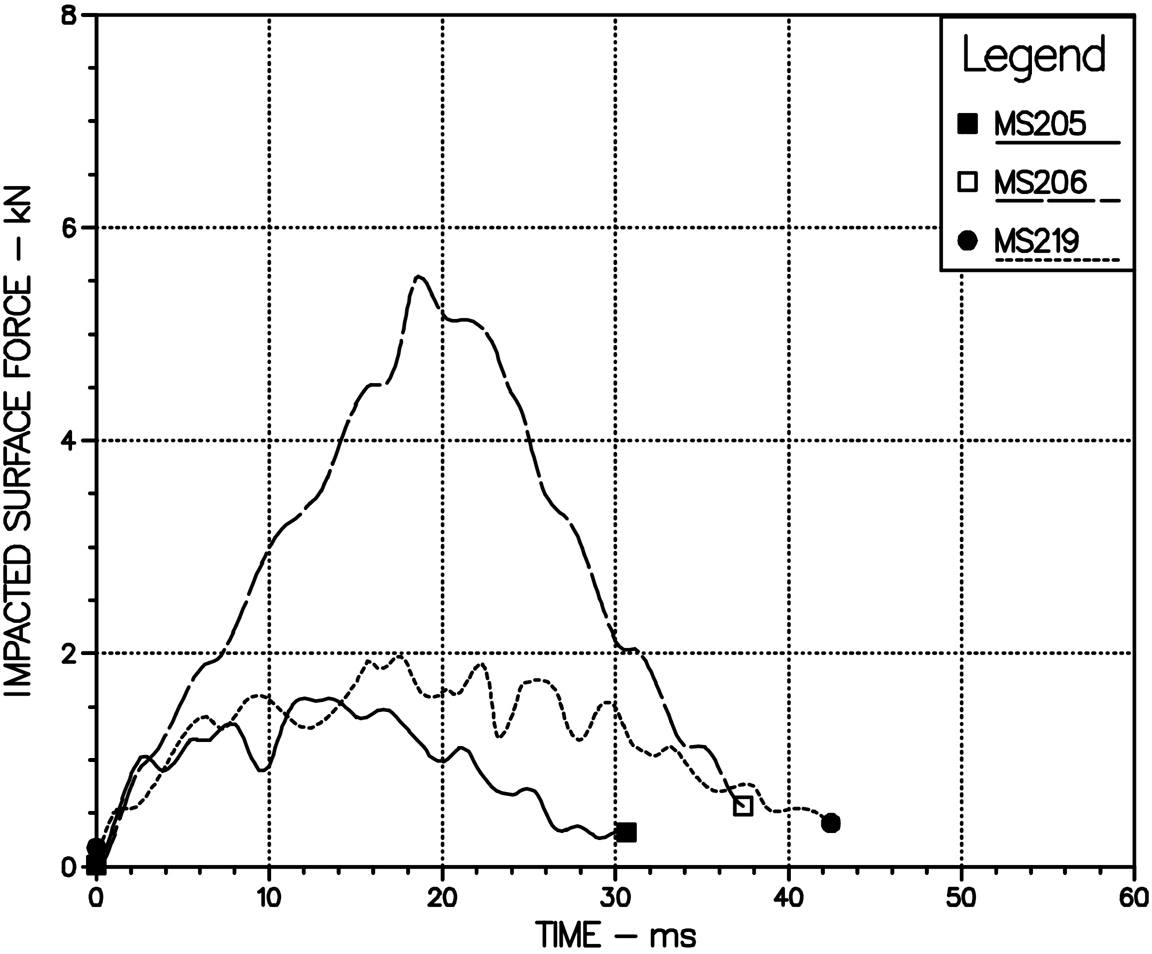


Figure J.2 – Lateral abdominal impact surface force versus time histories for cadavers subjected to 1 m drops onto a rigid surface

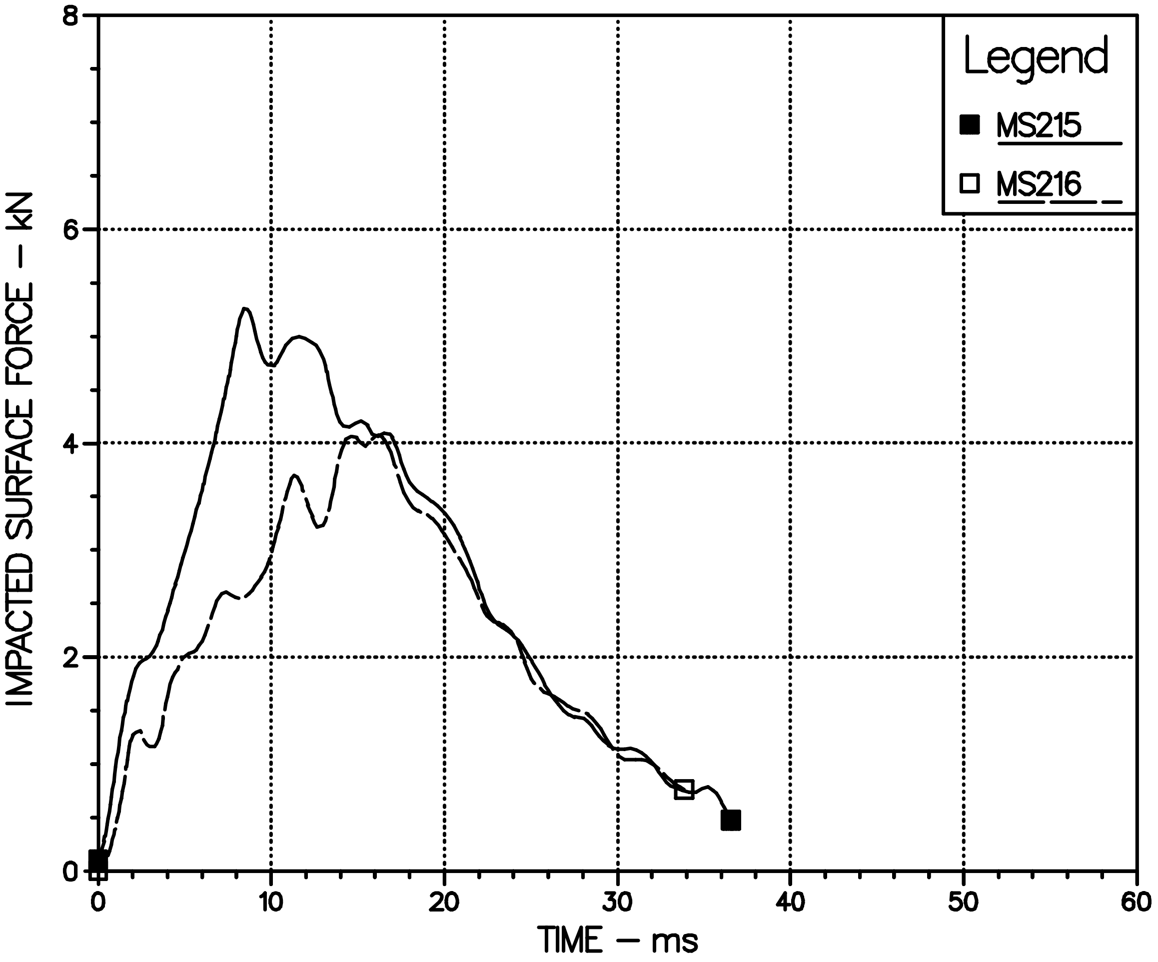


Figure J.3 — Lateral Abdominal impact surface force versus time histories for cadavers subjected to 2 m drops onto a rigid surface

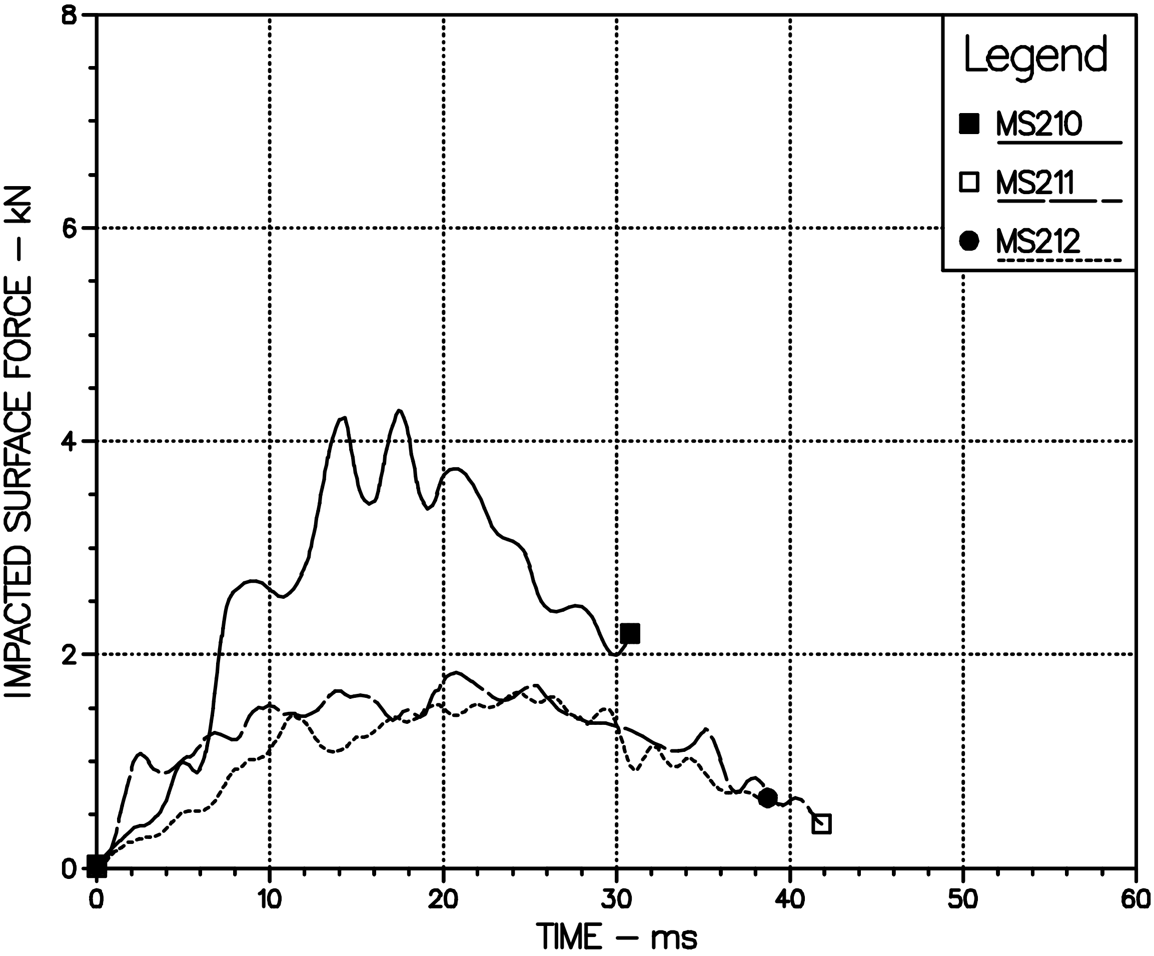


Figure J.4 — Lateral Abdominal impact surface force versus time histories for cadavers subjected to 1 m drops onto a crushable surface

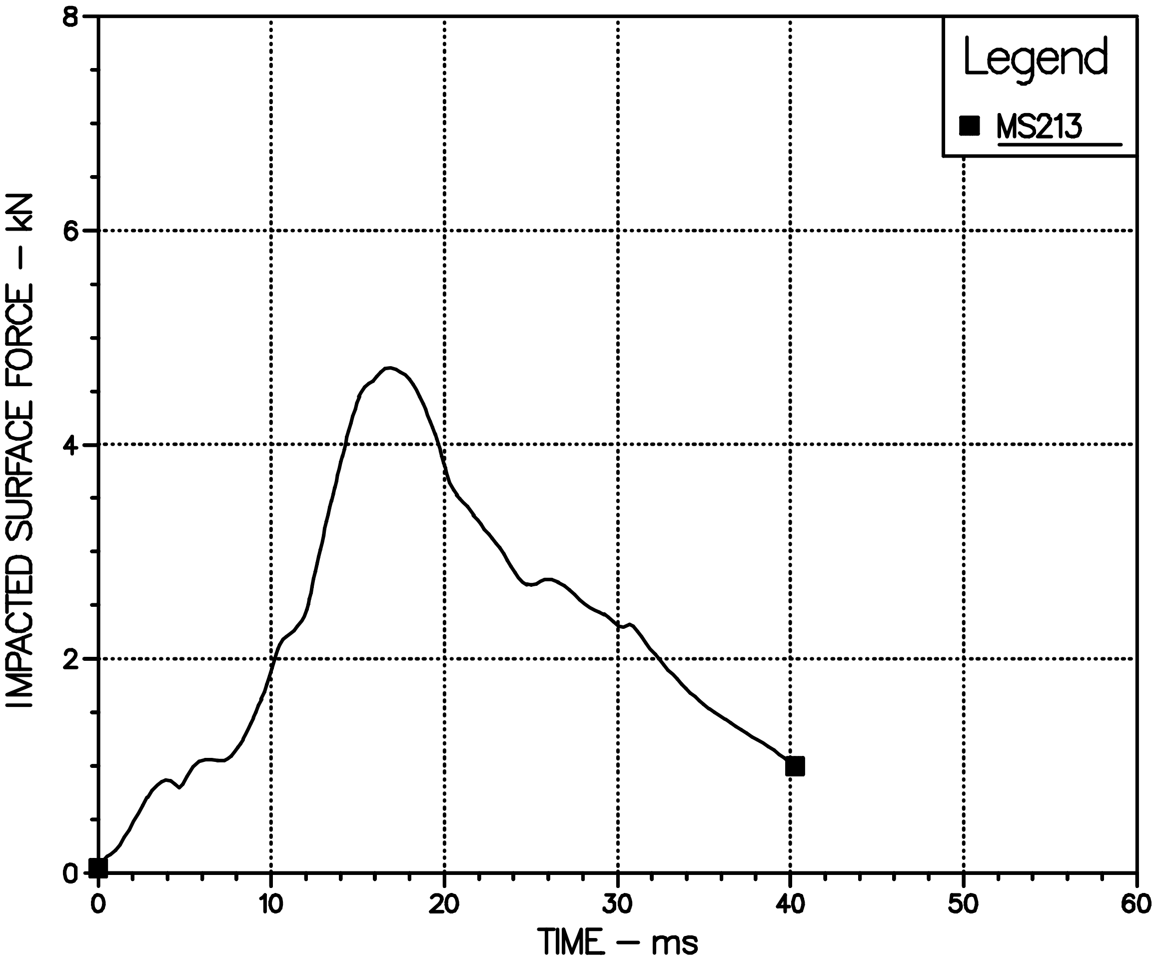


Figure J.5 — Lateral Abdominal impact surface force versus time histories for cadavers subjected to 2 m drops onto a crushable surface

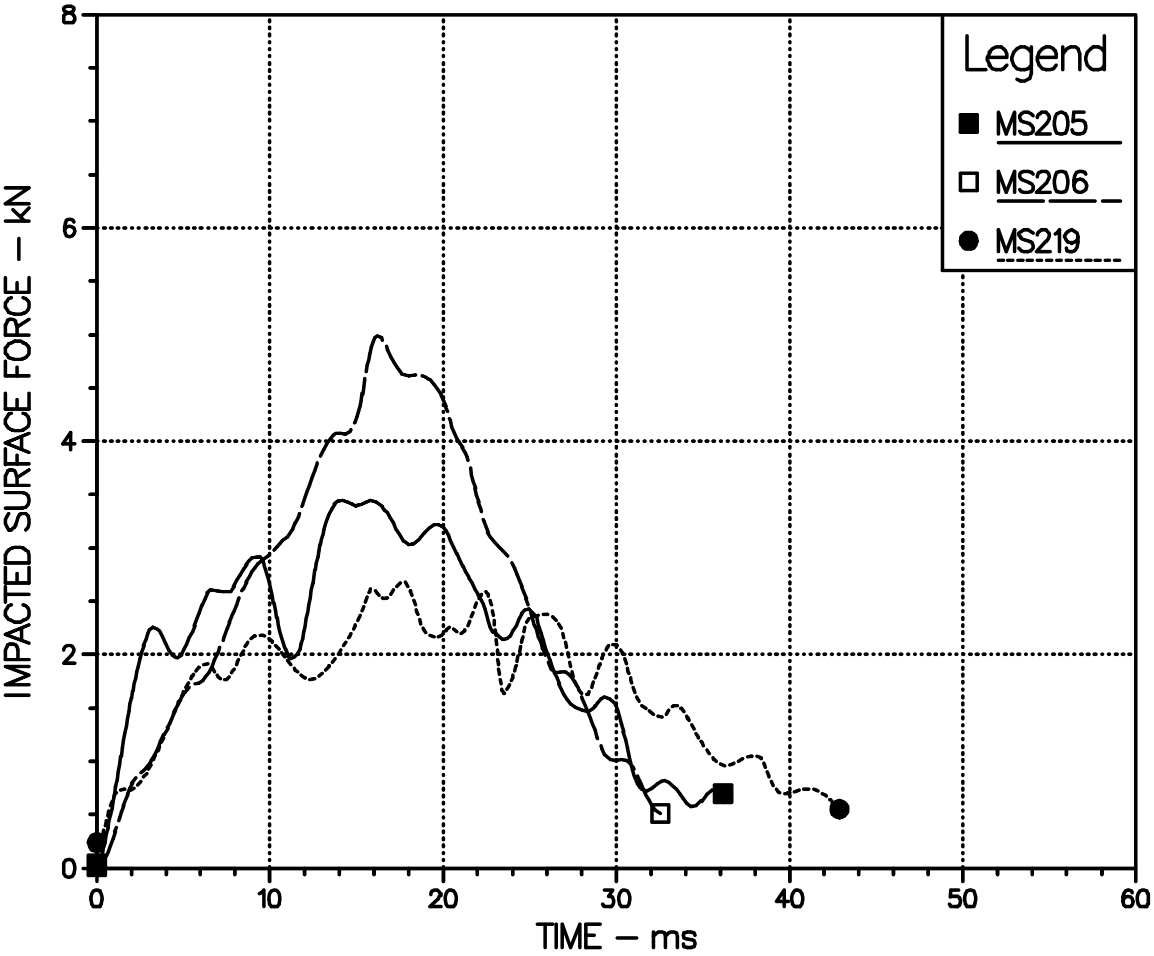


Figure J.6 — Normalized Abdominal impact surface force versus time histories for cadavers subjected to 1 m drops onto a rigid surface

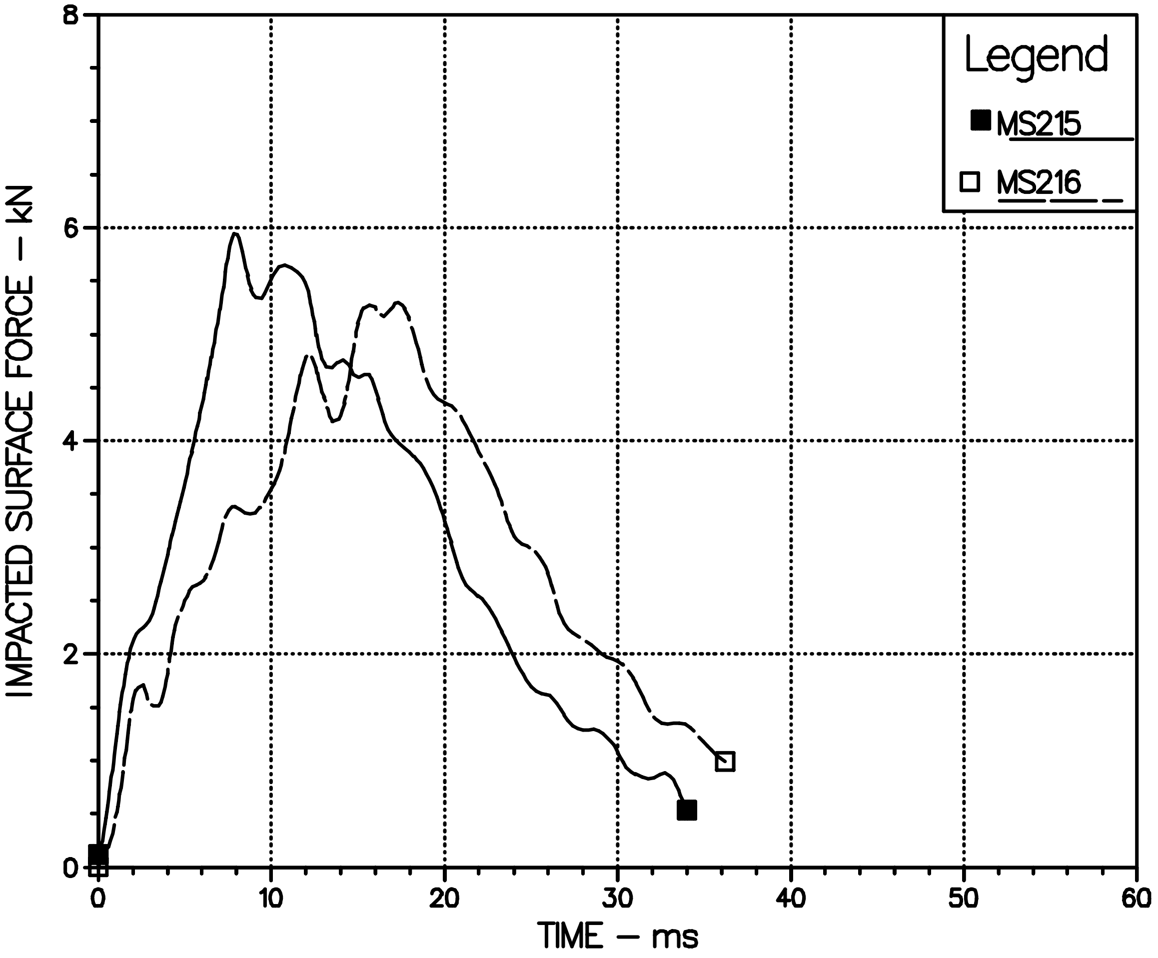


Figure J.7 — Normalized Abdominal impact surface force versus time histories for cadavers subjected to 2 m drops onto a rigid surface

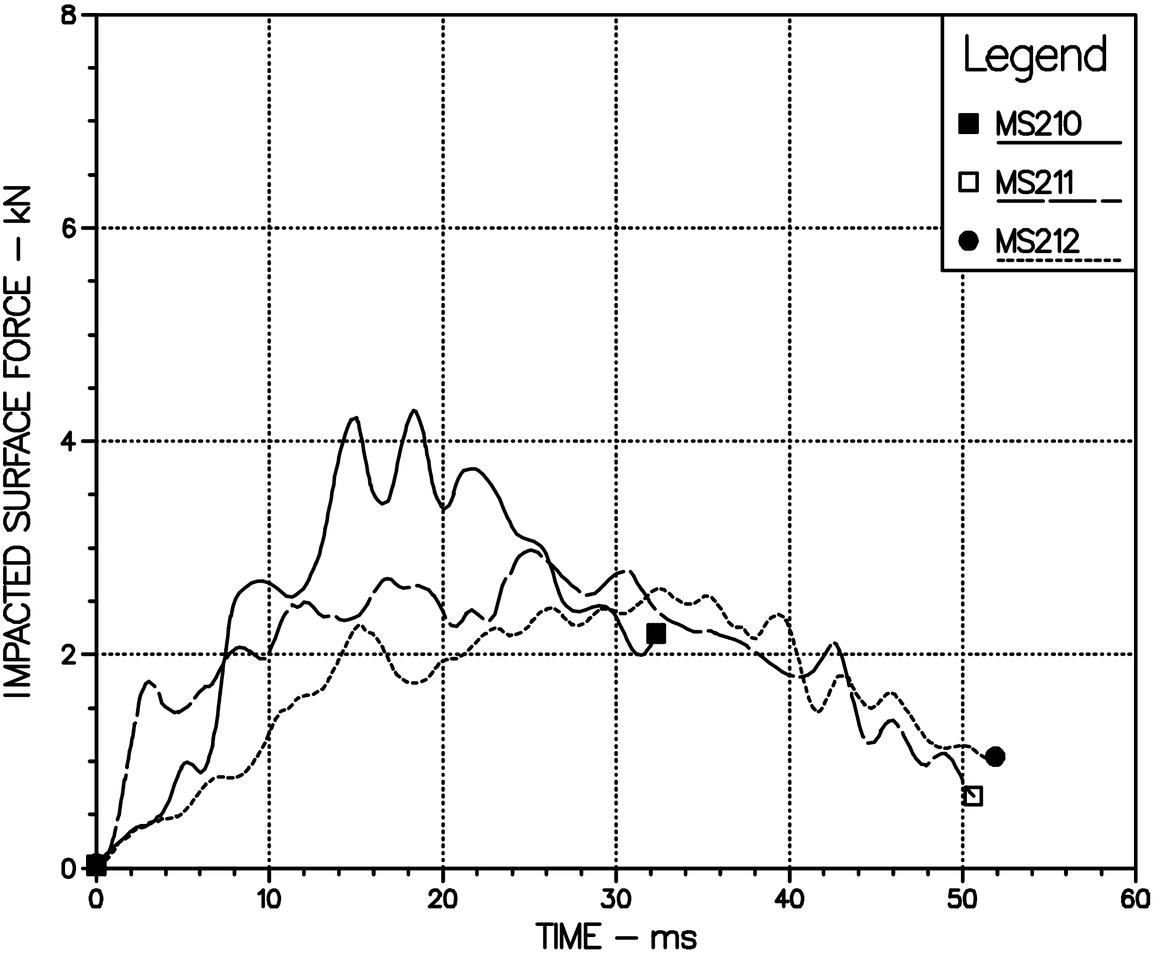


Figure J.8 — Normalized Abdominal impact surface force versus time histories for cadavers subjected to 1 m drops onto a crushable surface

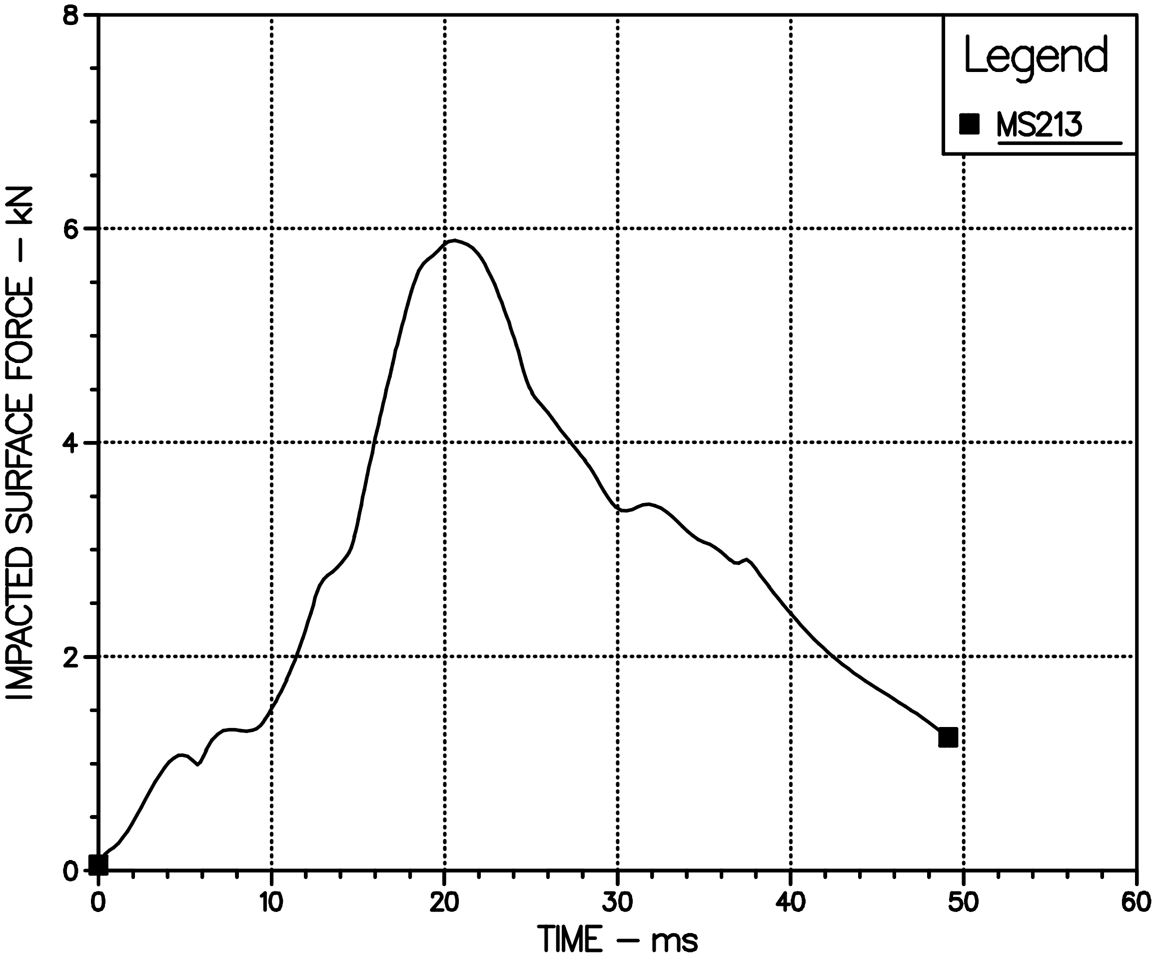


Figure J.9 — Normalized Abdominal impact surface force versus time histories for cadavers subjected to 2 m drops onto a crushable surface

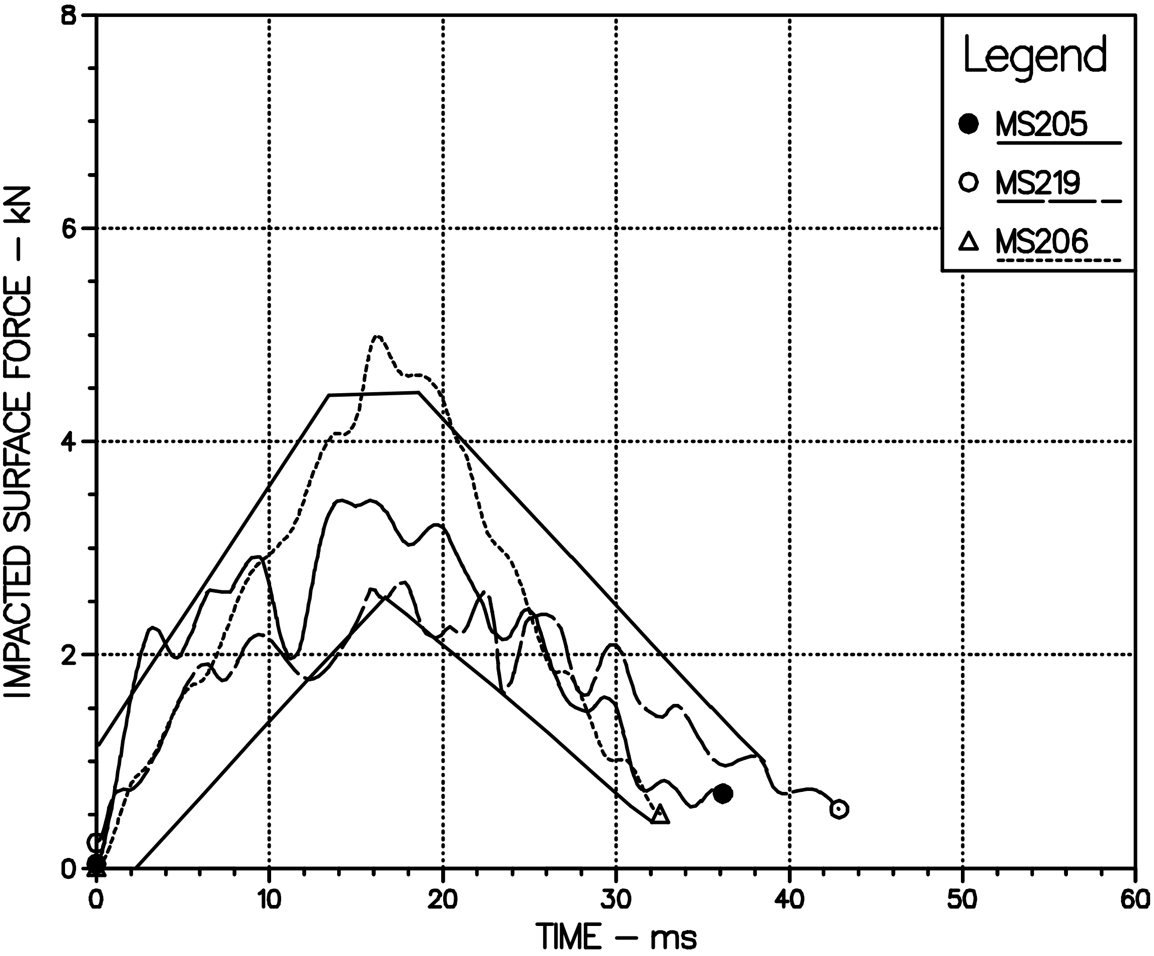


Figure J.10 — Normalized Abdominal impact surface force versus time histories and corridor for 1 m drops onto a rigid surface

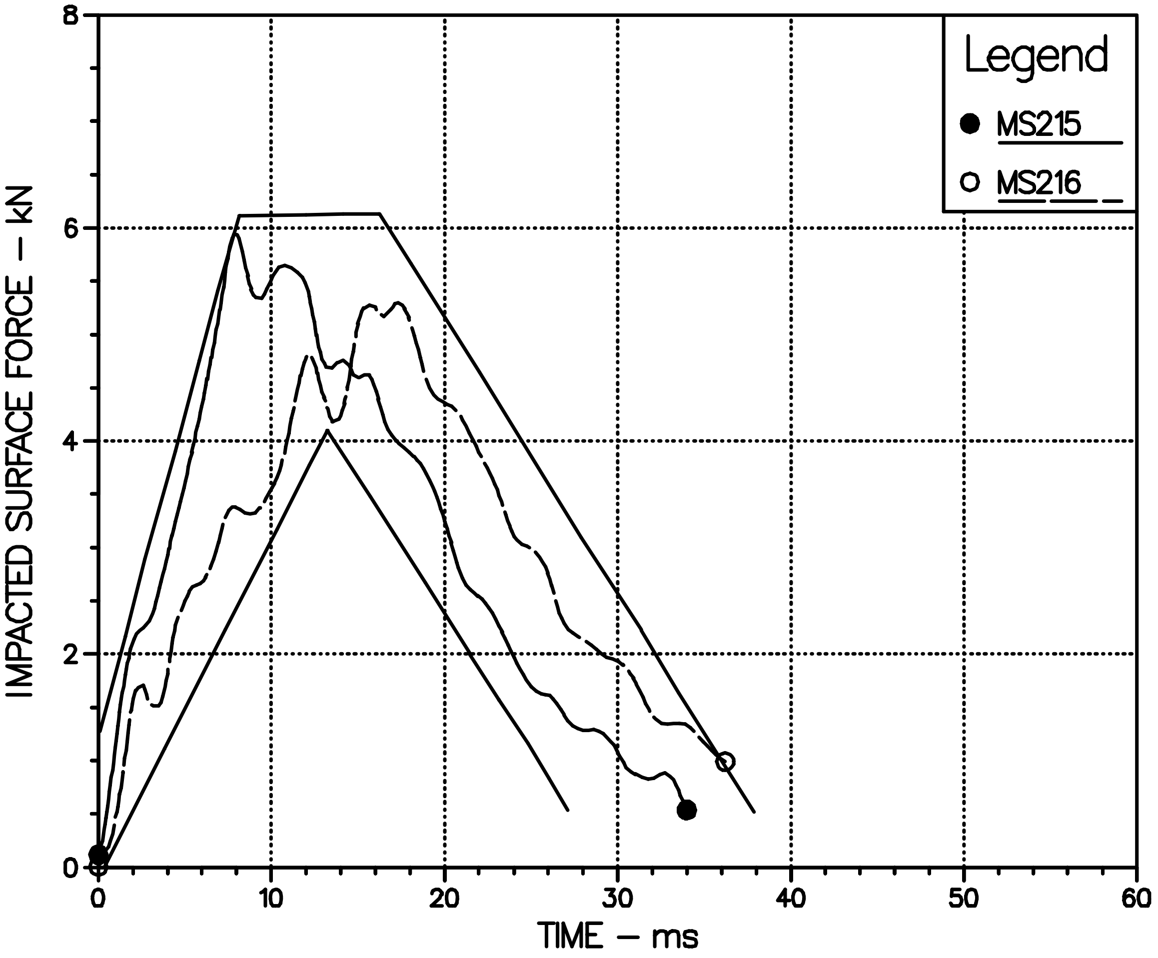


Figure J.11 — Normalized Abdominal impact surface force versus time histories and corridor for 2 m drops onto a rigid surface

Annex K

Analysis of EWING – Lateral neck bending and shoulder displacement data

This annex describes the lateral neck bending response data of Ewing et al. (11) and the biomechanical impact response requirements based on the data.

K.1 Original data

Ewing et al. (11) conducted a series of volunteer, lateral neck bending tests using their HYGE accelerator. The volunteers were seated upright on the HYGE sled fixture, but facing sideways to the direction of sled travel. They were positioned snugly against a lightly padded wooden board which restricted upper torso rotation and supported the torso during sled translation. Both shoulders were restrained by straps. The volunteers' pelves were restrained by a lap belt and an inverted V-pelvis strap which was tied to the lap belt. They held their heads upright prior to sled accelerations.

The data used for this requirement were taken from an analysis by Wismans et al. (12) of 9 tests with 9 subjects. Table K.1 summarizes the most important test conditions. The mean sled acceleration versus time history (together with standard deviation) for these tests are depicted in Figure K.1.

Figure K.2 presents the mean T1 horizontal acceleration versus time history together with the standard deviation. The maximum value of this mean acceleration is 15 G.

Figure K.3 presents the trajectories of the T1 origin relative to the sled. The mean horizontal displacement is 55 mm and the mean vertical (upward) displacement is 17 mm.

Figure K.4 presents the trajectories of the center of gravity of the head relative to T1. Rotations of T1 are neglected here. In other words, the X- and Z-axis in Figure K.4 are parallel to the laboratory horizontal and vertical axis. Note that all trajectories have been shifted such that they coincide initially. Peak horizontal and vertical (downward) displacements of the center of gravity of the head are summarized in Table K.2. The mean values for the horizontal and vertical (downward) displacements are 146 and 79 mm, respectively. Table K.2 also includes the time of maximum head excursion. The mean value for this time is 0,167 s.

Mean values for the acceleration versus time history of the head center of gravity are shown in Figure K.5. The components in the local head coordinate system (x + forward, y + left, and z + upward) are given.

Table K.2 presents the maximum angle of head flexion (i.e. the angle between head inferior-superior axis and vertical) and the maximum angle of head twist (i.e. the rotation about inferior-superior axis) for each test. For these measurements, it is assumed that the T1 target does not rotate. The mean values for these rotations are 51,8° for flexion and -38,6° for twist.

K.2 Response requirements

The average of the volunteers' responses is the best estimate of the response of an average subject. Response requirements are summarized in Table K.3.

Table K.1 — Summary of Test Conditions from the Lateral Neck Bending Tests of Ewing et al. (11)

Test No.	Subject	Peak Sled Acceleration (G)	Rate of Onset (G/s)	Sled Velocity (m/s)
LX4125	H00133	7,2	164	7,02
LX4126	H00134	7,1	167	6,90
LX4129	H00138	7,2	162	6,92
LX4130	H00140	7,1	161	6,89
LX4131	H00135	7,3	164	6,94
LX4133	H00139	7,2	165	6,91
LX4134	H00141	7,1	161	6,85
LX4135	H00142	7,2	161	6,87
LX4153	H00136	7,1	157	6,86
Mean		7,2	162	6,91
Standard Deviation		0,1	3	0,05

Table K.2 — Peak Displacements of the Center of Gravity of the Head with Respect to T1, Time of Maximum Excursions and the Maximum Angles of Flexion and Twist from the Lateral Neck Bending Tests of Ewing et al. (11)

Test Number	Subject	X_{max} (mm)	Time of X_{max} (s)	Z_{max} (mm)	Flexion[a] (degrees)	Twist[a] (degrees)
LX4125	H00133	137	0,174	68	52,3	-26,4
LX4126	H00134	129	0,166	72	49,5	-39,8
LX4129	H00138	168	0,172	100	57,3	-38,2
LX4130	H00140	155	0,166	79	41,7	-40,2
LX4131	H00135	122	0,168	61	41,7	-35,6
LX4133	H00139	134	0,148	70	67,6	-33,2
LX4134	H00141	158	0,170	106	51,6	-42,8
LX4135	H00142	152	0,177	80	52,2	-42,3
LX4153	H00136	157	0,166	76	52,3	-49,3
Mean		146	0,167	79	51,8	-38,6
Standard Deviation		16	0,008	15	7,8	6,5

[a] T1 is assumed not to rotate

Table K.3 — Neck Response Requirements for the Lateral Neck Bending Test Determined from the Response Data of Ewing et al. (11), as Analyzed by Wismans et al. (12)

Measurement	Units	Lower Bound	Upper Bound
Peak Horizontal Acceleration of T1	G	12	18
Peak Horizontal Displacement of T1 Relative to the Sled	mm	46	63
Peak Horizontal Displacement of the Head C,G, Relative to T1	mm	130	162
Peak Vertical Displacement of the Head C,G, Relative to T1	mm	64	94
Time of Peak Head Excursion	s	0,159	0,175
Peak Lateral Acceleration of the Head	G	8	11
Peak Vertical (Downward) Acceleration of the Head	G	8	10
Peak Flexion Angle	degrees	44	59
Peak Twist Angle	degrees	-45	-32

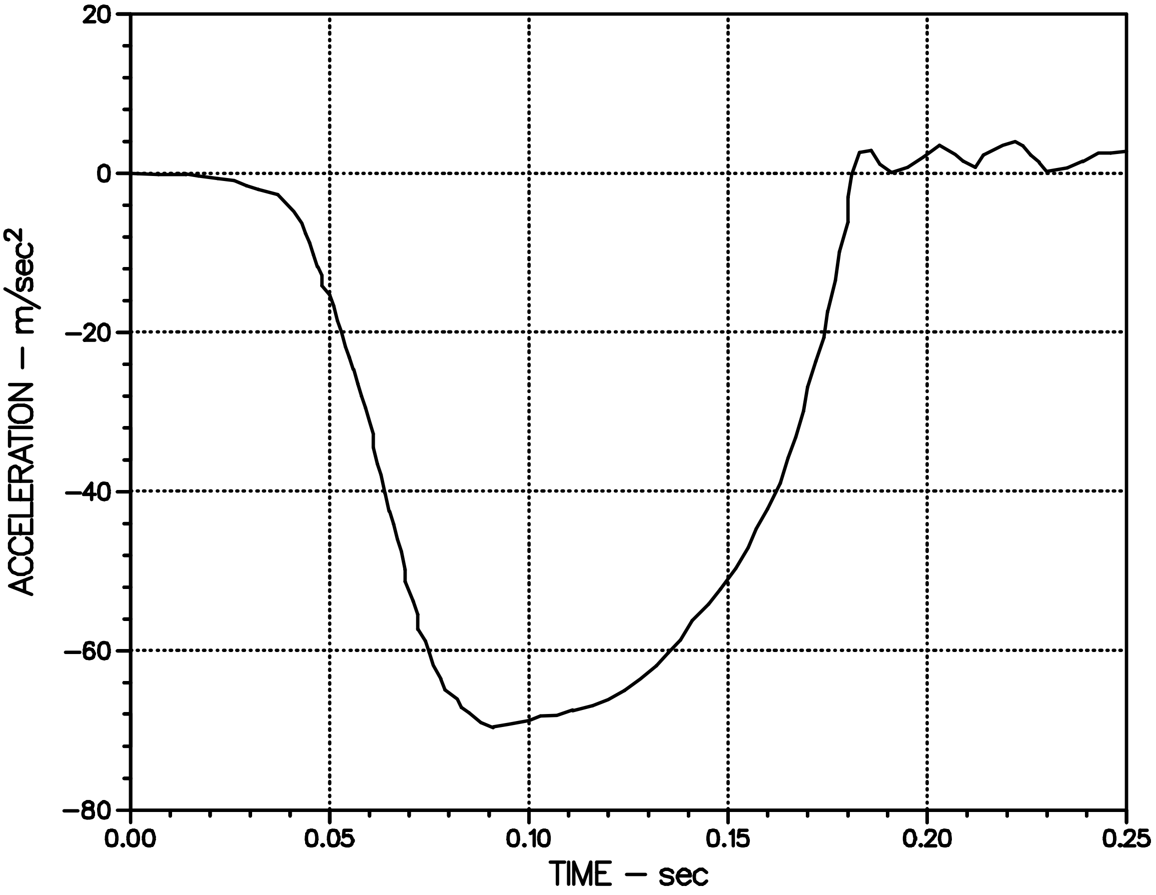


Figure K.1 — Mean Sled Acceleration Versus Time History

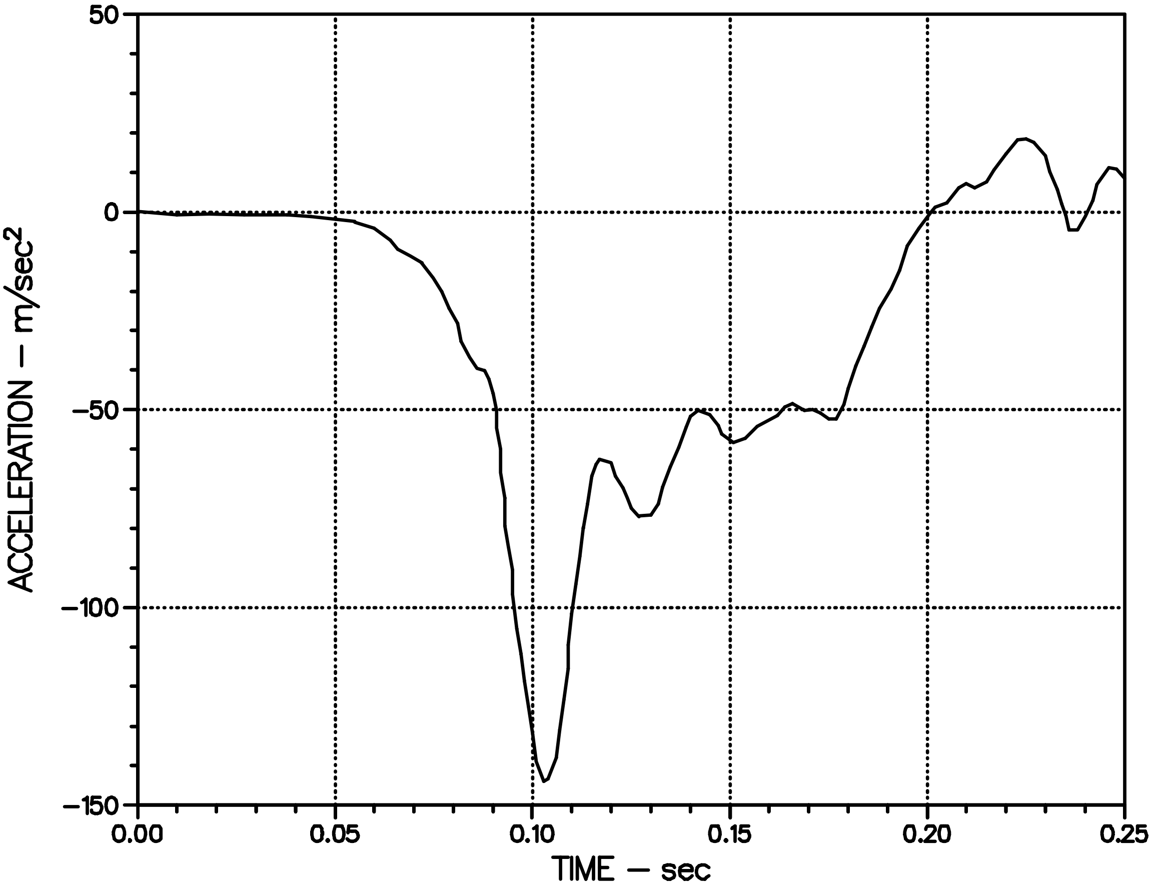


Figure K.2 — Mean Horizontal T1 Acceleration Versus Time History

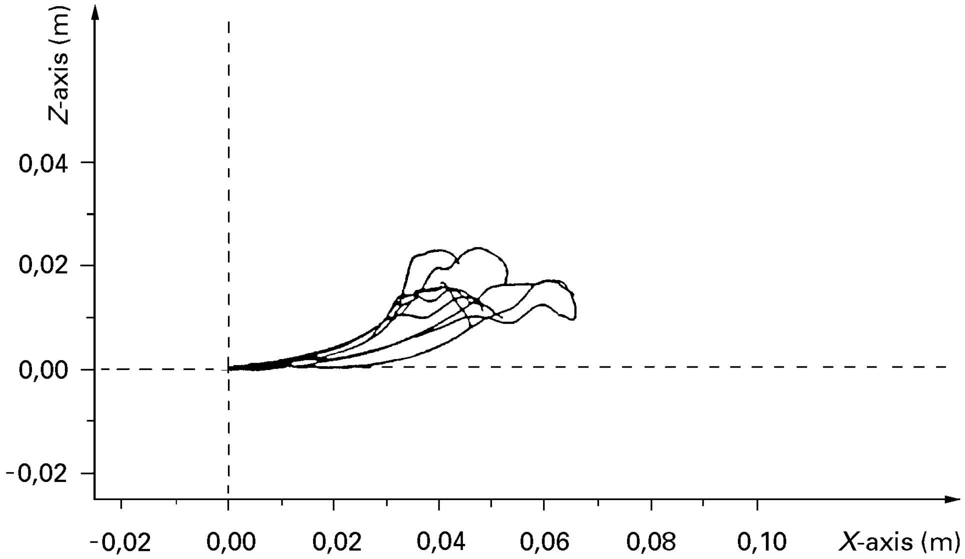


Figure K.3 — T1 Origin Trajectories with Respect to the Sled

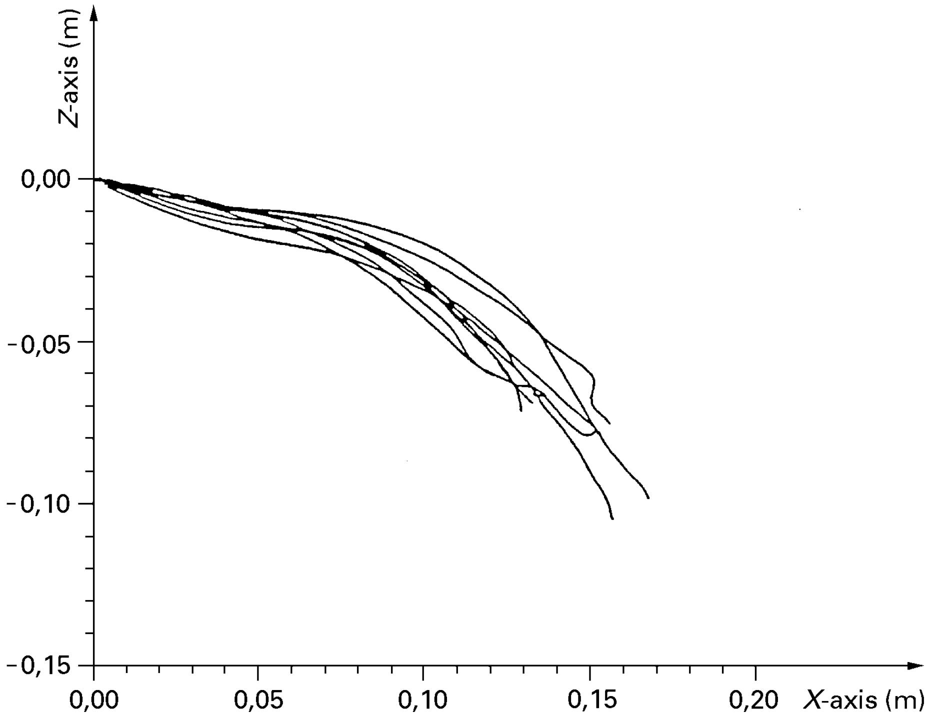


Figure K.4 — Head Center of Gravity Trajectories with Respect to T1 (T1 rotations are neglected)

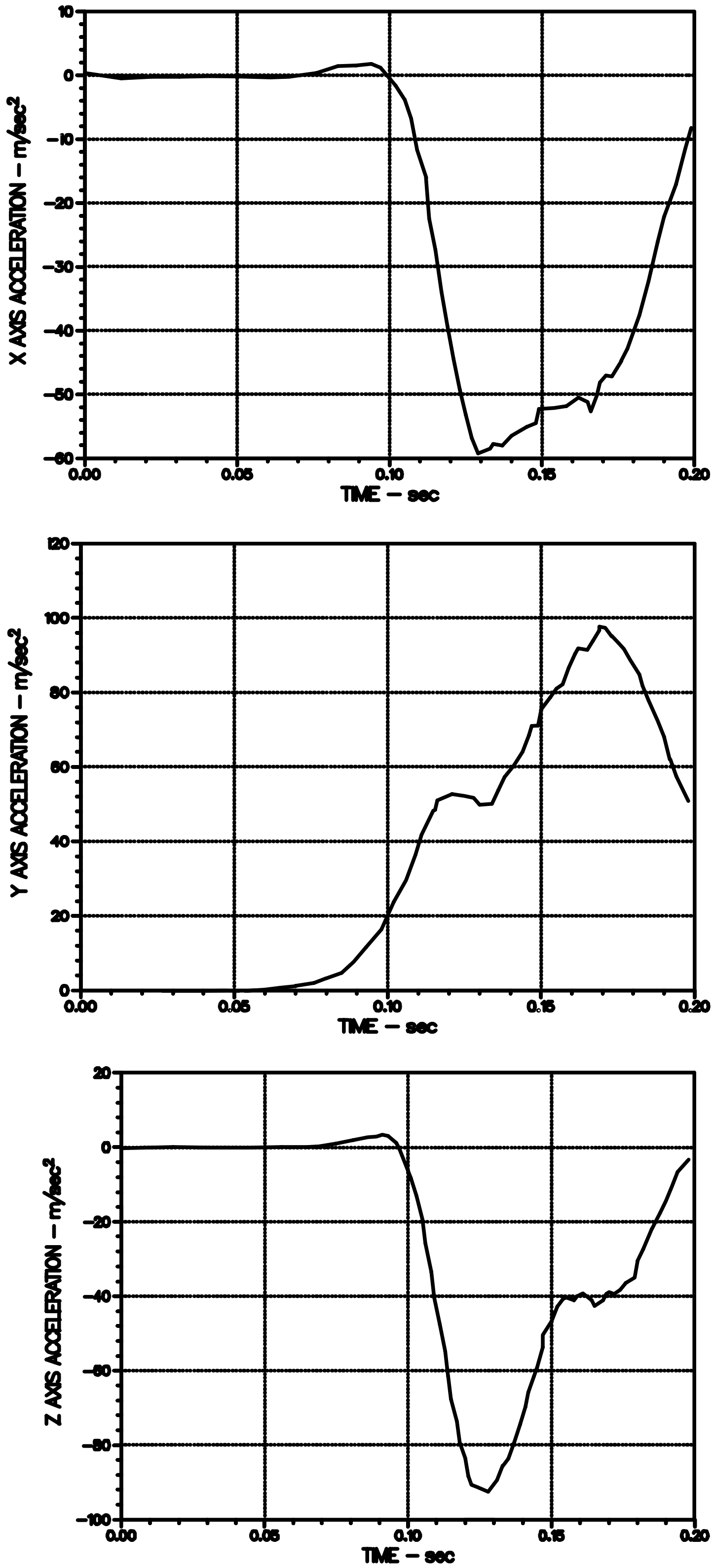


Figure K.5 — Mean Head Center of Gravity Acceleration Versus Time Histories: Components in Head Local x, y, and z Direction

Annex L

Analysis of Patrick and Chou — Lateral neck bending response data

This annex describes the lateral neck bending response data of Patrick and Chou (13) and the biomechanical impact response requirements based on the data.

L.1 Original data

Patrick and Chou (13) conducted a series of volunteer, lateral neck bending tests using their decelerator sled, the WHAM III. A rigid seat with a 15° seat back angle was attached to the sled, sideways to the direction of travel. One side of the seat had a rigid, vertically oriented, side support which restricted upper torso rotation and supported the torso during sled translation. The volunteer was seated in the chair with his shoulder and hip against the side board. A belt restraint system consisting of cross chest shoulder straps, lap strap, crotch strap and a horizontal chest strap was used to secure the volunteer to the seat. The sled was accelerated gently over a 60 foot distance and then abruptly decelerated at a prescribed constant deceleration level with a hydraulic shock absorber.

The data from the most severe test, SAE 156, were used to specify the dummy response requirement. In that test, the sled velocity was 5,8 m/s and its constant deceleration level was 6,7 G. Figure L.1 shows the volunteer's internal neck bending moment calculated about the anterior-posterior axis, lying in the midsagittal plane of the head, at the level of the occipital condyles, as a function of the angular displacement of the head relative to the torso. The other test results are given in Table L.1.

L.2 Response requirements

The response requirements were based on the results of the single, severe test and are given in Table L.1.

Table L.1 — Neck Response Data from the Lateral Neck Bending Tests of Patrick and Chou (13) and the Neck Response Requirements Based on These Data

Measurement (Units)	Test SAE156	Lower Bound	Upper Bound
Peak Flexion Angle (degrees)	43,2	40	50
Peak Bending Moment about A-P Axis at Occipital Condyles (N·m)	45,2	40	50
Peak Bending Moment about R-L Axis at Occipital Condyles (N·m)	26,2	20	30
Peak Twist Moment (N·m)	17,4	15	20
Peak Shear Force at Occipital Condyles (N)	794	750	850
Peak Tension Force at Occipital Condyles (N)	387	350	400
Peak P-A Shear Force (N)	351	325	375
Peak Resultant Head Acceleration (G)	21	18	24

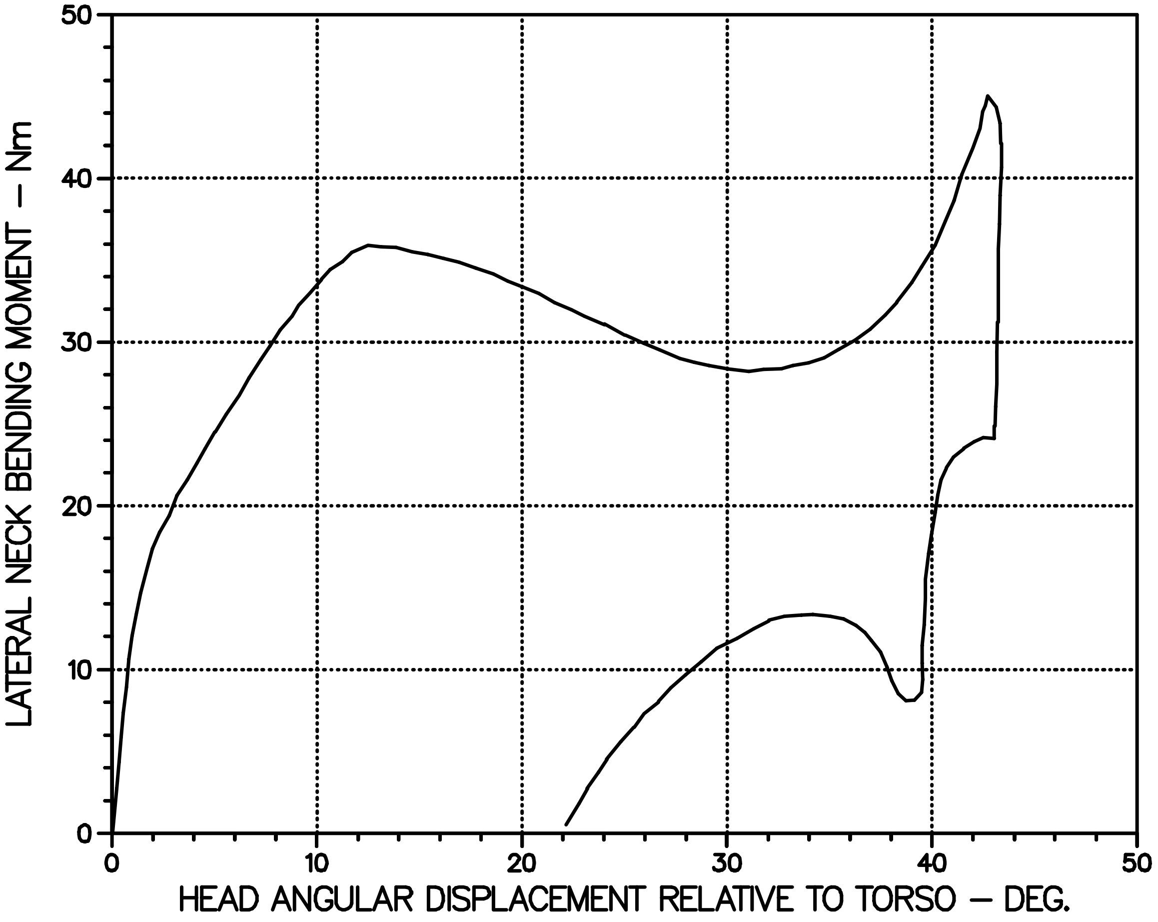


Figure L.1 — Lateral Neck Bending Moment Measured at the Occipital Condyles as a Function of the Head Angular Displacement Relative to the Torso for Human Volunteer KJD, Test SAE 156

Annex M

Analysis of TARRIERE lateral neck bending response data

This annex describes the lateral neck bending response data of Tarriere (30) and the biomechanical impact response requirements based on the data.

M.1 Original data

Tarriere (30) conducted four high G-level cadaver tests to obtain data that could be used to define lateral neck bending response in a test environment of greater severity than used for volunteer testing. A summary of the sled kinematics and cadaver responses is given in Table M.1. Unfortunately, each test had an abnormality. The cadaver's neck was fractured in Test MS 249. The cadaver was not initially against the side board in Test MS 297. The cadaver's humerus was fractured in Test MS 360. The shoulder straps were not fastened in Test MS 361. Tarriere selected Test MS 249 as being the most appropriate test to use for defining a set of high-G response requirements. Based on ratios of cadaver response compared to volunteer response obtained for low-G sled tests, the cadaver data for maximum horizontal and vertical head displacement and peak head flexion and torsion angles were modified by Tarriere to reflect human response. These values were 205,8 mm, 102,9 mm, 86,6°, 68,6°, respectively. No corrections were made to the accelerations of the head or T1.

M.2 Response requirements

The response requirements were based on the results of the single, severe test and are given in Table M.2. The corridor for the sled pulse is shown in Figure M.1.

Table M.1 — Results of the High G-Level Lateral Neck Bending Sled Tests of Tarriere (30)

	Test Number			
Measurement (Units)	MS 249	MS 297	MS 361	MS 360
Peak Sled Deceleration (G)	12,2	14,2	14,0	14,6
Initial Sled Velocity (m/s)	6,08	6,19	6,25	8,61
Peak Horizontal Acceleration of T1 (G)	20	44	31,5	34,4
Peak Horizontal Acceleration of Head C.G, (G)	36	17,3	8,2	9,7
Head Lateral Flexion (degrees)	78	36	59	78
Peak Head Torsion (degrees)	42	30	70	102
Peak Horizontal Displacement of Head C.G, Relative to the Sled (mm)	294	445	260	415
Peak Vertical Displacement of Head C.G, Relative to the Sled (mm)	79	78	64	110
Peak Horizontal Velocity of Head C.G, Relative to the Sled (m/s)	4,3	5,3	4,8	5,7

Table M.2 — Modified Neck Response Data from the Lateral Neck Bending Tests of Tarriere (30) and the Neck Response Requirements Based on These Data

Measurement (Units)	MS 249	Lower Bound	Upper Bound
Peak Lateral Acceleration of T1 (G)	20	17	23
Peak Lateral Acceleration of the Head C.G. (G)	36	25	47
Peak Horizontal Displacement of the Head C.G. Relative to the Sled (mm)	206 [a]	185	226
Peak Flexion Angle (degrees)	68,6 [a]	62	75
Peak Twist Angle (degrees)	68,6	62	75
[a] Modified by Tarriere			

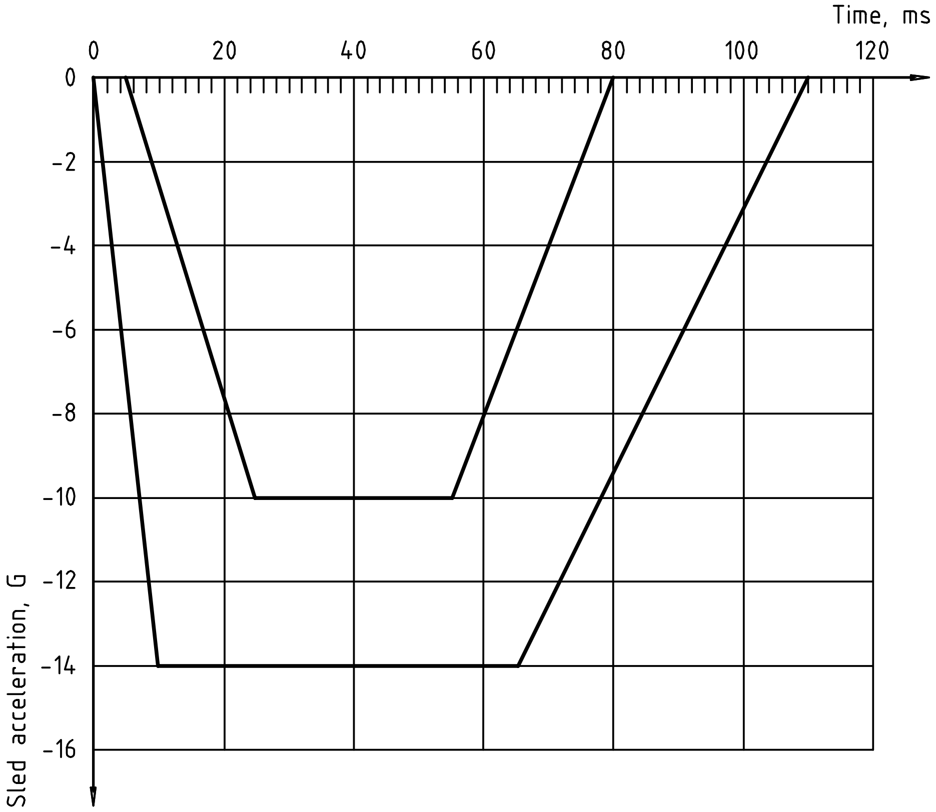


Figure M.1 — Corridor for the Sled Acceleration

Annex N

Analysis of University of Heidelberg — Lateral Thoracic impact data

This annex describes the application of the normalization techniques of Mertz (17) to the lateral thoracic impact data collected by researchers of the University of Heidelberg (23) and the definition of biomechanical impact response requirements based on the normalized data.

N.1 Original Data

A series of cadaver sled tests was conducted at the University of Heidelberg for the NHTSA (23). The unembalmed cadavers were each instrumented with accelerometers on T1, T12 and the 4th rib on the impacted side. The thoracic and pelvic impact surfaces were instrumented to measure the contact forces.

Each cadaver was seated on a low-friction bench that was mounted sideways to the direction of sled travel. The cadavers were positioned 1 m from a vertical side panel and slid into it upon rapid sled deceleration. In all tests, the side panel was stopped prior to the cadaver striking it. For the 6,8 m/s rigid surface impact tests, the side panel was of sufficient height to allow the cadaver's head to strike it. For the 8,9 m/s tests, the impact surface was 540 mm high, measured from the seat pan. Each padded impact consisted of a 140 mm high padded block at the level of the seat pan and a similar block at the top of the impact surface.

Table N.1 summarizes the cadaver data and test conditions for the Heidelberg lateral sled tests. Table N.2 summarizes the peak lateral accelerations of T1, T12 and the 4th rib on the impacted side. The loads of the thoracic impact surface are shown in Figures N.1, N.2, and N.3 for the 6,8 m/s rigid, 8,9 m/s rigid and 8,9 m/s padded tests, respectively. The accelerations and loads were filtered using a 100 Hz Finite Impulse Response (FIR) filter (18).

N.2 Normalized data

The technique described by Mertz (17) was used to normalize the force versus time histories and the peak thoracic accelerations to represent the response characteristics of a 50th percentile adult male. If the normalization procedure was exact, then for each impact configuration, every normalized cadaver curve would map onto a single response curve. This curve would be the force versus time history of a 50th percentile adult male.

The effective thoracic mass, M_e, for each cadaver was calculated from the following equation,

$$M_e = \left[\int_0^T F dt \right] \Big/ V_0 \qquad \text{(N.1)}$$

where $\int_0^T F dt$ is the impulse, V_0 is the impact velocity and T is the pulse duration corresponding to a velocity change of V_0.

The effective thoracic masses for the cadavers subjected to the 6,8 m/s rigid, 8,9 m/s rigid and 8,9 m/s padded impacts are given in Table N.2. An effective thoracic mass of 38 kg was chosen for a 50th percentile adult male. This is 50% of the total body mass of a 50th percentile adult male and is within the range of percent body mass for the cadavers.

The characteristic ratio for the effective thoracic mass, R_m, is defined as,

$$R_m = 38\,\text{kg}/M_e \qquad \text{(N.2)}$$

The calculated mass ratios are given in Table N.2.

The stiffness ratio, R_k, is defined as,

$$R_k = K_s / K_i \tag{N.3}$$

where K_s is the stiffness of the standard subject and K_i is the stiffness of the i-th subject. Mertz (17) has shown that for geometrically similar structures with the same elastic modulus, the stiffness is proportional to the characteristic length. The thoracic depth was the characteristic length chosen for the normalization of these data. For a 50th percentile adult male, this length is 236 mm. The characteristic ratio for the thoracic stiffness, R_k, was calculated by,

$$R_k = 236\,\text{mm} / L_i \tag{N.4}$$

where L is the chest depth of the cadaver whose data were to be normalized. The stiffness ratios for the cadavers are given in Table N.2.

The normalizing factors for force, R_f, acceleration, R_a, and time, R_t, were calculated from the equations given by Mertz (17),

$$R_f = (R_m R_k)^{1/2} \tag{N.5}$$

$$R_a = (R_k / R_m)^{1/2} \tag{N.6}$$

$$R_t = (R_m / R_k)^{1/2} \tag{N.7}$$

The characteristic ratios and normalizing factors for each cadaver are given in Table N.2. The normalized force versus time histories were obtained by multiplying each value of force by its force normalizing factor and each value of time by its time normalizing factor. Figures N.4, N.5 and N.6 show the normalized force versus time histories for the 6,8 m/s rigid, 8,9 m/s rigid, and 8,9 m/s padded impacts, respectively. The normalized peak lateral accelerations of T1, T12 and the 4th rib on the impacted side were obtained by multiplying the respective peak lateral acceleration values by the acceleration normalizing factor for that cadaver. The normalized peak lateral accelerations are given in Table N.2.

N.3 Inclusion of massively damaged cadavers

Table N.1 gives the number of ribs fractured for each cadaver. Note that each fractured rib may have one or more fractures. The response requirements were established from all cadavers subjected to the 6,8 m/s rigid impact. If the results of cadavers sustaining 6 or more rib fractures were eliminated, than the response corridor would be based on one cadaver (H-82-015) that appeared to be quite stiff. If the results of this stiff cadaver were excluded, than the response corridor would be based only on cadavers sustaining massive damage to the rib cage.

N.4 Response requirements

The normalized cadaver response for each impact configuration is the best estimate of the normalized response of the 50th percentile adult male. Response requirements for the side impact test device consist of a corridor around the normalized cadaver force versus time history and ranges for the peak normalized lateral accelerations of T1, T12 and the 4th rib on the impacted side.

Figure N.7 shows the force versus time response corridors for the 6,8 m/s rigid impact. This corridor was constructed around the normalized cadaver curves which are also shown. The normalized force versus time curves of the side impact dummies should lie within the corridor.

Due to the sparsity of the data, deviations of ±20% of the peak normalized accelerations were used to define requirements for peak lateral accelerations of T1, T12 and the 4th rib on the impacted side. The proposed range for the peak normalized lateral acceleration of T1 is 82 to 122 G. The proposed range for the peak normalized lateral acceleration of T12 is 71 to 107 G. The proposed range for the peak normalized lateral acceleration of the impacted rib is 64 to 100 G. The corresponding normalized peak lateral accelerations of any side impact dummy should lie within their corresponding ranges.

Table N.1 — Cadaver Data and Test Conditions from the Lateral Sled Tests Performed by the University of Heidelberg (23)

Test No.	Cadaver Data						Test Conditions	
	Age	**Sex**	**Mass** (kg)	**Height** (m)	**Chest Depth** (mm)	**Number of Ribs** Fractured	**Impact Velocity** (m/s)	**Impact Surface**
H-82-015	18	M	69	1,82	190	2	6,8	rigid
H-82-018	28	F	85	1,81	240	9	6,8	rigid
H-82-019	47	F	67	1,65	210	7	6,8	rigid
H-82-014	22	F	61	1,78	200	12	8,9	rigid
H-82-016	21	M	50	1,87	200	8	8,9	rigid
H-82-021	48	M	99	1,80	260	13	8,9	padded
H-82-022	50	M	77	1,67	220	15	8,9	padded

Table N.2 — Test Results from the Lateral Sled Tests Performed by the University of Heidelberg (23); and Effective Mass, Characteristic Ratios, Normalizing Factors, and Normalized Test Results for These Data

Test No.	Test Results			Effective Mass		Character. Ratios		Normalizing Factors			Normalized Test Results		
	T1 Accel. (G)	**T12 Accel.** (G)	**Rib 4 Accel.** (G)	M_e (kg)	**Body mass** (%)	**Mass** R_m	**Stiff.** R_k	**Force** R_f	**Accel** R_a	**Time** R_t	**T1 Accel.** (G)	**T12 Accel.** (G)	**Rib 4 Accel.** (G)
H-82-015	92	98	81	36	52,2	1,06	1,24	1,15	1,08	0,92	99	106	87
H-82-018	84	71	62	42	49,4	0,90	0,98	0,94	1,04	0,96	87	74	64
H-82-019	116	85	93	37	55,2	1,03	1,12	1,07	1,04	0,96	121	88	97
H-82-014	127	189	168	33	54,1	1,15	1,18	1,16	1,01	0,99	128	191	170
H-82-016	45	135	169	30	60,0	1,27	1,18	1,22	0,96	1,04	43	130	162
H-82-021	61	74	55	50	50,5	0,76	0,91	0,83	1,09	0,91	66	81	60
H-82-022	84	109	104	47	61,0	0,81	1,07	0,93	1,15	0,87	97	125	120

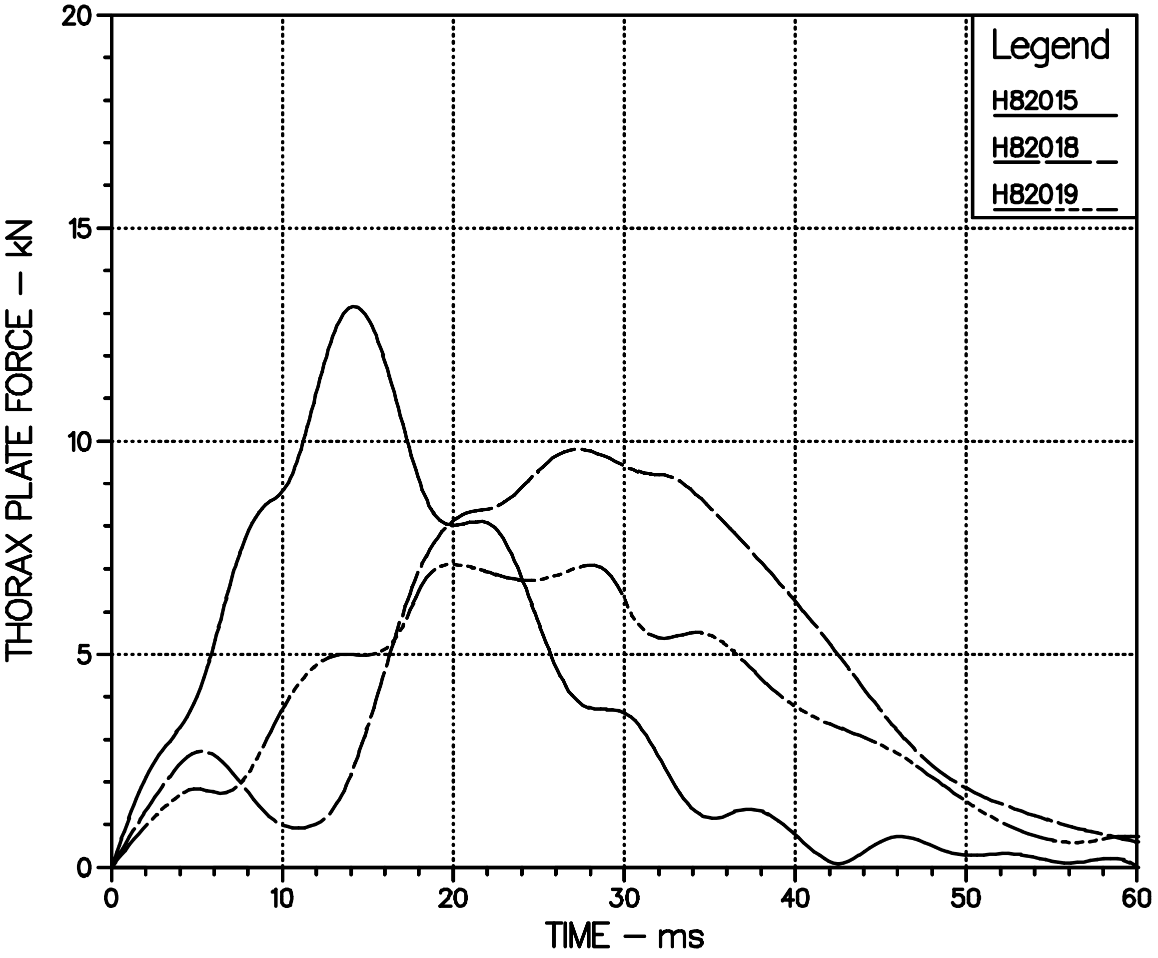


Figure N.1 — Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to a 6,8 m/s Rigid Wall Impact

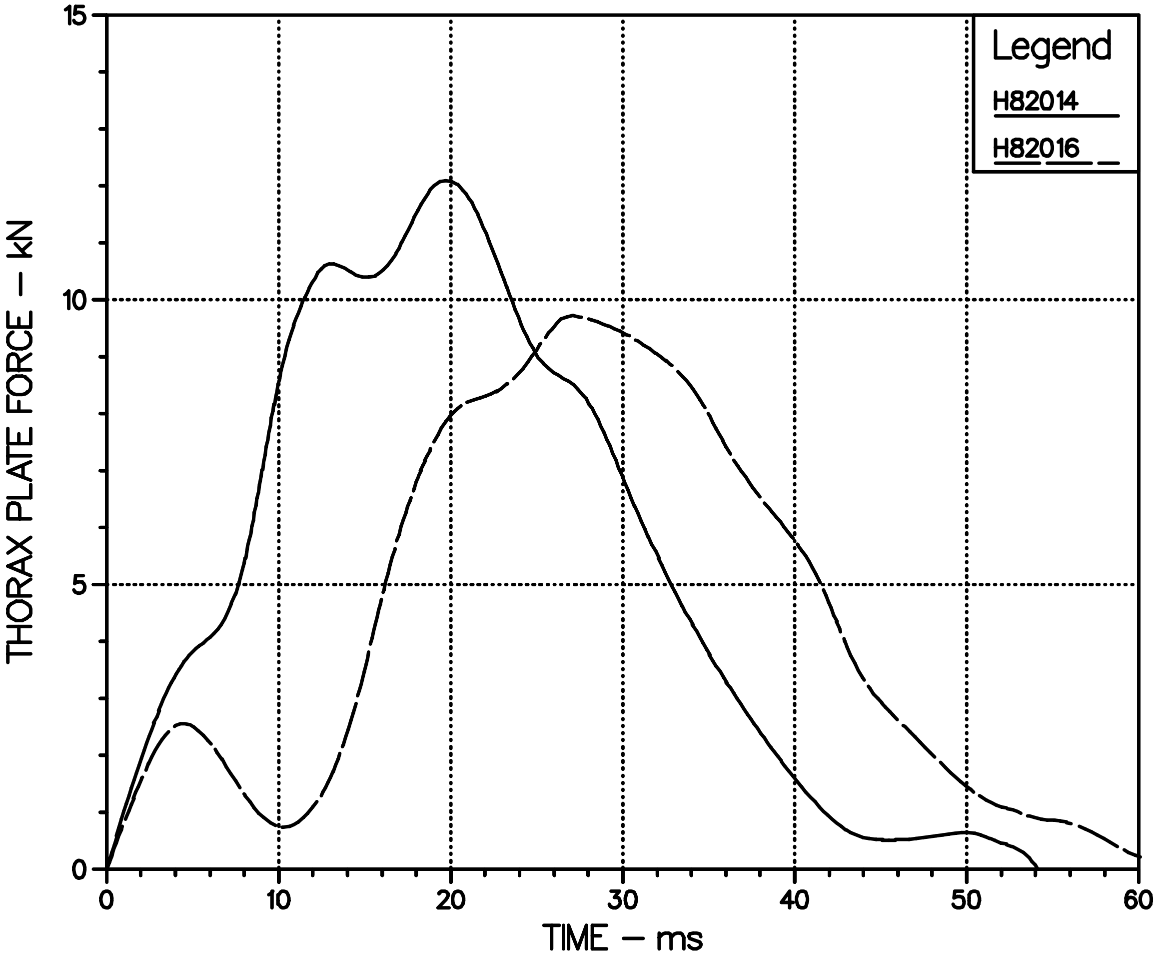


Figure N.2 — Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to a 8,9 m/s Rigid Wall Impact

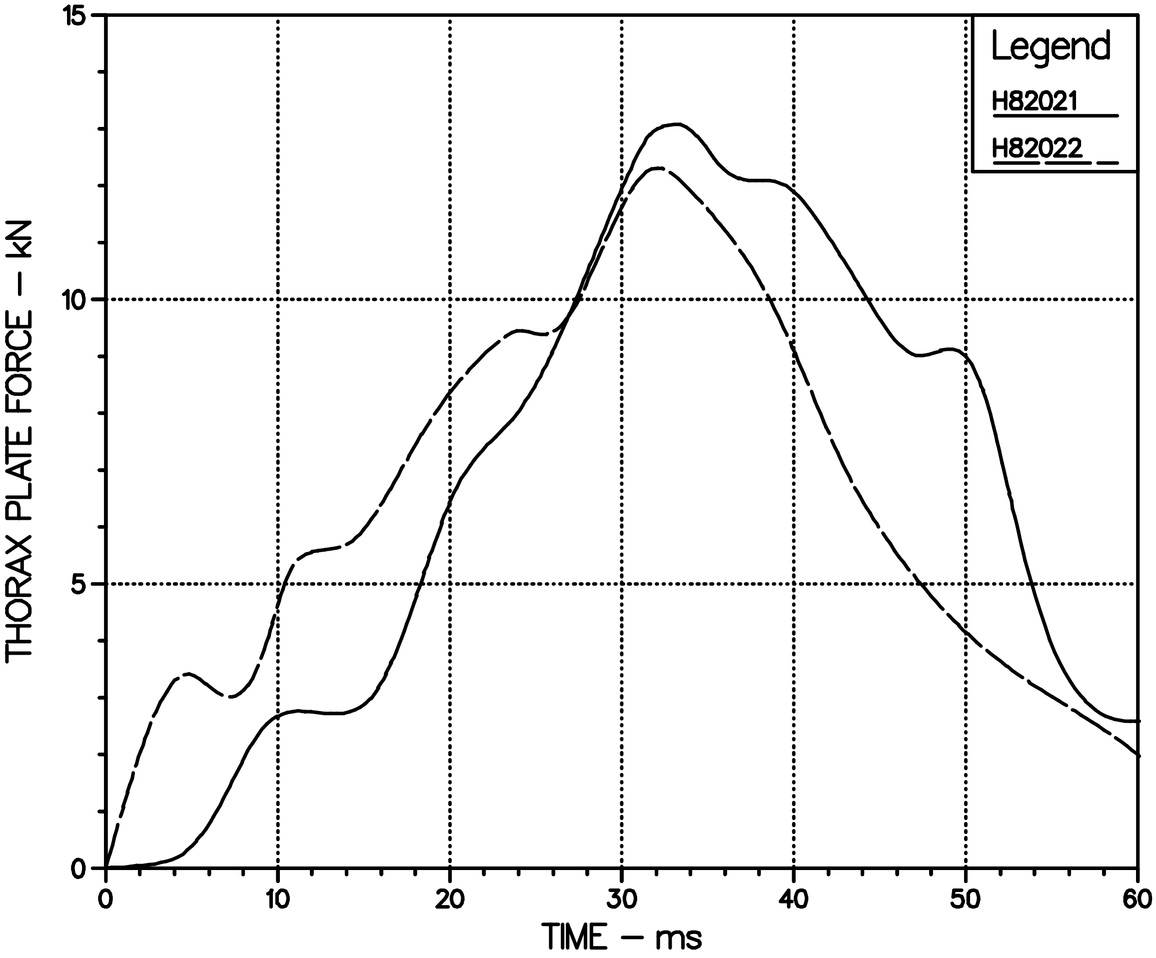


Figure N.3 — Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to a 8,9 m/s APR Padded Wall Impact.

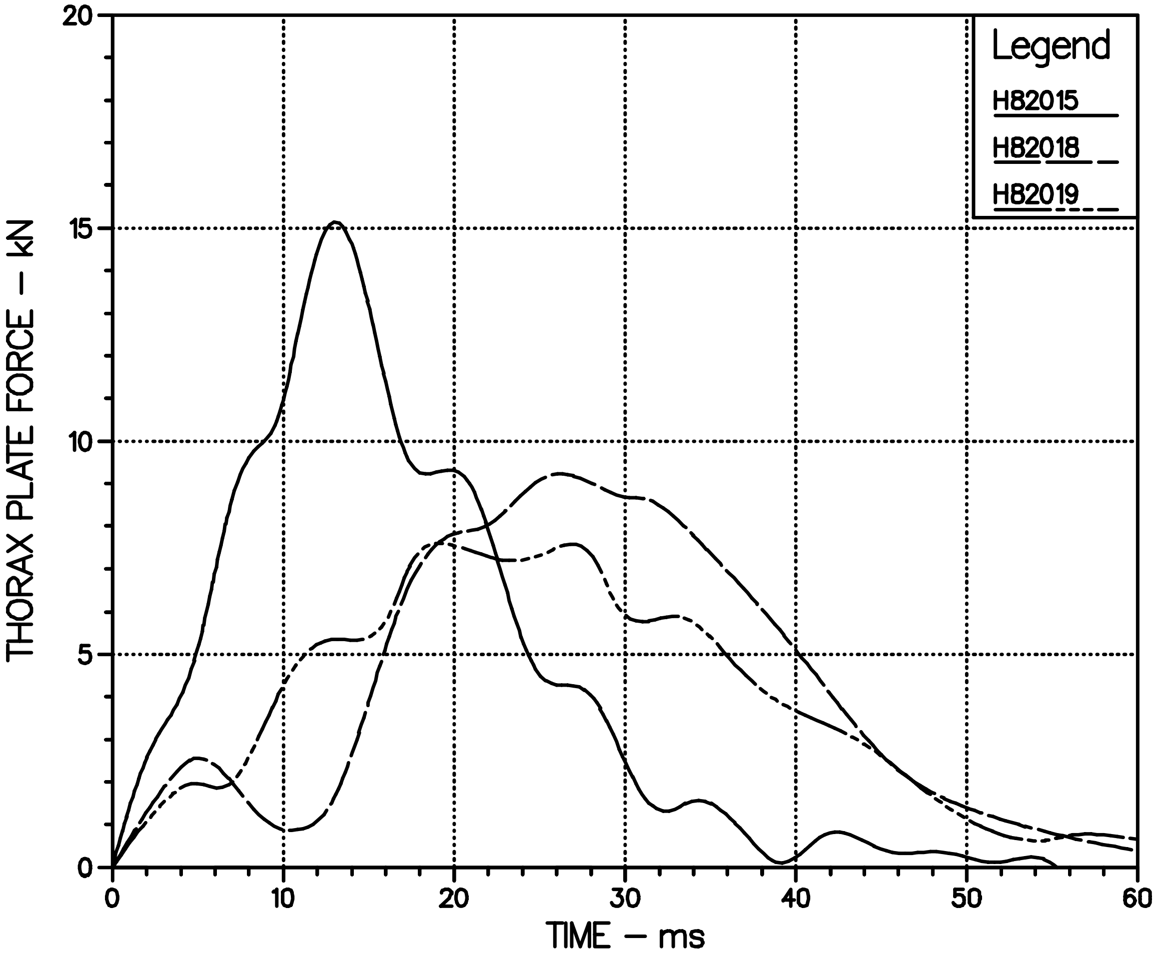


Figure N.4 — Normalized Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to a 6,8 m/s Rigid Wall Impact

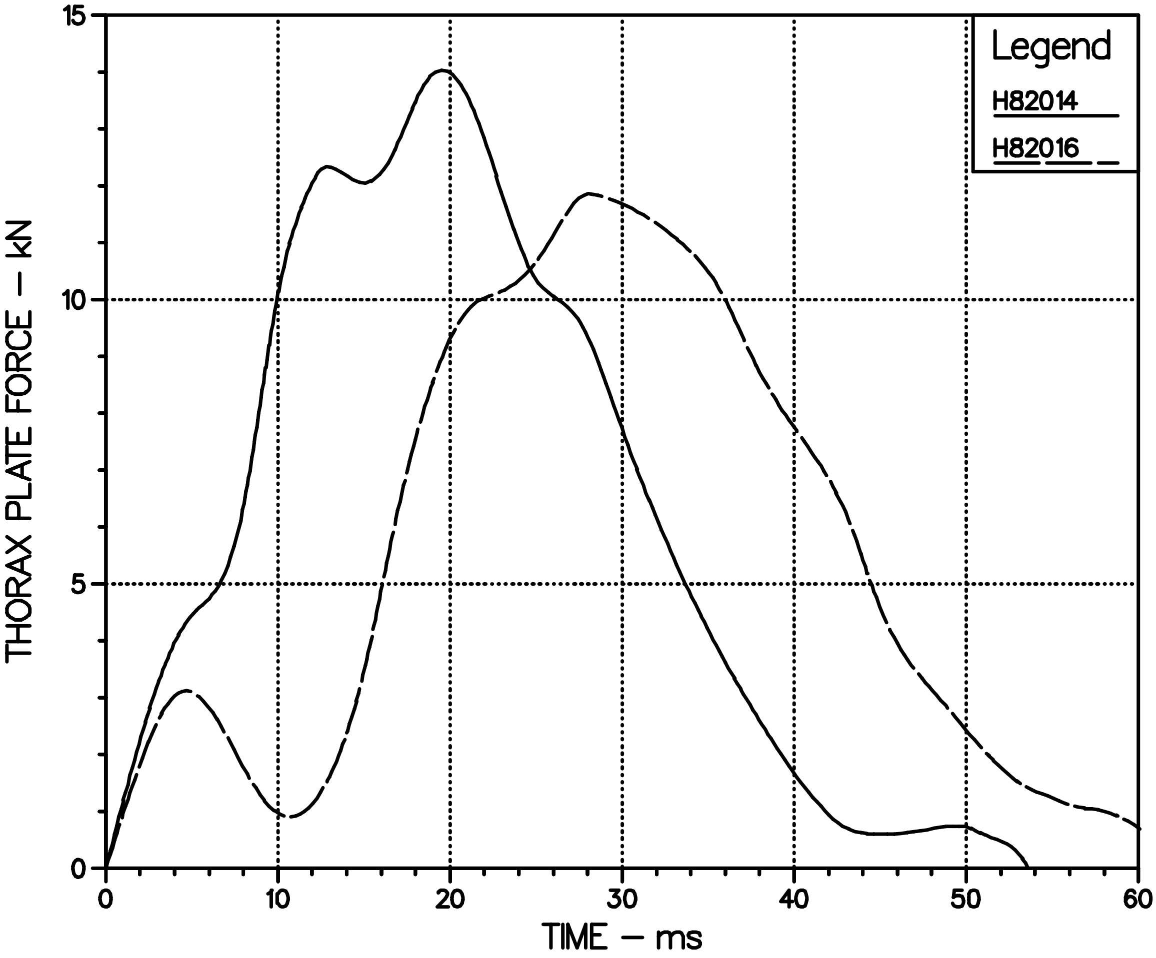


Figure N.5 — Normalized Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to a 8,9 m/s Rigid Wall Impact

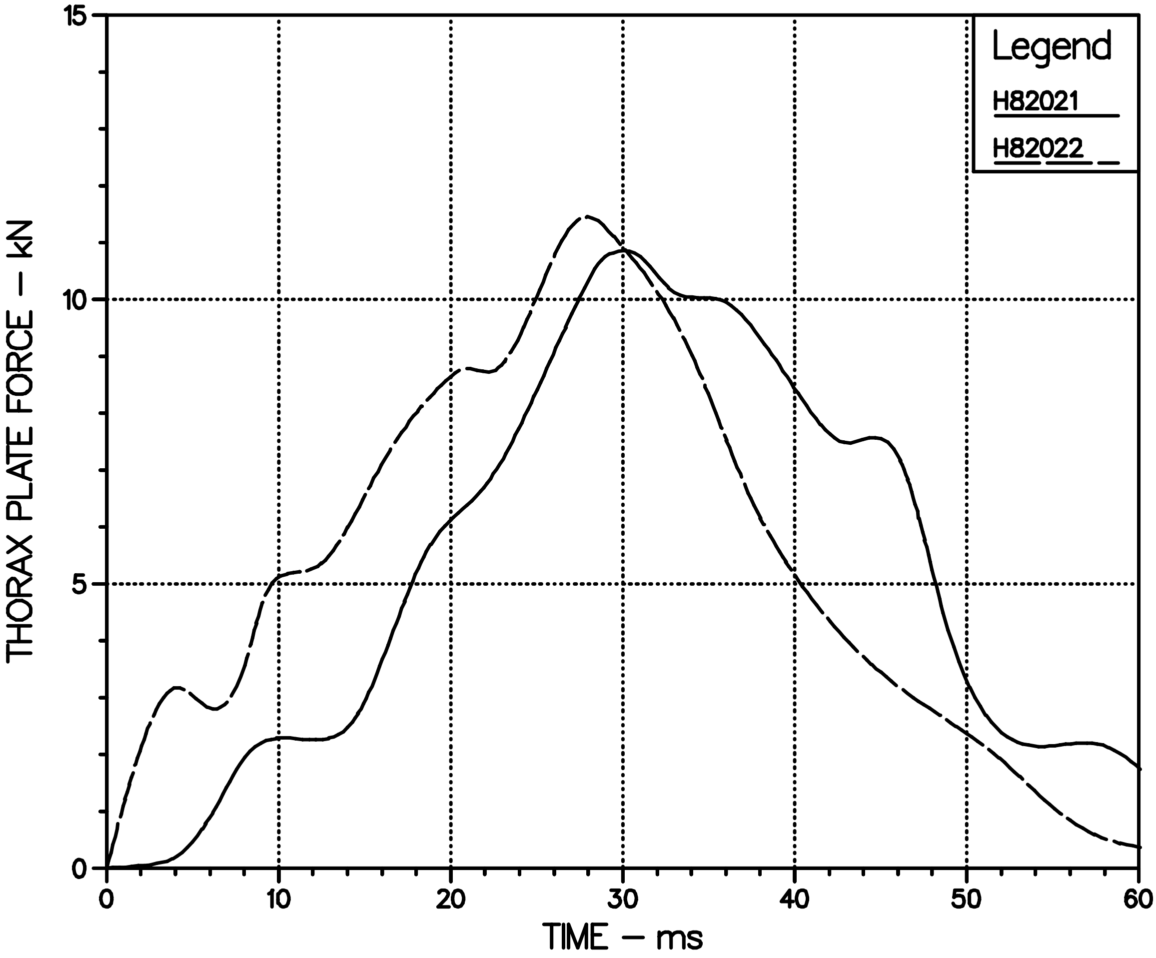


Figure N.6 — Normalized Thoracic Impact Surface Force Versus Time Histories for Cadavers Subjected to a 8,9 m/s APR Padded Wall Impact

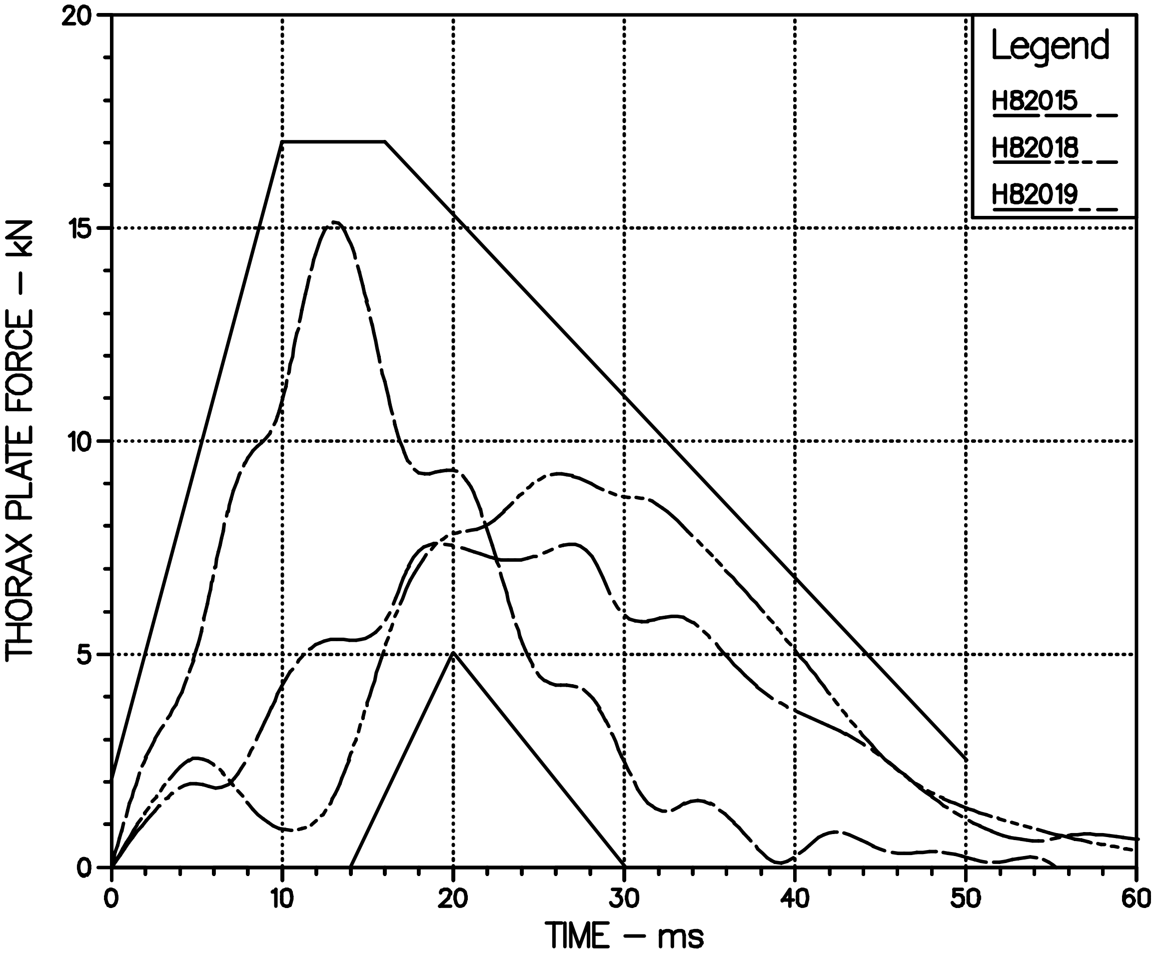


Figure N.7 — Normalized Thoracic Impact Surface Force Versus Time History and Proposed Response Corridor for a 6,8 m/s Rigid Wall Impact

Annex O

Analysis of University of Heidelberg — Lateral pelvic impact data

This annex describes the application of the normalization techniques of Mertz (17) to the lateral pelvic impact data collected in two studies at the University of Heidelberg (23). Data from these tests were provided by NHTSA who funded the studies.

O.1 Original Data

In the first study, researchers of the University of Heidelberg subjected 10 unembalmed cadavers to lateral impacts at either 6,8 m/s into a rigid surface, or 8,9 m/s into either rigid or padded surfaces. Each cadaver was instrumented with 24 accelerometers, three of which provided triaxial acceleration measurements of the pelvis. Following each test, the cadaver was autopsied for injuries.

Each cadaver was seated on a low-friction bench that was mounted sideways to the direction of sled travel. The cadavers were positioned 1 m from a vertical side panel and slid into it upon rapid deceleration of the sled. In all tests, the side panel was stopped prior to the cadaver striking it. For the 6,8 m/s rigid surface impact tests, the side panel was of sufficient height to allow the cadaver's head to strike it. For the 8,9 m/s tests, the impact surface was 540 mm high, measured from the seat pan. Each padded impact consisted of a 140 mm high padded block at the level of the seat pan and a similar block at the top of the impact surface. Two of the padded impact tests used 140 mm thick blocks of open cell urethane and two tests used 89 mm thick blocks of fiberglass matrix pad. Table O.1 summarizes the mass and standing heights of the cadavers for these tests. The impact velocity, impact surface material and peak pelvic acceleration are also given for each cadaver subject.

In the second study, cadavers were subjected to either 6,8 m/s impacts into a rigid wall, or 8,9 m/s impacts into either a rigid or padded wall. The results of one cadaver were not used in this study because the cadaver's body mass was not reported. The cadaver data, test conditions, peak pelvic accelerations and peak forces are given in Table O.2 for this test series.

In both studies, the data were filtered using a 100 Hz FIR filter (23). Similar filtering must be done to the dummy data since the FIR filter may have significantly distorted the amplitude and phase of the cadaver data.

O.2 Normalized data

The force versus time and acceleration versus time histories were not available for the Heidelberg data. Consequently, the mass ratio, R_m, was calculated using the total body mass, or,

$$R_m = 76\,\text{kg}/M_i \tag{O.1}$$

where 76 kg is the total body mass of the 50th percentile adult male and M_i is the total body mass of the i-th cadaver subject. The mass ratios are listed in Tables O.1 and O.2.

The characteristic dimension used to calculate the stiffness ratios was standing height since Kallieris et al. (23) did not report any pelvic dimensions. Stiffness ratios were calculated using the following equation,

$$R_k = 1.74\,\text{m}/L_i \tag{O.2}$$

where 1,74 m is the standing height of the 50th percentile adult male and L_i is the standing height of the i-th cadaver subject. The stiffness ratios for the cadavers are given in Tables O.1 and O.2.

The normalizing factors for force, R_f, and acceleration, R_a, were calculated from the equations given by Mertz (17),

$$R_f = (R_m R_k)^{1/2} \quad (O.3)$$

$$R_a = (R_k / R_m)^{1/2} \quad (O.4)$$

The acceleration normalizing factors along with the normalized peak pelvic accelerations for the first set of the cadaver impacts are listed in Table O.1. The force and acceleration normalizing factors for the second set of cadaver impacts are listed in Table O.2, along with the normalized peak pelvic accelerations and normalized peak impact forces.

O.3 Comparison of normalized test results from both series

The results of the two studies were considerably different. There is also considerable variation within groups of similar test conditions for each test series. The implication of these observations is that the normalization method was not very effective. It is suspected that the use of total body mass in the mass ratio instead of effective mass determined by impulse-momentum analysis is responsible for these large variations.

O.4 Response requirements

To define response requirements, the 6,8 m/s rigid surface data were grouped and the average normalized peak pelvic acceleration and average normalized peak impact force were calculated. These values along with proposed bounds are given in Table O.3. The same type of analysis was done to the 8,9 m/s rigid data and the 8,9 m/s APR padding data, and their proposed bounds are given in Table O.3. The acceleration data for Test H-82-021 were not used in the analysis of the APR padding data because it appears to be an outlier. The fiberglass padding data was not used since there were only two tests conducted using this material.

Table O.1 — Cadaver Data, Test Conditions, and Test Results from the Lateral Sled Tests Performed by the University of Heidelberg (23); and Characteristic Ratios, Normalizing Factors, and Normalized Test Results for These Data

Test No.	Cadaver Data		Test Conditions		Test Results	Characteristic Ratios		Normal-izing Factors	Normalized Test Results
	Body Mass (kg)	Standing Height (m)	Impact Velocity (m/s)	Impact Surface	Peak Pelvic Accel. (G)	Mass R_m	Stiff-ness R_k	Accel. R_a	Peak Pelvic Accel. (G)
H-80-011	89	1,80	6,8	rigid	49	0,85	0,97	1,07	52
H-80-014	84	1,69	6,8	rigid	63	0,90	1,03	1,07	67
H-80-017	70	1,75	6,8	rigid	58	1,09	0,99	0,95	55
H-80-024	65	1,76	8,9	rigid	108	1,17	0,99	0,92	99
H-80-002	65	1,65	8,9	rigid	88	1,17	1,05	0,95	83
H-80-004	80	1,65	8,9	rigid	95	0,95	1,05	1,05	99
H-80-018	61	1,66	8,9	APR pad	72	1,25	1,05	0,92	66
H-80-020	67	1,67	8,9	APR pad	54	1,13	1,04	0,96	52
H-80-021	63	1,80	8,9	fiberglass	34	1,21	0,97	0,90	31
H-80-023	82	1,59	8,9	fiberglass	69	0,93	1,09	1,08	75

Table O.2 — Cadaver Data, Test Conditions, and Test Results from the Lateral Sled Tests Performed by the University of Heidelberg (23); and Characteristic Ratios, Normalizing Factors, and Normalized Test Results for These Data

Test No.	Cadaver Data		Test Conditions		Test Results		Characteristic Ratios		Normalizing Factors		Normalized Test Results	
	Body Mass (kg)	Standing Height (m)	Impact Velocity (m/s)	Impact Surface	Peak Force (kN)	Peak Accel. (G)	Mass R_m	Stiff-ness R_k	Force R_f	Accel. R_a	Peak Force (kN)	Peak Accel. (G)
H-82-015	69	1,90	6,8	rigid	4,5	83	1,10	1,24	1,17	1,06	5,3	88
H-82-018	85	2,40	6,8	rigid	10,2	110	0,89	0,98	0,93	1,05	9,5	116
H-82-019	67	2,10	6,8	rigid	5,8	44	1,13	1,12	1,12	1,00	6,5	44
H-82-014	61	2,00	8,9	rigid	22,0	154	1,25	1,18	1,21	0,97	26,6	149
H-82-016	50	2,00	8,9	rigid	16,6	114	1,52	1,18	1,34	0,88	22,2	100
H-82-021	99	2,60	8,9	APR pad	15,3	136	0,77	0,91	0,84	1,09	12,9	148
H-82-022	77	2,20	8,9	APR pad	11,9	86	0,99	1,07	1,03	1,04	12,3	85

Table O.3 — Pelvic Response Requirements for the Lateral Sled Tests Determined from the Response Data of the University of Heidelberg (23)

Test Conditions		Normalized Peak Pelvic Acceleration (G)			Normalized Peak Impact Force (kN)		
Impact Velocity (m/s)	Impact Surface	Average	Lower Bound	Upper Bound	Average	Lower Bound	Upper Bound
6,8	rigid	70	63	77	7,1	6,4	7,8
8,9	rigid	106	96	116	24,4	22,4	26,4
8,9	APR pad	68	61	75	12,6	11,6	13,6

Annex P

Analysis of Wayne State University — Lateral shoulder and thoracic impact data

This annex describes the lateral shoulder and thoracic impact data collected by researchers of Wayne State University (WSU) and analyzed by Irwin (16).

P.1 Original Data

A series of lateral sled impacts was conducted at WSU and funded by a grant from the Centers for Disease Control (31). These tests were similar to the sled tests conducted at the University of Heidelberg, except the impact wall was configured as shown in Figure P.1, and paper honeycomb was used in the padded tests. Three-dimensional film analysis was performed on 7 of the 17 tests and the instrumentation and film data were normalized by Irwin (15, 16), according to the normalization procedure recommended by Mertz (17). The remaining 10 tests were not analyzed in this manner because the film calibration information was insufficient for three-dimensional film analysis.

Table P.1 summarizes the cadaver data and test conditions for the WSU lateral sled tests. The sums of the loads of the shoulder and thoracic impact surfaces are shown in Figures P.2 and P.3 for the rigid and padded impacts, respectively. Note that the loads of the shoulder and thorax beams were summed to minimize the effect of the cadaver's shoulder height on the load distribution between the two beams. Peak lateral accelerations of T1, T12 and the impacted shoulder are given in Table P.2. Peak lateral displacements of T1, T5, the sternum, and the non-impacted shoulder and ribs are also given in Table P.2.

P.2 Normalized data

The technique described by Mertz (17) was used by Irwin (15, 16) to normalize the force versus time histories and the peak thoracic accelerations and displacements to estimate the response characteristics of a 50th percentile adult male.

The effective shoulder plus thoracic mass, M_e, for each cadaver was calculated from the impulse of the shoulder beam load, F_s, plus thorax beam load, F_t, as shown below.

$$M_e = \left[\int_0^T (F_s + F_t)dt\right] \Big/ V_0 \tag{P.1}$$

where $\int_0^T (F_s + F_t)dt$ is the impulse, V_0 is the impact velocity and T is the pulse duration corresponding to a velocity change of V_0.

Table P.3 gives the effective mass and the percent of the total body mass for the shoulder and thorax of each subject. The average percent of body mass for the tests analyzed here was 31,2%, which would yield an effective mass of 24 kg for the 76 kg total body weight of a 50th percentile adult male.

The characteristic ratio for the effective thoracic mass, R_m, is defined as,

$$R_m = 24\,\text{kg}/M_e \tag{P.2}$$

The calculated mass ratios are given in Table P.3.

The stiffness ratio, R_k, is defined as,

$$R_k = K_s/K_i \tag{P.3}$$

where K_s is the stiffness of the standard subject and K_i is the stiffness of the i-th subject. Mertz (17) has shown that for geometrically similar structures with the same elastic modulus, the stiffness is proportional to the characteristic length. The chest depth was the characteristic length chosen for the normalization of these data. For a 50th percentile adult male, this length is 236 mm. The characteristic ratio for the thoracic stiffness, R_k, was calculated by,

$$R_k = 236\,\text{mm}/L_i \qquad (P.4)$$

where L_i is the chest depth of the cadaver whose data were to be normalized. The stiffness ratios for the cadavers are given in Table P.3.

The normalizing factors for force, R_f, acceleration, R_a, deflection, R_x, and time, R_t, were calculated from the equations given by Mertz (17),

$$R_f = (R_m R_k)^{1/2} \qquad (P.5)$$

$$R_a = (R_k / R_m)^{1/2} \qquad (P.6)$$

$$R_x = (R_m / R_k)^{1/2} \qquad (P.7)$$

$$R_t = (R_m / R_k)^{1/2} \qquad (P.8)$$

The characteristic ratios and normalizing factors for each cadaver are given in Table P.3. The normalized force versus time histories were obtained by multiplying each value of force by its force normalizing factor and each value of time by its time normalizing factor. Figures P.3 and P.4 show the normalized force versus time histories for the rigid and padded impacts, respectively. The normalized peak lateral accelerations of T1, T12 and the 4th rib on the impacted side were obtained by multiplying the respective peak lateral acceleration values by the acceleration normalizing factor for that cadaver. Similarly, the normalized peak lateral displacements were obtained by multiplying the respective peak lateral displacement values by the displacement normalizing factor for that cadaver. The normalized peak lateral accelerations and displacements are given in Table P.4.

P.3 Elimination of massively damaged cadavers

Table P.1 gives the number of rib fractures sustained by each cadaver used in the WSU sled tests. The response requirements were established from cadavers which sustained less than 6 fractures to the ribs. This cutoff level was chosen arbitrarily. If this cutoff level were set lower, too little data remained to define the responses of the thorax. The WSU tests remaining are SIC 10, SIC 15 and SIC 17. The response requirements for the shoulder and thorax are set on the results of these 3 tests only.

P.4 Response requirements

The normalized cadaver response for each impact configuration is the best estimate of the normalized response of the 50th percentile adult male. Response requirements for the side impact test device consist of a corridor around the normalized time history of the shoulder plus thorax force.

Figure P.5 shows the force versus time response requirement for the 8,9 m/s padded impact. This corridor was constructed around the normalized cadaver curves which are also shown. The normalized force versus time curves of the side impact dummies should lie within the corridor.

Table P.4 indicates a wide spread in the peak lateral accelerations of T1, T12 and the 4th rib on the impacted side. The average normalized acceleration of T1 is 68 G, but none of the peak values of SIC 10, SIC 15 and SIC 17 lie within a ±15% bound of the average. The average normalized acceleration of T12 is 89 G, and only SIC 17 has a peak value within a ±15% bound of the average. The average normalized acceleration of the impacted shoulder is 203 G, but none of the peak values of the 3 tests lie within a ±15% bound of the average. Therefore, no requirements on accelerations are proposed based on these test data.

The displacement data for the 3 remaining tests are sparse, as indicated in Table P.4. No requirements are proposed for the lateral displacement of the non-impacted shoulder since SIC 15 and SIC 17 both sustained separation of the impacted acromion, and the displacements of the non-impacted clavicle are included in the cadavers' responses, but irrelevant to the performance of a side impact dummy. A response requirement of 80 to 108 mm is proposed for the peak lateral displacement of T12. This represents a spread of ±15% of the average normalized displacement of T12. No response requirements are proposed for the lateral displacements of the sternum and the non-impacted ribs, since considerable variability exists in these results.

Table P.1 — Cadaver Data and Test Conditions from the Lateral Sled Tests Performed by WSU (31 and 15)

Test No.	Cadaver Data					Test Conditions						
	Age	Sex	Mass	Chest Depth	No. of Rib	Pad Thickness	Compression Rating of Paper Honeycomb Pad (psi)					Sled Velocity
			(kg)	(mm)	Fx	(mm)	Shoulder	Thorax	Abdomen	Pelvis	Knee	(m/s)
SIC 07	66	M	74,8	240	16	0	[a]	[a]	[a]	[a]	[a]	6,7
SIC 04	69	M	57,6	210	22	0	[a]	[a]	[a]	[a]	[a]	9,1
SIC 10	60	M	62,1	190	5	152	15	15	15	15	15	8,8
SIC 14	72	M	55,3	190	18	102	15	15	15	23	23	9,4
SIC 15	43	F	68,9	210	0	102	23	15	15	23	23	8,9
SIC 16	58	F	56,7	155	26	76	23	16	16	23	23	8,9
SIC 17	65	M	93,0	210	2	152	23	15	15	23	23	8,9

[a] Paper Honeycomb padding was not used in these rigid impacts.

Table P.2 — Test Results from the Lateral Sled Tests Performed by WSU (31 and 15)

Test No.	Peak Lateral Accel. (G)			Peak Lateral Displacement (mm)						
	T1	T12	Impacted Shoulder	T1	T12	Upper Sternum	Lower Sternum	Non-impacted Shoulder	Non-impacted Rib 6	Non-impacted Rib 8
SIC 07	76	51	275	97	74	[a]	86	98	[a]	151
SIC 04	84	84	324	93	82	[a]	[a]	121	[a]	145
SIC 10	55	134	105	[a]	85	72	76	106	[a]	178
SIC 14	83	142	104	113	100	85	92	125	135	208
SIC 15	93	56	347	[a]	[a]	127	95	130	[a]	[a]
SIC 16	57	90	205	109	98	89	88	138	[a]	[a]
SIC 17	51	77	142	[a]	104	[a]	[a]	120	120	139

[a] These data could not be determined from film analysis.

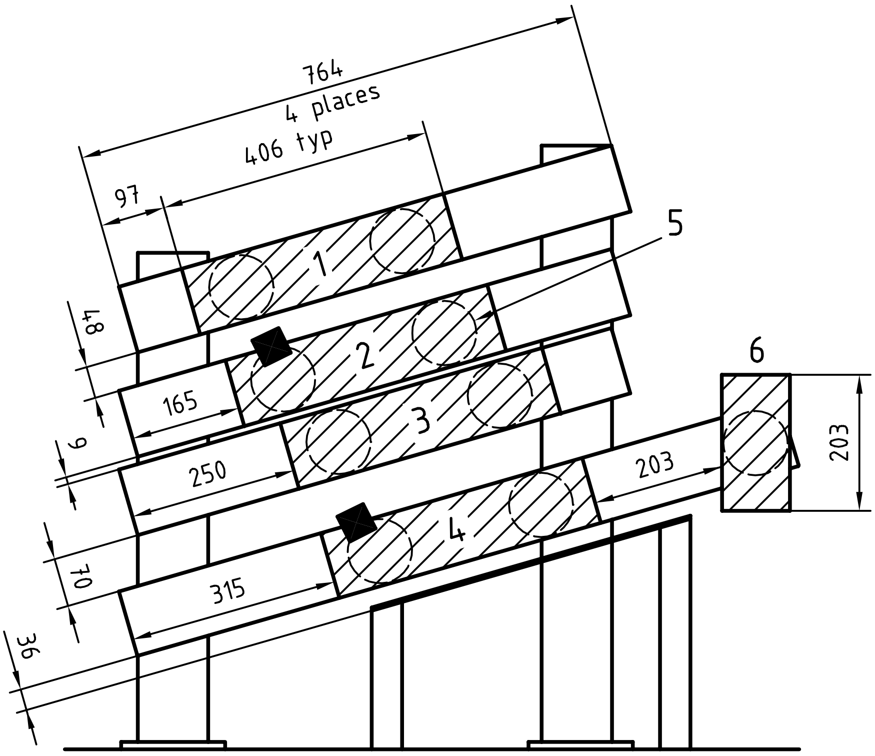
Table P.3 — Effective Mass, Characteristic Ratios and Normalizing Factors from the Lateral Sled Tests Performed by WSU (15 and 16)

Test No.	Effective Mass		Characteristic Ratios		Normalizing Factors			
	M_e (kg)	Body mass (%)	Stiffness R_k	Mass Rm	Time R_t	Defl. R_x	Accel. R_a	Force R_f
SIC 07	24,3	32,5	0,98	0,99	1,01	1,01	0,99	0,98
SIC 04	15,6	21,7	1,12	1,54	1,17	1,17	0,85	1,31
SIC 10	16,4	26,3	1,24	1,47	1,09	1,09	0,92	1,35
SIC 14	26,5	48,0	1,24	0,90	0,85	0,85	1,17	1,06
SIC 15	22,5	32,7	1,12	1,07	0,98	0,98	1,02	1,09
SIC 16	13,1	23,0	1,52	1,84	1,10	1,10	0,91	1,67
SIC 17	26,8	28,8	1,12	0,90	0,90	0,90	1,12	1,00

Table P.4 — Normalized Test Results from the Lateral Sled Tests Performed by WSU (31 and 15)

Test No.	Peak Normalized Lateral Accel. (G)			Peak Normalized Lateral Displacement (mm)						
	T1	T12	Impacted Shoulder	T1	T12	Upper Sternum	Lower Sternum	Non-impacted Shoulder	Non-impacted Rib 6	Non-impacted Rib 8
SIC 07	75	50	272	98	75	[a]	87	99	[a]	153
SIC 04	71	71	275	109	96	[a]	[a]	141	[a]	170
SIC 10	51	123	97	[a]	93	78	83	115	[a]	194
SIC 14	97	166	122	96	85	72	78	106	115	177
SIC 15	95	57	354	[a]	[a]	125	93	127	[a]	[a]
SIC 16	52	82	187	120	108	98	97	152	[a]	[a]
SIC 17	57	86	159	[a]	94	[a]	[a]	108	108	125

[a] These data could not be determined from film analysis.



Key

1 Shoulder beam
2 Thorax beam
3 Abdomen beam
4 Pelvis beam
5 Load cell 9 places
6 Knee beam

Figure P.1 — Impact Wall Configuration for the Lateral Sled Impacts

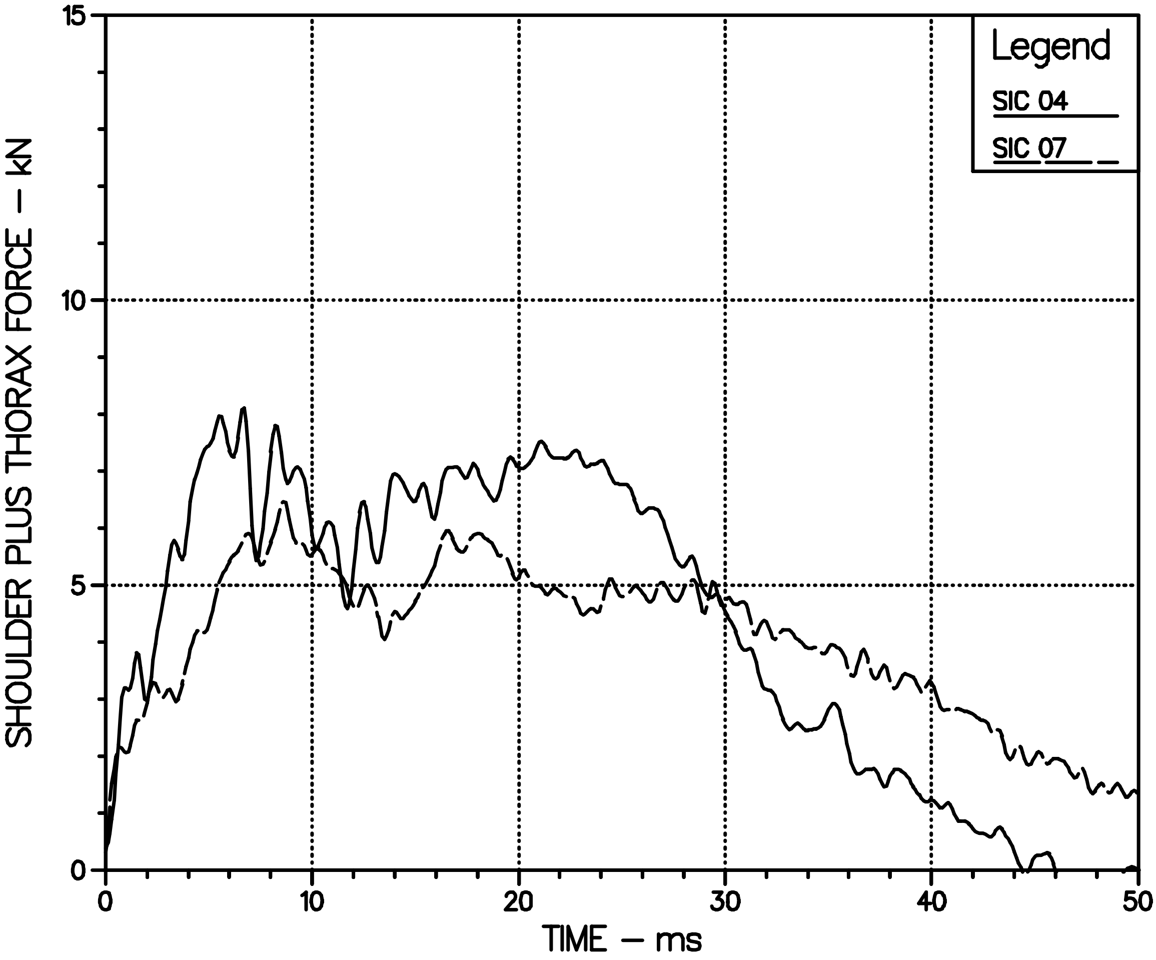


Figure P.2 — Shoulder Plus Thorax Impact Surface Force Versus Time Histories for Cadavers Subjected to Rigid Wall Impacts

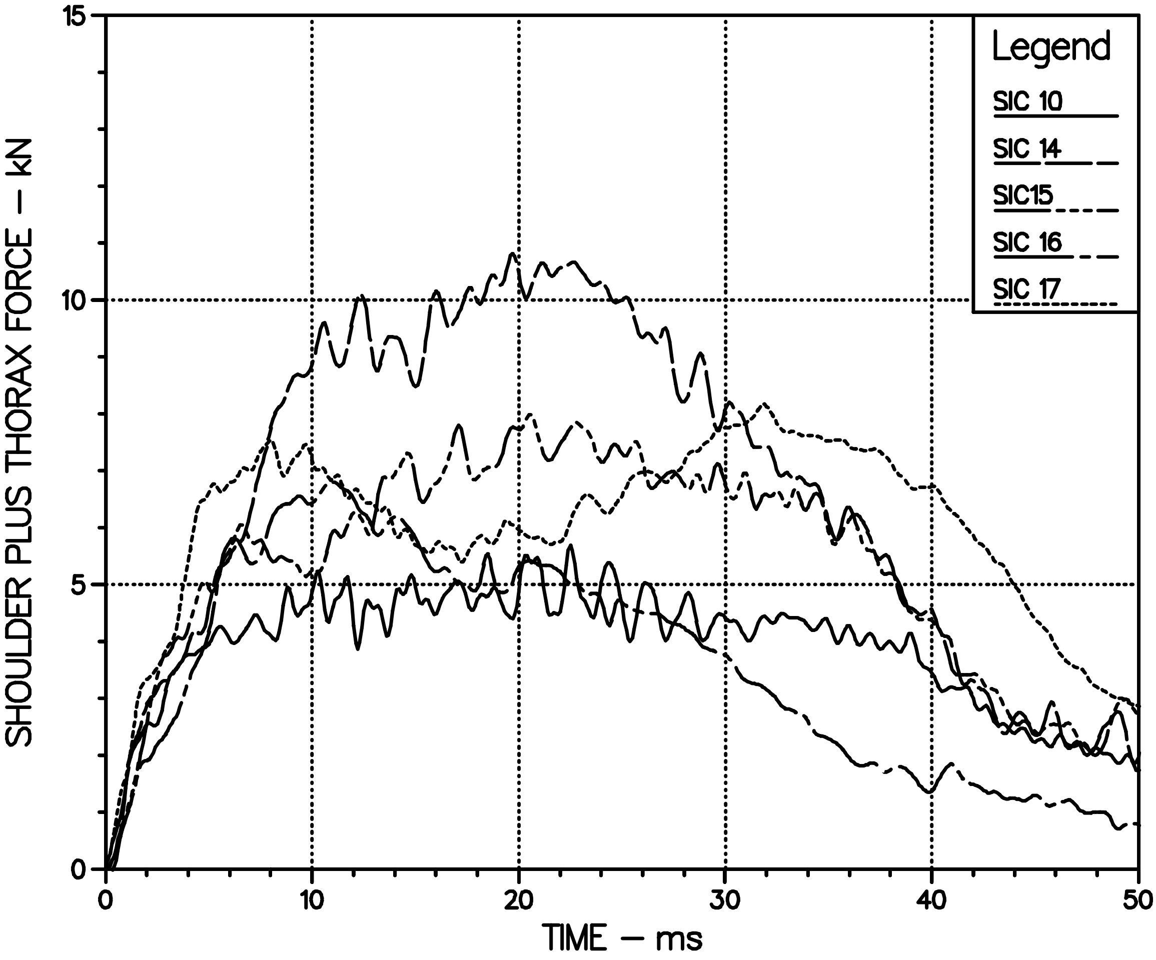


Figure P.3 — Shoulder Plus Thorax Impact Surface Force Versus Time Histories for Cadavers Subjected to a 8,9 m/s Padded Wall Impact

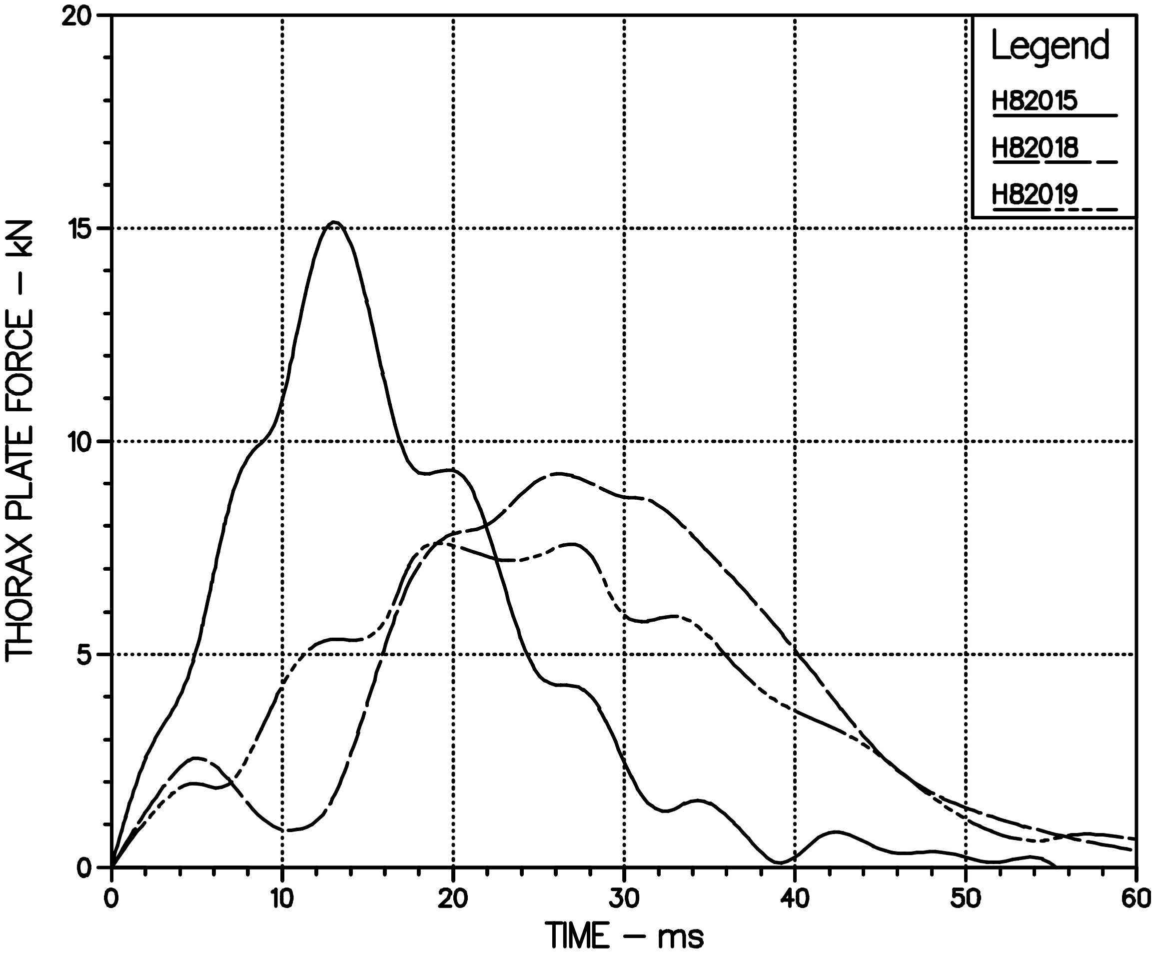


Figure P.4 — Normalized Shoulder Plus Thorax Impact Surface Force Versus Time Histories for Cadavers Subjected to Rigid Wall Impacts

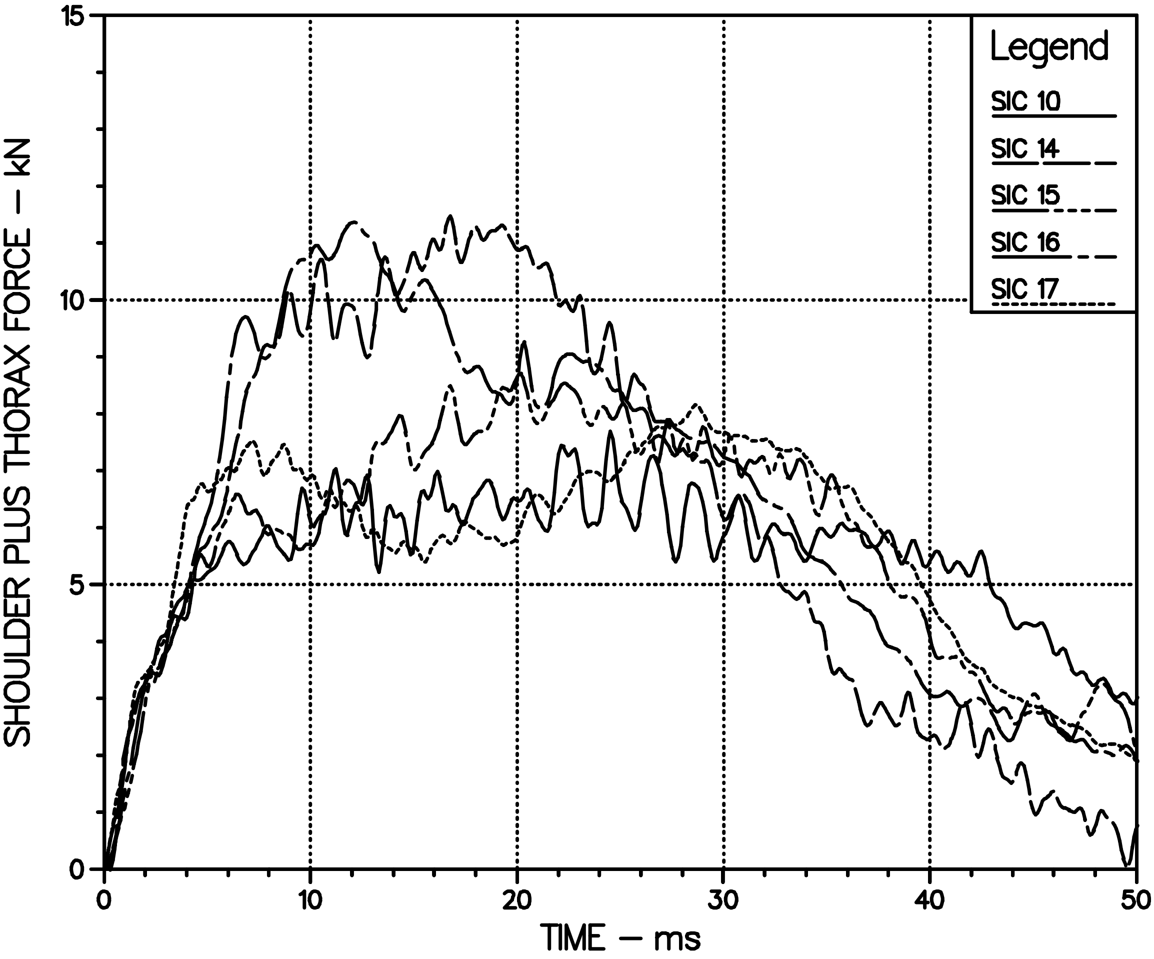


Figure P.5 — Normalized Shoulder Plus Thorax Impact Surface Force Versus Time Histories for Cadavers Subjected to a 8,9 m/s Padded Wall Impact

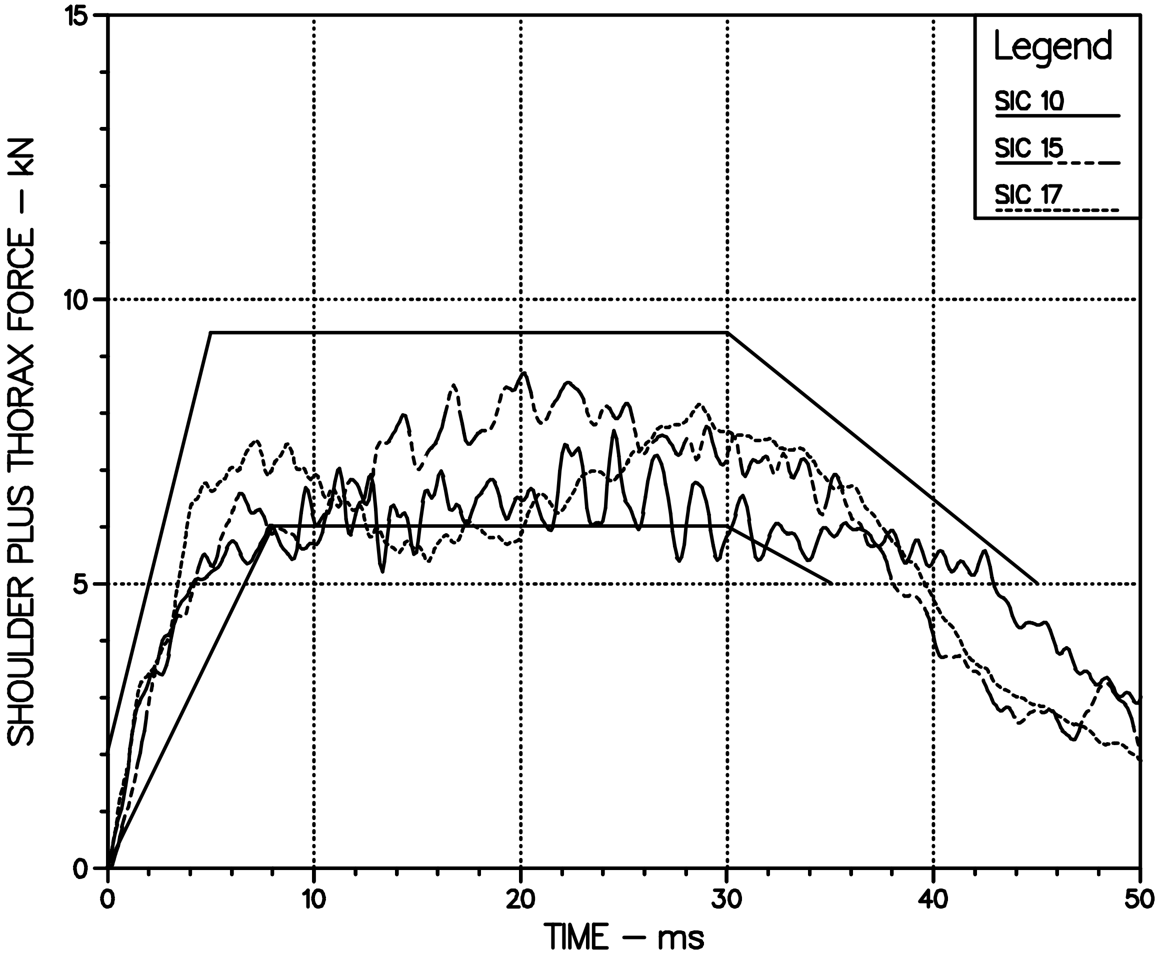


Figure P.6 — Normalized Shoulder Plus Thorax Impact Surface Force Versus Time Histories and Proposed Response Corridor for an 8,9 m/s Padded Wall Impact

Annex Q

Analysis of Wayne State University – Lateral abdominal impact data

This annex describes the lateral abdominal impact data collected by researchers of Wayne State University (WSU) and analyzed by Irwin (16).

Q.1 Original Data

A series of lateral sled impacts was conducted at WSU and funded by a grant from the Centers for Disease Control (31, 32). These tests were similar to the sled tests conducted at the University of Heidelberg, except the impact wall was configured as shown in Figure Q.1, and paper honeycomb was used in the padded tests. Three-dimensional film analysis was performed on 7 of the 17 tests and the instrumentation and film data were normalized by Irwin (16), according to the normalizing technique recommended by Mertz (17). The remaining 10 tests were not analyzed in this manner because the film calibration information was insufficient for three-dimensional film analysis.

Table Q.1 summarizes the cadaver data and test conditions for the WSU lateral sled tests. The force versus time histories of the abdominal impact surfaces are shown in Figures Q.2 and Q.3 for the rigid and padded impacts, respectively.

Q.2 Normalized data

The technique described by Mertz (17) was used by Irwin (16) to normalize the force versus time histories to estimate the response characteristics of a 50th percentile adult male.

The effective abdominal mass, M_e, for each cadaver was calculated from the impulse of the abdomen beam load, F_a, as shown below.

$$M_e = \left[\int_0^T (F_a)dt\right] \Big/ V_0 \qquad (Q.1)$$

where $\int_0^T (F_a)dt$ is the impulse, V_0 is the impact velocity and T is the pulse duration corresponding to a velocity change of V_0.

Table Q.2 gives the effective mass and the percent of the total body mass for the abdomen of each subject. The average percent of body mass for the tests analyzed here was 13,9%, which would yield an effective abdominal mass of 10,6 kg for the 76 kg total body weight of a 50th percentile adult male.

The characteristic ratio for the effective abdominal mass, R_m, is defined as,

$$R_m = 10{,}6\,\text{kg}/M_e \qquad (Q.2)$$

The calculated mass ratios are given in Table Q.2.

The stiffness ratio, R_k, is defined as,

$$R_k = K_s/K_i \qquad (Q.3)$$

where K_s is the stiffness of the standard subject and K_i is the stiffness of the i-th subject. Mertz (17) has shown that for geometrically similar structures with the same elastic modulus, the stiffness is proportional to the characteristic length. The characteristic length was chosen to be the erect sitting height. For a 50th percentile adult male, the erect sitting height is 907 mm. The characteristic ratio for the abdominal stiffness, R_k, was calculated by,

$$R_k = 907\,\text{mm}/L_i \qquad (Q.4)$$

where L_i is the erect sitting height of the cadaver whose data were to be normalized. The stiffness ratios for the cadavers are given in Table Q.2.

The normalizing factors for force, R_f, and time, R_t, were calculated from the equations given by Mertz (17),

$$R_f = (R_m R_k)^{1/2} \tag{Q.5}$$

$$R_t = (R_m / R_k)^{1/2} \tag{Q.6}$$

The characteristic ratios and normalizing factors for each cadaver are given in Table Q.2. The normalized abdominal force versus time histories were obtained by multiplying each value of force by its force normalizing factor and each value of time by its time normalizing factor. Figures Q.4 and Q.5 show the normalized force versus time histories for the rigid and padded impacts, respectively.

Q.3 Response requirements

The normalized cadaver response for each impact configuration is the best estimate of the normalized response of the 50th percentile adult male. Response requirements for the side impact test device consist of corridors around the normalized time histories of the abdomen force.

Figures Q.6, Q.7 and Q.8 show the force versus time response requirements for the 6,8 m/s rigid, 8,9 m/s rigid, and 8,9 m/s padded impacts. These corridors were constructed around the normalized cadaver curve(s) which are also shown. The normalized force versus time curves of the side impact dummies should lie within these corridors.

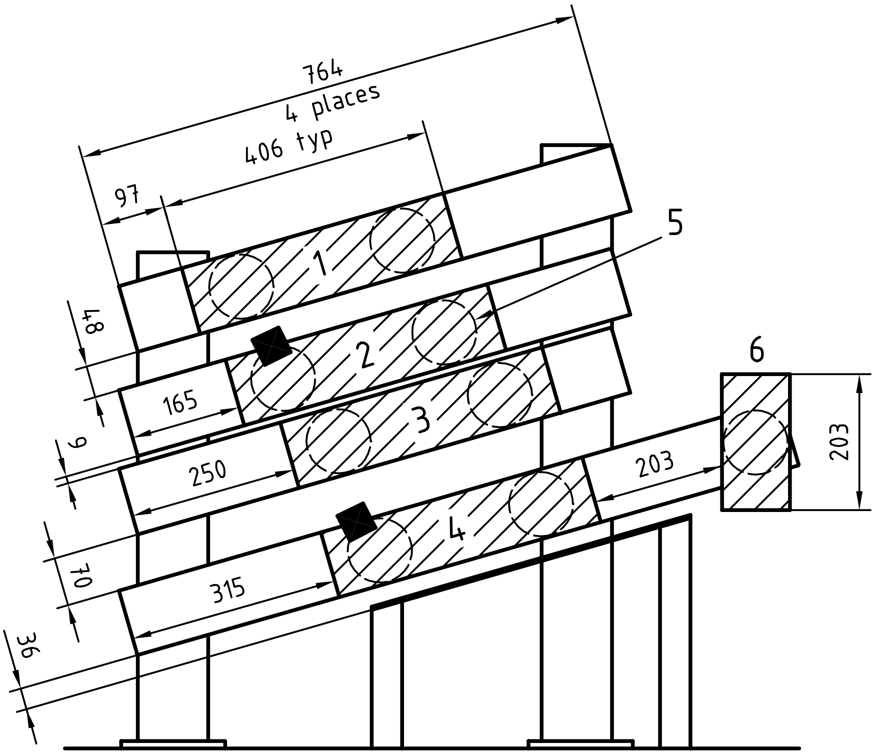
Table Q.1 — Cadaver Data and Test Conditions from the Lateral Sled Tests Performed by WSU (31 and 15)

Test No.	Cadaver Data					Test Conditions						
	Age	**Sex**	**Mass** (kg)	**Erect Sitting Height** (mm)	**No. of Rib Fractures**	**Pad Thick-ness** (mm)	**Compression Rating of Paper Honeycomb Pad** (psi)					**Sled Velocity** (m/s)
							Shoulder	**Thorax**	**Abdomen**	**Pelvis**	**Knee**	
SIC 07	66	M	74,8	900	16	0	[a]	[a]	[a]	[a]	[a]	6,7
SIC 04	69	M	57,6	880	22	0	[a]	[a]	[a]	[a]	[a]	9,1
SIC 10	60	M	62,1	860	5	152	15	15	15	15	15	8,8
SIC 14	72	M	55,3	910	18	102	15	15	15	23	23	9,4
SIC 15	43	F	68,9	850	0	102	23	15	15	23	23	8,9
SIC 16	58	F	56,7	800	26	76	23	16	16	23	23	8,9
SIC 17	65	M	93,0	930	2	152	23	15	15	23	23	8,9

[a] Paper Honeycomb padding was not used in these rigid impacts.

Table Q.2 — Effective Mass, Characteristic Ratios and Normalizing Factors from the Lateral Sled Tests Performed by WSU (16)

Test No.	Effective Mass		Characteristic Ratios		Normalizing Factors	
	M_e (kg)	**Body mass** (%)	**Stiffness** R_k	**Mass** R_m	**Force** R_f	**Time** R_t
SIC 07	11,0	14,7	1,01	0,96	0,98	0,97
SIC 04	8,3	14,4	1,03	1,28	1,15	1,11
SIC 10	11,2	18,0	1,05	0,95	1,00	0,95
SIC 14	5,6	10,2	1,00	1,88	1,37	1,37
SIC 15	8,6	12,5	1,07	1,23	1,15	1,07
SIC 16	9,1	16,1	1,13	1,16	1,14	1,01
SIC 17	10,8	11,6	0,98	0,98	0,98	1,00



Key

1 Shoulder beam
2 Thorax beam
3 Abdomen beam
4 Pelvis beam
5 Load cell 9 places
6 Knee beam

Figure Q.1 – Impact wall configuration for the lateral sled impacts

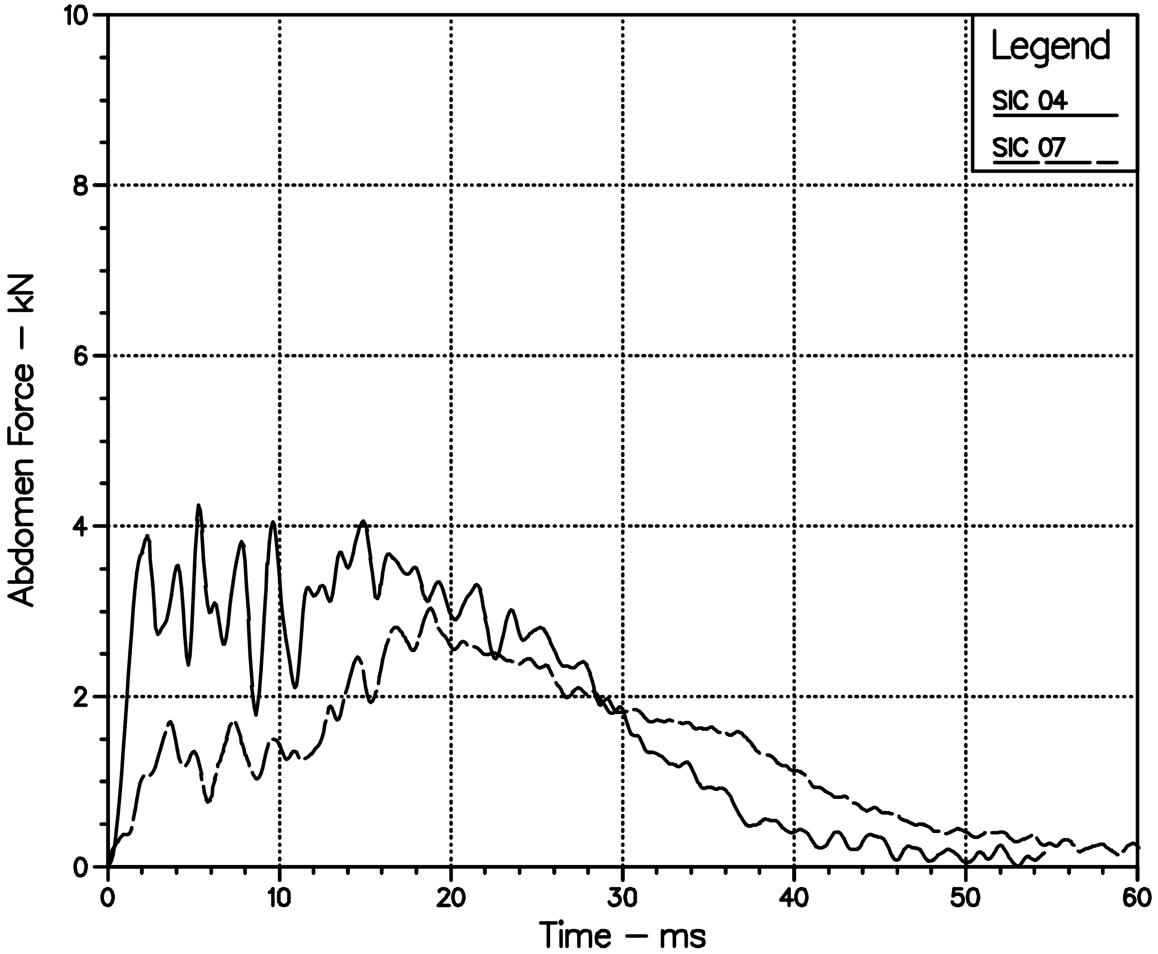


Figure Q.2 – Abdominal impact surface force versus time histories for cadavers subjected to rigid wall impacts

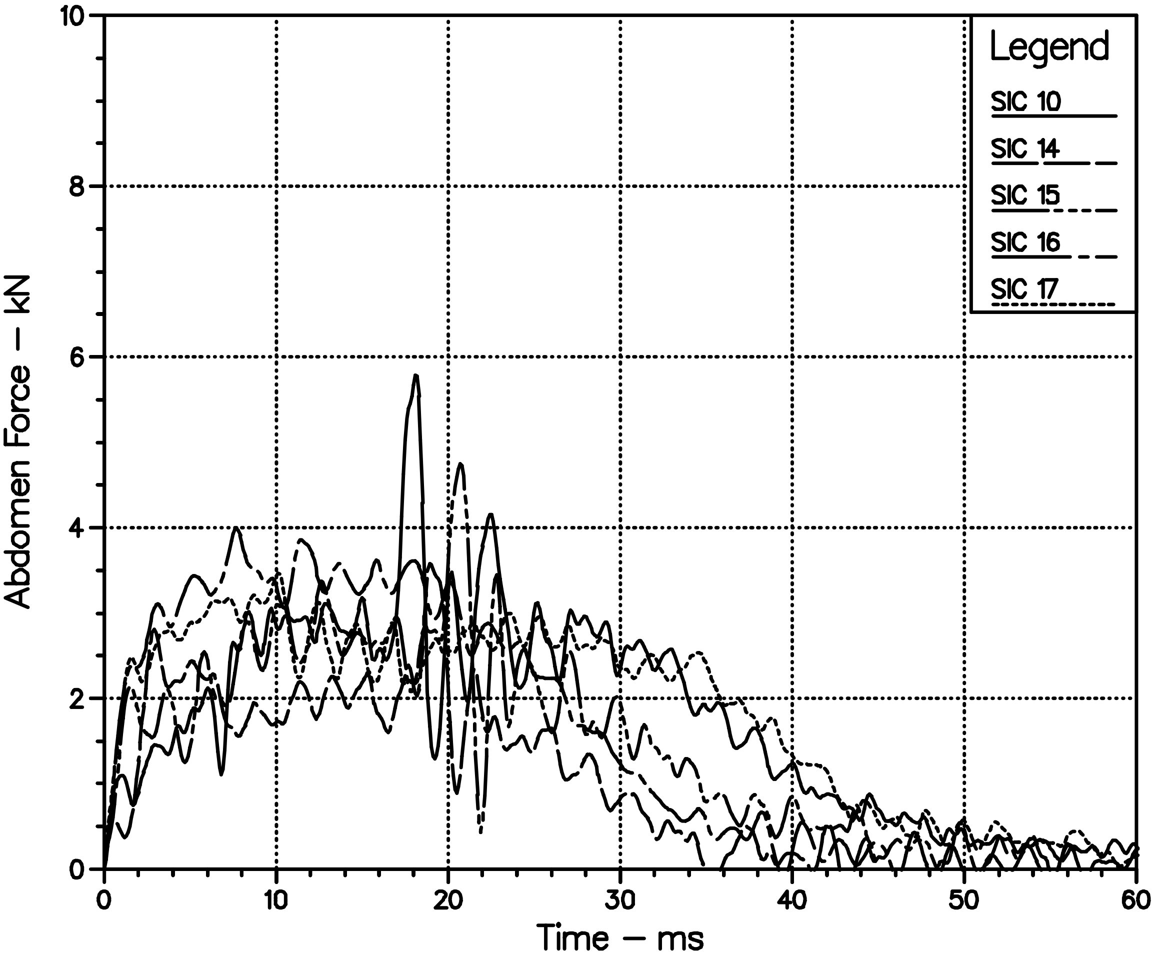


Figure Q.3 – Abdominal impact surface force versus time histories for cadavers subjected to a 8,9 m/s padded wall impact

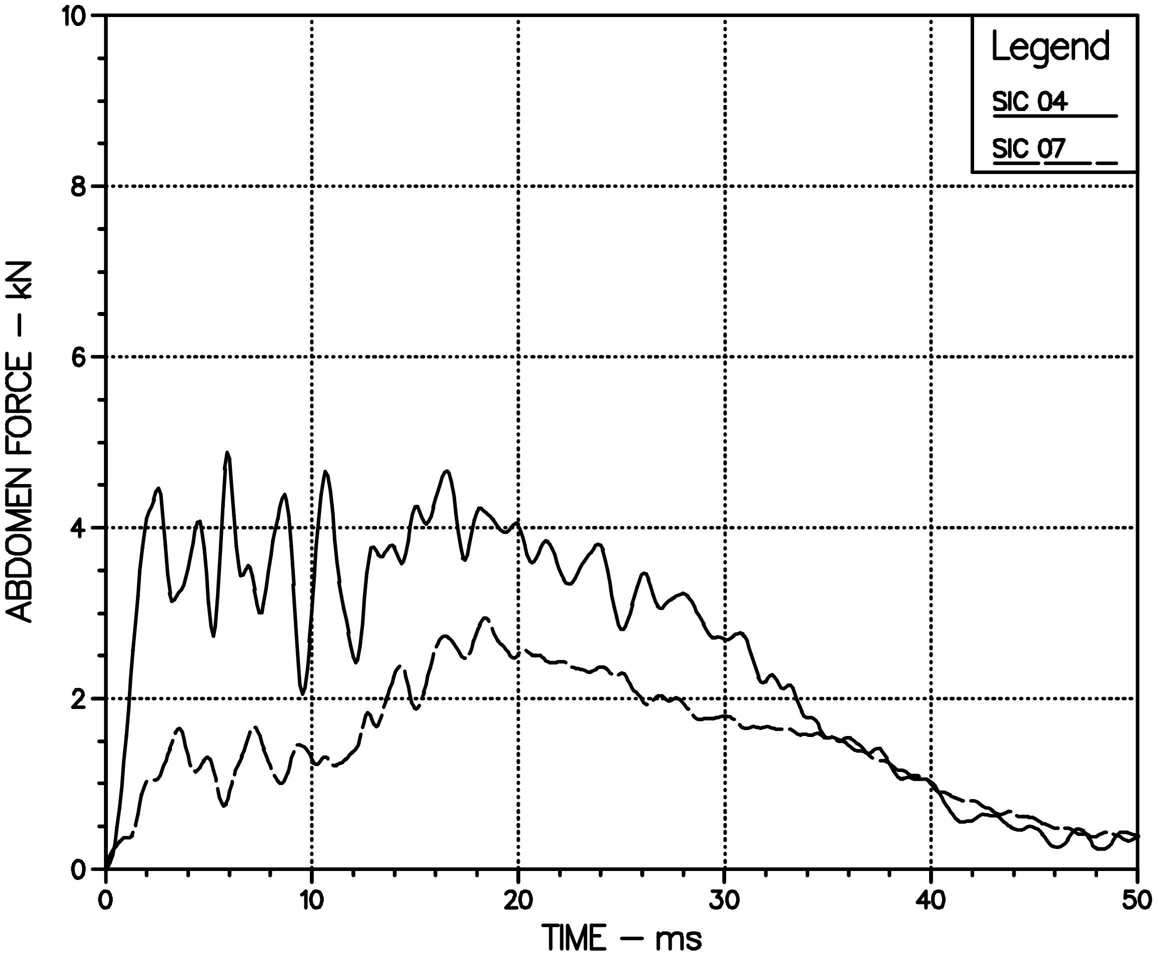


Figure Q.4 – Normalized abdominal impact surface force versus time histories for cadavers subjected to rigid wall impacts

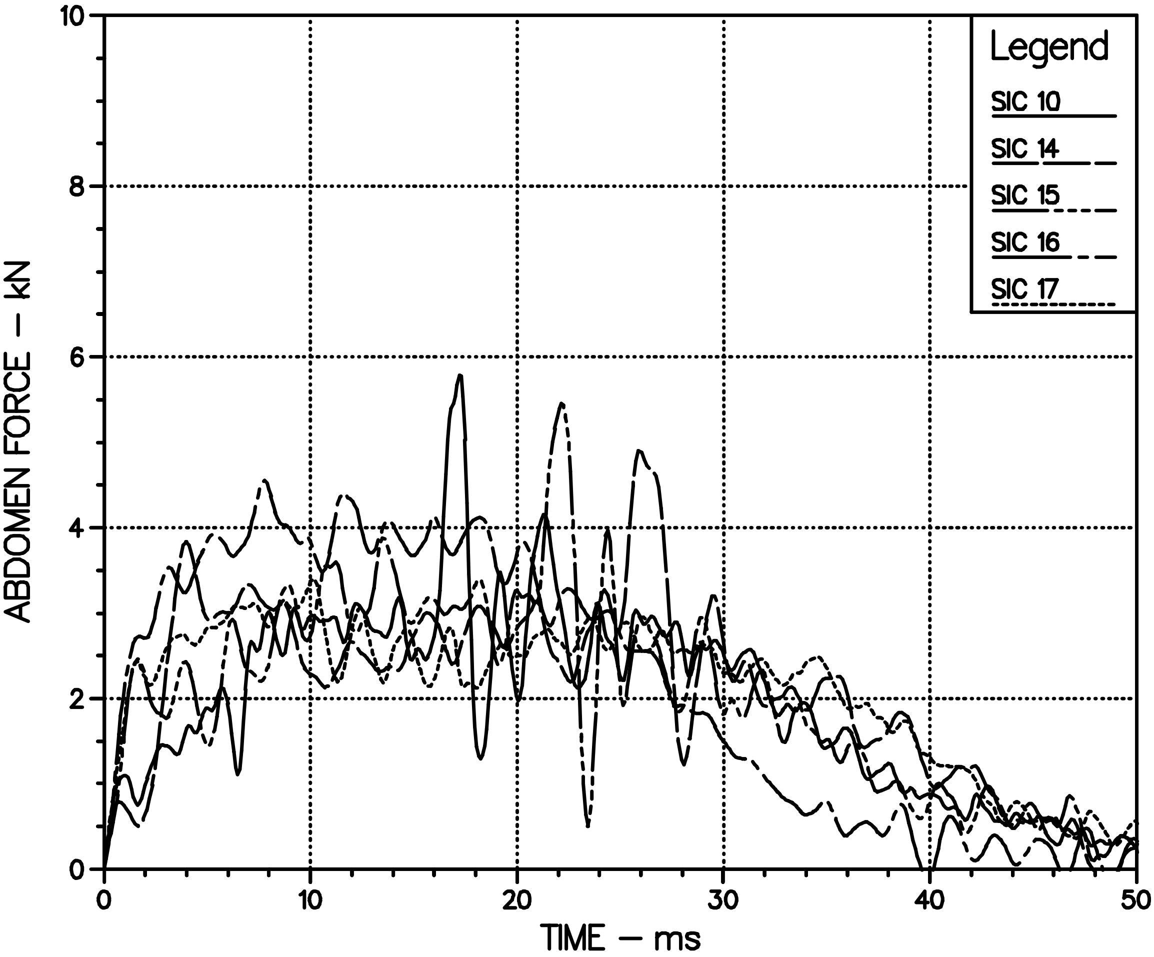


Figure Q.5 — Normalized abdominal impact surface force versus time histories for cadavers subjected to a 8,9 m/s padded wall impact

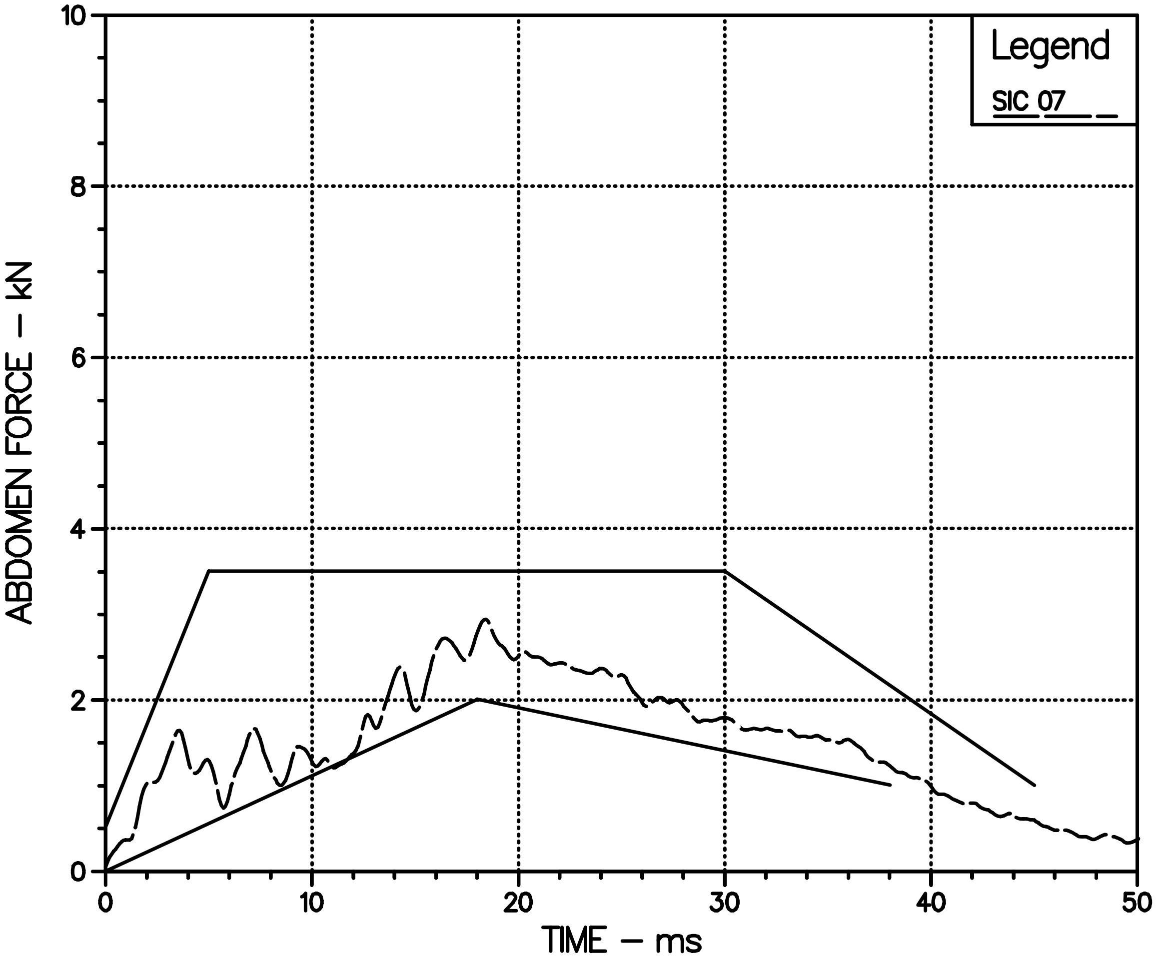


Figure Q.6 – Normaliszed abdominal impact surface force versus time histories and proposed response corridor for a 6,8 m/s rigid wall impact

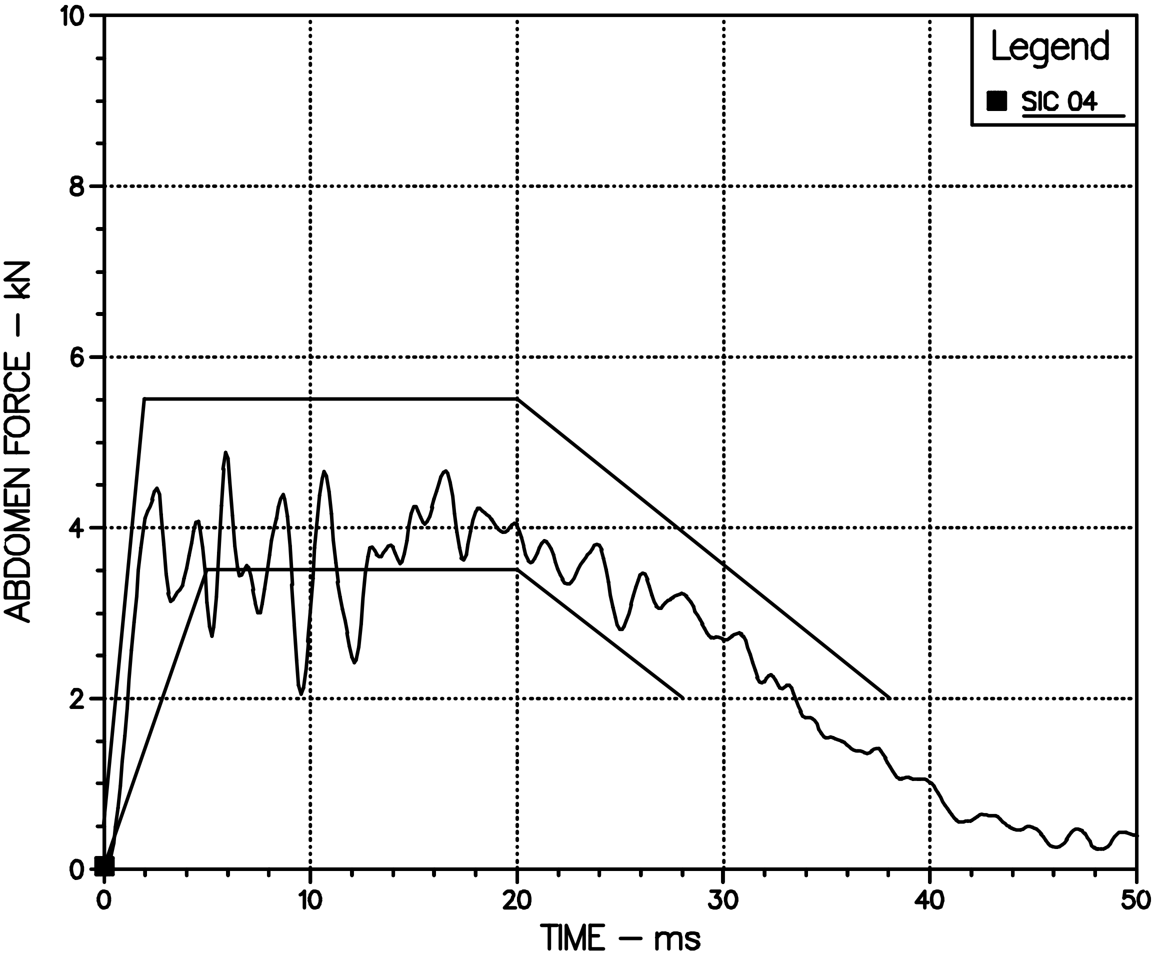


Figure Q.7 — Normaliszed abdominal impact surface force versus time histories and proposed response corridor for a 8,9 m/s rigid wall impact

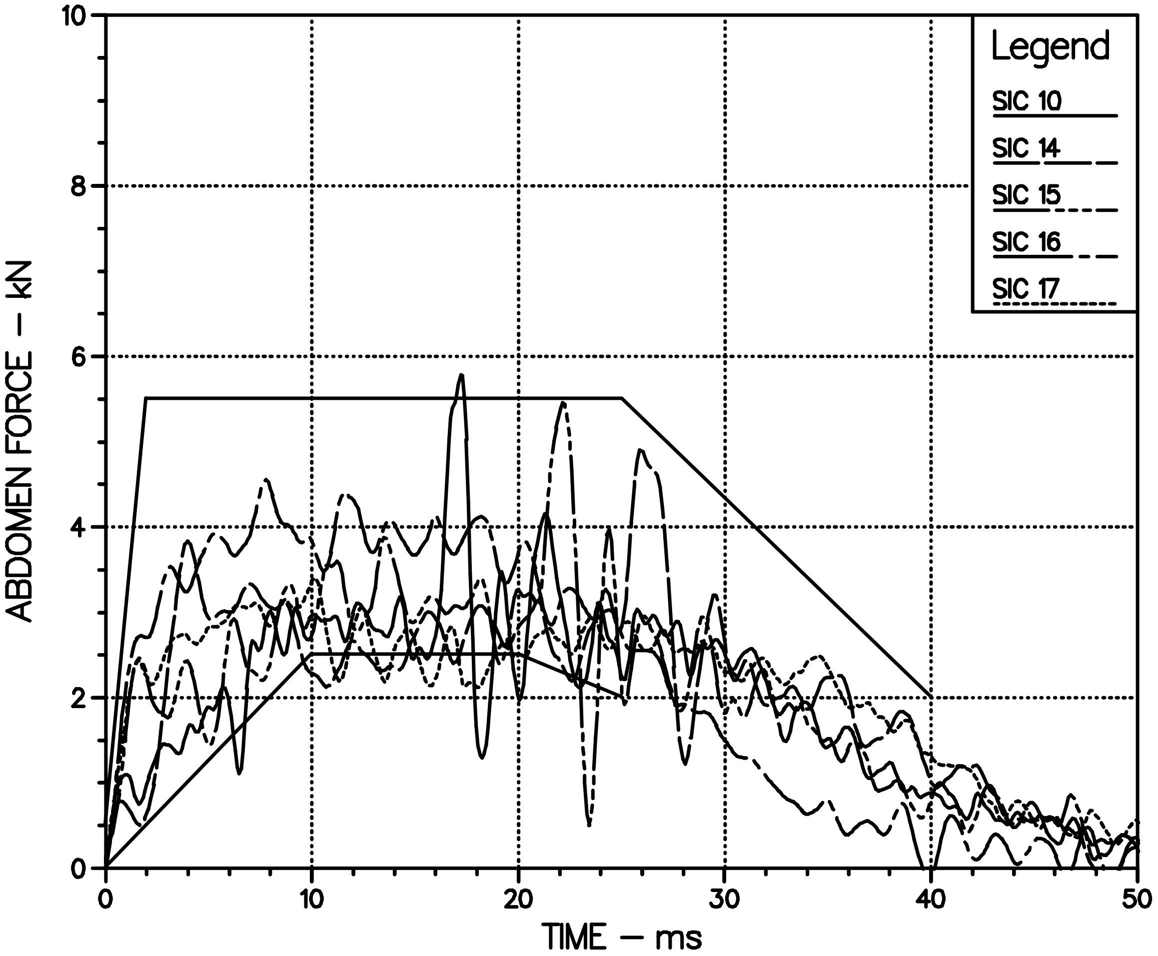


Figure Q.8 — Normaliszed abdominal impact surface force versus time histories and proposed response corridor for a 8,9 m/s padded wall impact

Annex R

Analysis of Wayne State University – Lateral pelvic impact data

This annex describes the lateral pelvic impact data collected by researchers of Wayne State University (WSU) and analyzed by Irwin (16).

R.1 Original Data

A series of lateral sled impacts was conducted at WSU and funded by a grant from the Centers for Disease Control (32). These tests were similar to the sled tests conducted at the University of Heidelberg, except the impact wall was configured as shown in Figure R.1, and paper honeycomb was used in the padded tests. Three-dimensional film analysis was performed on 7 of the 17 tests and the instrumentation and film data were normalized by Irwin (16), according to the normalization procedure recommended by Mertz (17). The remaining 10 tests were not analyzed in this manner because the film calibration information was insufficient for three-dimensional film analysis.

Table R.1 summarizes the cadaver data and test conditions for the WSU lateral sled tests. The force versus time histories of the pelvic impact surface are shown in Figures R.2 and R.3 for the rigid and padded impacts, respectively. Peak lateral accelerations of sacrum are given in Table R.2.

R.2 Normalized data

The technique described by Mertz (17) was used by Irwin (16) to normalize the force versus time histories and the peak sacral accelerations to estimate the response characteristics of a 50th percentile adult male.

The effective pelvic mass, M_e, for each cadaver was calculated from the impulse of the pelvic beam load, F_a, as shown below.

$$M_e = \left[\int_0^T \left(F_p\right)dt\right] \Big/ V_0 \qquad \text{(R.1)}$$

where $\int_0^T \left(F_p\right)dt$ is the impulse, V_0 is the impact velocity and T is the pulse duration corresponding to a velocity change of V_0.

Table R.2 gives the effective mass and the percent of the total body mass for the pelvis of each subject. The average percent of body mass for the tests analyzed here was 22,5%, which would yield an effective mass of 17,1 kg for the 76 kg total body weight of a fiftieth percentile adult male.

The characteristic ratio for the effective pelvic mass, R_m, is defined as,

$$R_m = 17.1\,\text{kg}/M_e \qquad \text{(R.2)}$$

The calculated mass ratios are given in Table M.2.

The stiffness ratio, R_k, is defined as,

$$R_k = K_s/K_i \qquad \text{(R.3)}$$

where K_s is the stiffness of the standard subject and K_i is the stiffness of the i-th subject. Mertz (17) has shown that for geometrically similar structures with the same elastic modulus, the stiffness is proportional to the characteristic length. The characteristic length was chosen to be the erect sitting height. For a 50th percentile adult male, the erect sitting height is 907 mm. The characteristic ratio for the thoracic stiffness, R_k, was calculated by,

$$R_k = 907\,\text{mm}/L_i \qquad \text{(R.4)}$$

where L is the erect sitting height of the cadaver whose data were to be normalized. Since the erect sitting height was also chosen to be the characteristic length for the abdomen, the stiffness ratios calculated for the abdomen and pelvis of a particular cadaver are equal. The stiffness ratios for the cadavers are given in Table R.2.

The normalizing factors for force, R_f, acceleration, R_a, and time, R_t, were calculated from the equations given by Mertz (17),

$$R_f = \left(R_m R_k\right)^{1/2} \tag{R.5}$$

$$R_a = \left(R_k / R_m\right)^{1/2} \tag{R.6}$$

$$R_t = \left(R_m / R_k\right)^{1/2} \tag{R.7}$$

The characteristic ratios and normalizing factors for each cadaver are given in Table R.2. The normalized force versus time histories were obtained by multiplying each value of force by its force normalizing factor and each value of time by its time normalizing factor. Figures R.4 and R.5 show the normalized force versus time histories for the rigid and padded impacts, respectively.

R.3 Response requirements

The normalized cadaver response for each impact configuration is the best estimate of the normalized response of the 50th percentile adult male. Response requirements for the side impact test device consist of corridors around the normalized force versus time histories of the pelvic impact surface and bounds for the peak normalized lateral acceleration of the sacrum.

Figures R.6, R.7, and R.8 show the force versus time response requirements for the 6,8 m/s rigid, 8,9 m/s rigid, and 8,9 m/s padded impacts, respectively. These corridors were constructed around the normalized cadaver curve(s) which are also shown. The normalized force versus time histories of the side impact dummies should lie within these corridors. Note that the normalized force versus time history of SIC 10 was similar to those of the other padded tests, even though SIC 10 impacted a paper honeycomb padding with a different compression rating than the others.

To define response requirements for the lateral acceleration of the sacrum, responses of SIC 14, SIC 15, SIC 16, and SIC 17 were averaged, since these four cadavers impacted paper honeycomb padding of the same compression rating. The proposed bounds for the lateral acceleration of the sacrum are given in Table R.3.

Table R.1 — Cadaver Data and Test Conditions from the Lateral Sled Tests Performed by WSU (31 and 15 1993)

	Cadaver Data				Test Conditions						
Test No.	Age	Sex	Mass (kg)	Erect Sitting Height (mm)	Pad Thickness (mm)	Compression Rating of Paper Honeycomb Pad (psi)					Sled Velocity (m/s)
						Shoulder	Thorax	Abdomen	Pelvis	Knee	
SIC 07	66	M	74,8	900	0	[a]	[a]	[a]	[a]	[a]	6,7
SIC 04	69	M	57,6	880	0	[a]	[a]	[a]	[a]	[a]	9,1
SIC 10	60	M	62,1	860	152	15	15	15	15	15	8,8
SIC 14	72	M	55,3	910	102	15	15	15	23	23	9,4
SIC 15	43	F	68,9	850	102	23	15	15	23	23	8,9
SIC 16	58	F	56,7	800	76	23	16	16	23	23	8,9
SIC 17	65	M	93,0	930	152	23	15	15	23	23	8,9

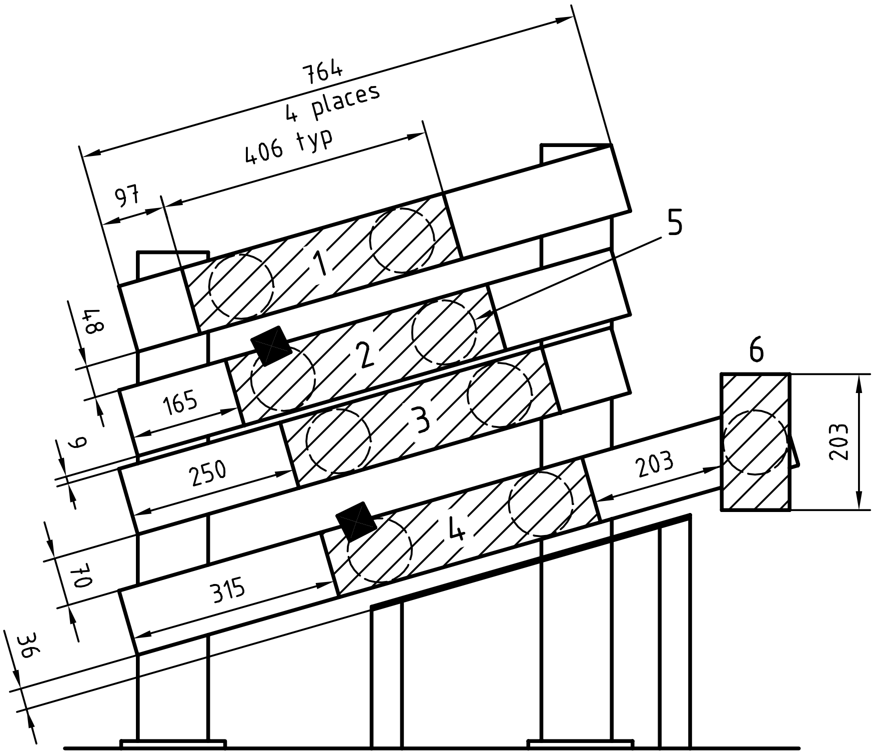
[a] Paper Honeycomb padding was not used in these rigid impacts.

Table R.2 — Test Results from the Lateral Sled Tests Performed by WSU (16); and Effective Mass, Characteristic Ratios and Normalizing Factors for These Data

Test No.	Test Results	Effective Mass		Characteristic Ratios		Normalizing Factors			Normalized Test Results
	Peak Lateral Accel. of the Sacrum (G)	M_e (kg)	Body mass (%)	Stiffness R_k	Mass R_m	Force R_f	Accel. R_a	Time R_t	Peak Lateral Accel. of the Sacrum (G)
SIC 07	127	17,8	23,9	1,01	0,96	0,98	1,03	0,97	131
SIC 04	106	14,7	25,5	1,03	1,16	1,09	0,94	1,06	100
SIC 10	45	15,8	25,4	1,05	1,09	1,07	0,98	1,02	44
SIC 14	118	9,0	16,3	1,00	1,89	1,37	0,73	1,37	86
SIC 15	74	13,4	19,4	1,07	1,28	1,17	0,91	1,09	67
SIC 16	77	14,2	25,1	1,13	1,20	1,16	0,97	1,03	75
SIC 17	72	20,6	22,2	0,98	0,83	0,90	1,09	0,92	78

Table R.3 — Pelvic Response Requirements for the Lateral Sled Tests Determined from the Response Data of WSU (16)

Test Conditions		Normalized Lateral Acceleration of the Sacrum		
Impact Velocity (m/s)	Compression Rating of the Pelvic Impact Surface (psi)	Average (G)	Lower Bound (G)	Upper Bound (G)
6,8	rigid	100	85	115
8,9	rigid	131	111	151
8,9	15	44	37	51
8,9	23	77	65	89



Key

1 Shoulder beam
2 Thorax beam
3 Abdomen beam
4 Pelvis beam
5 Load cell 9 places
6 Knee beam

Figure R.1 – Impact wall configuration for the lateral sled impacts

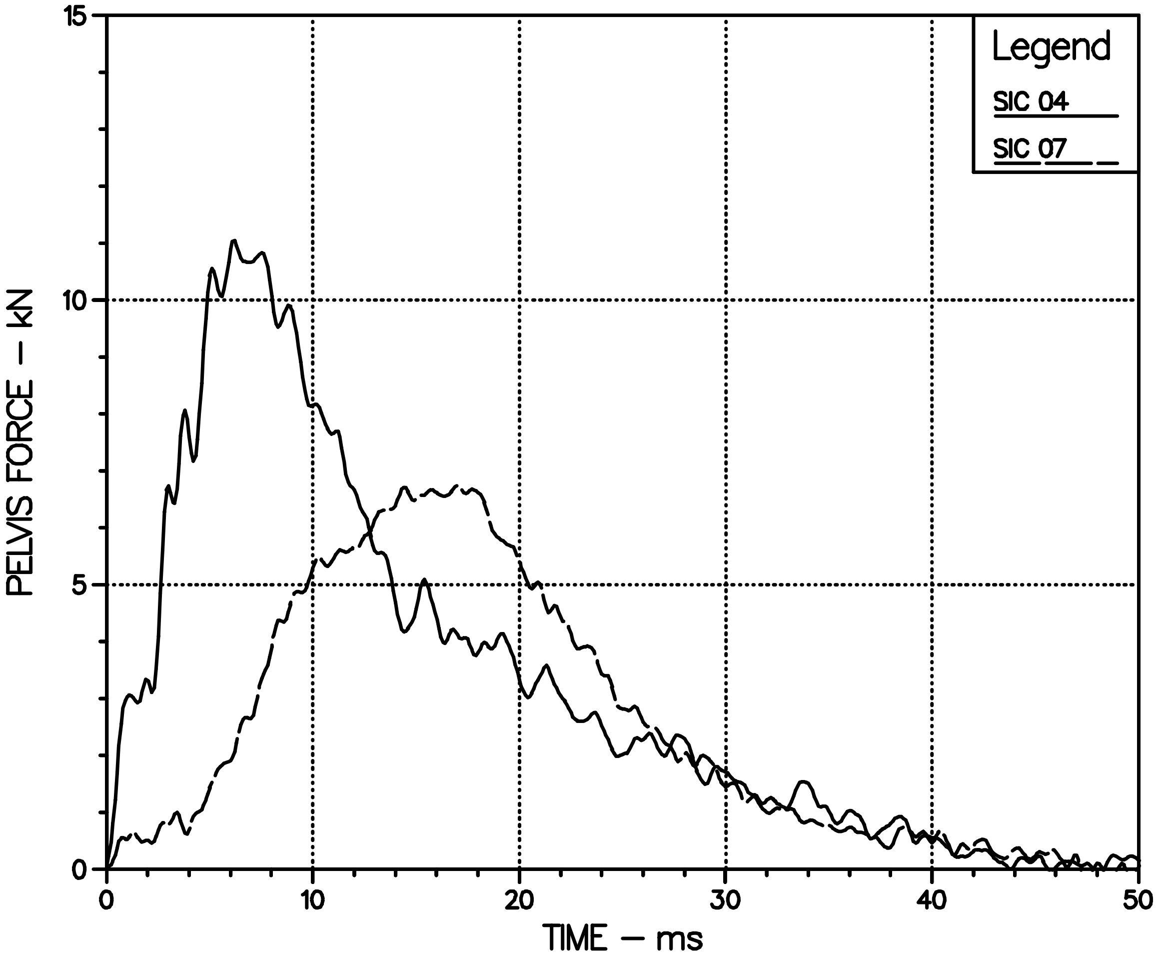


Figure R.2 – Pelvic impact surface force versus time histories for cadavers subjected to rigid wall impacts

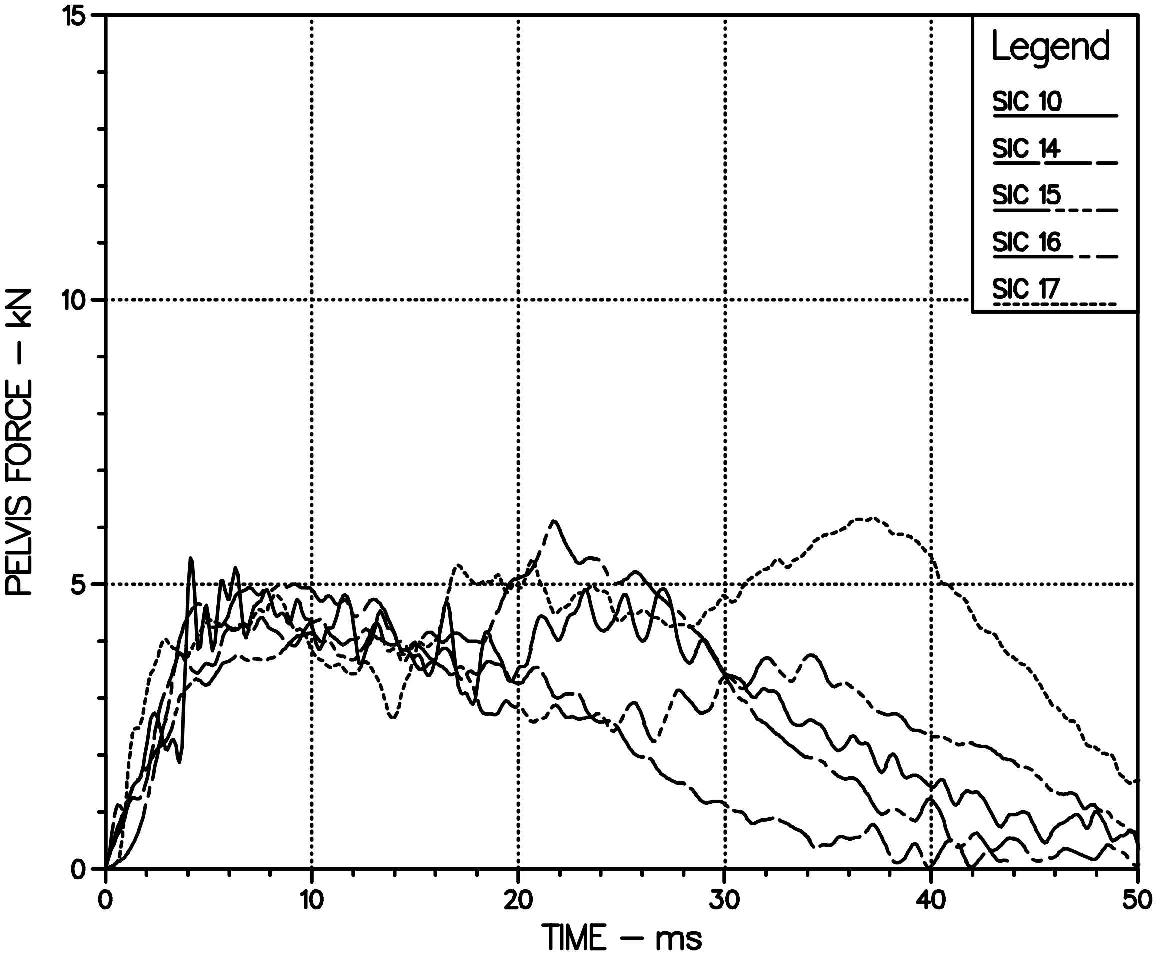


Figure R.3 – Pelvic impact surface force versus time histories for cadavers subjected to a 8,9 m/s padded wall impact

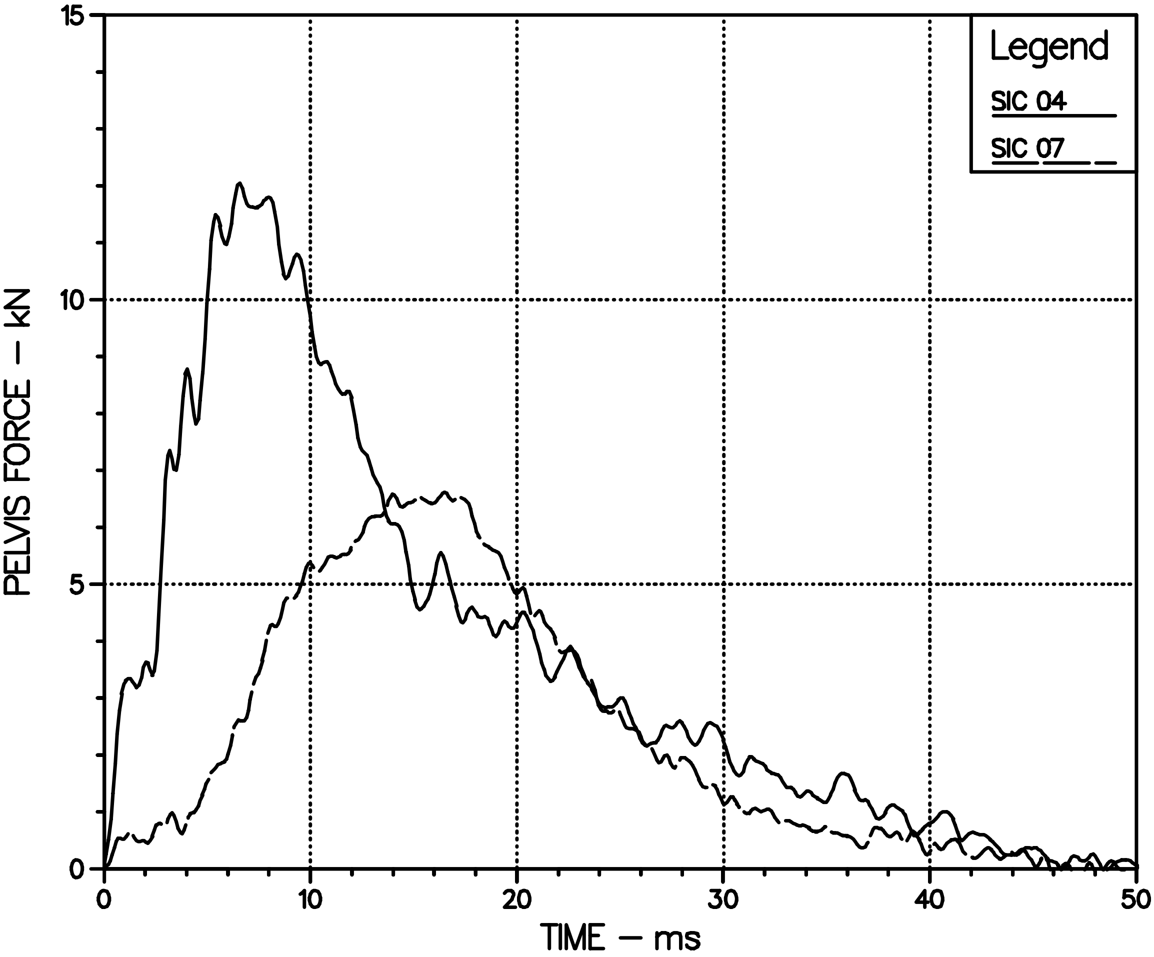


Figure R.4 – Normalized Pelvic impact surface force versus time histories for cadavers subjected to rigid wall impacts

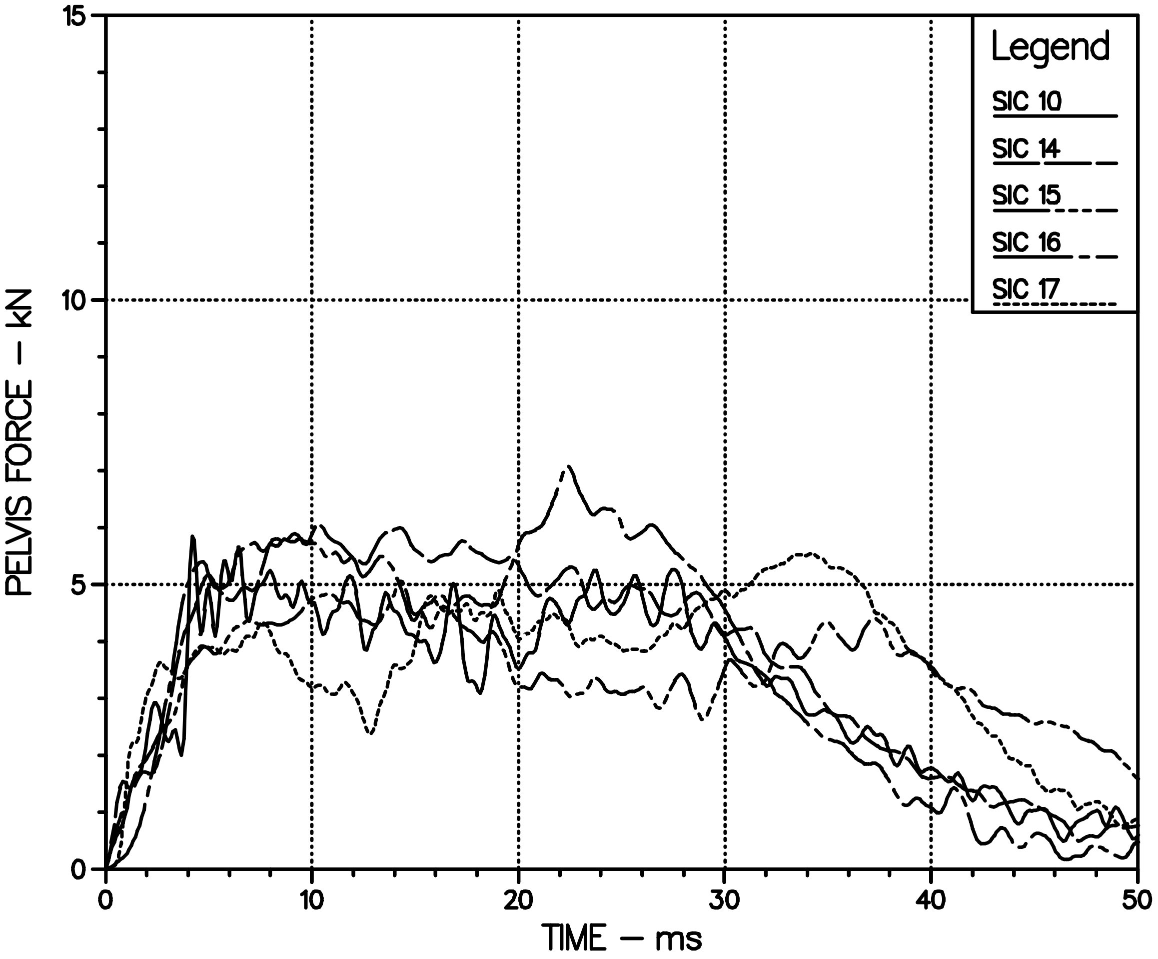


Figure R.5 — Normalized Pelvic impact surface force versus time histories for cadavers subjected to a 8,9 m/s padded wall impact

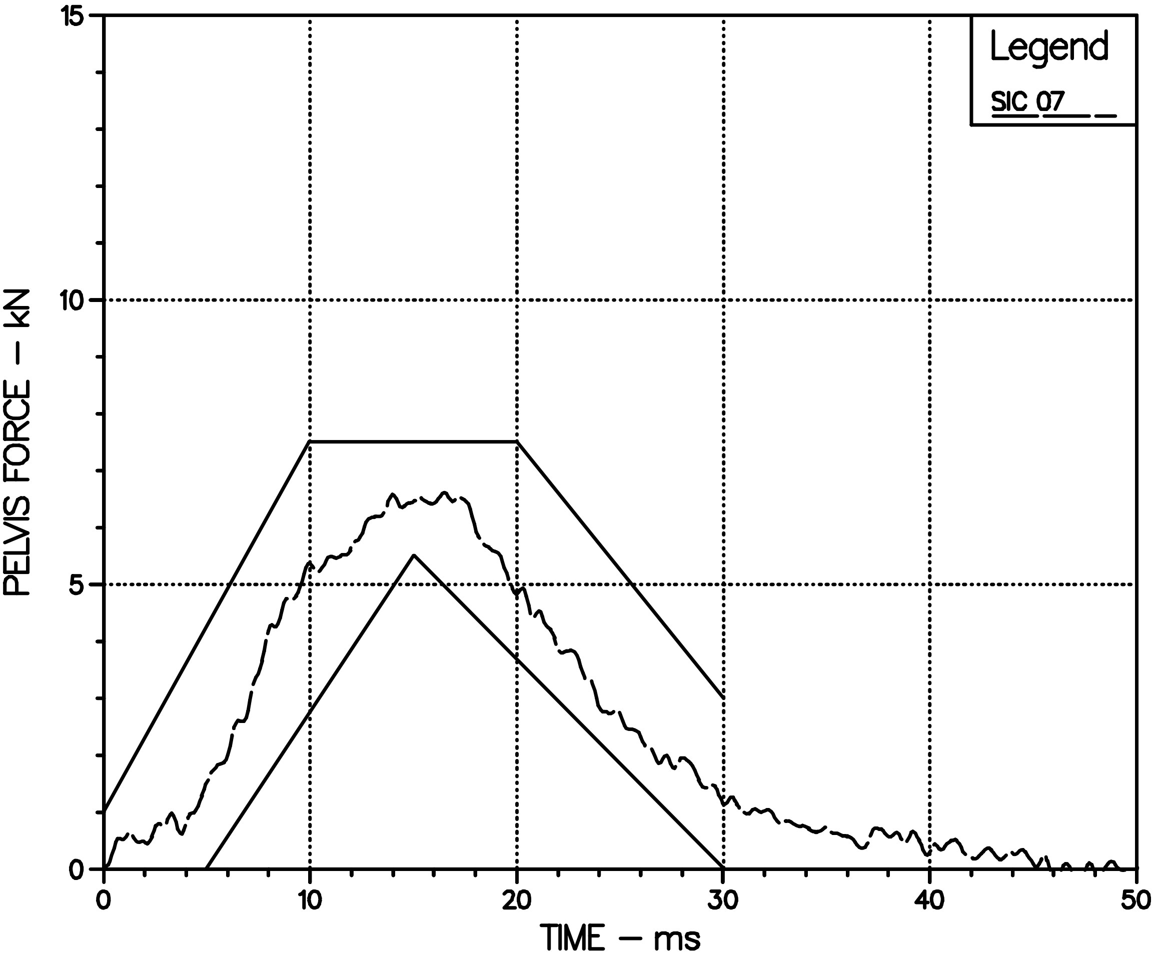


Figure R.6 — Normalized Pelvic impact surface force versus time histories and proposed response corridor for a 6,8 m/s rigid wall impact

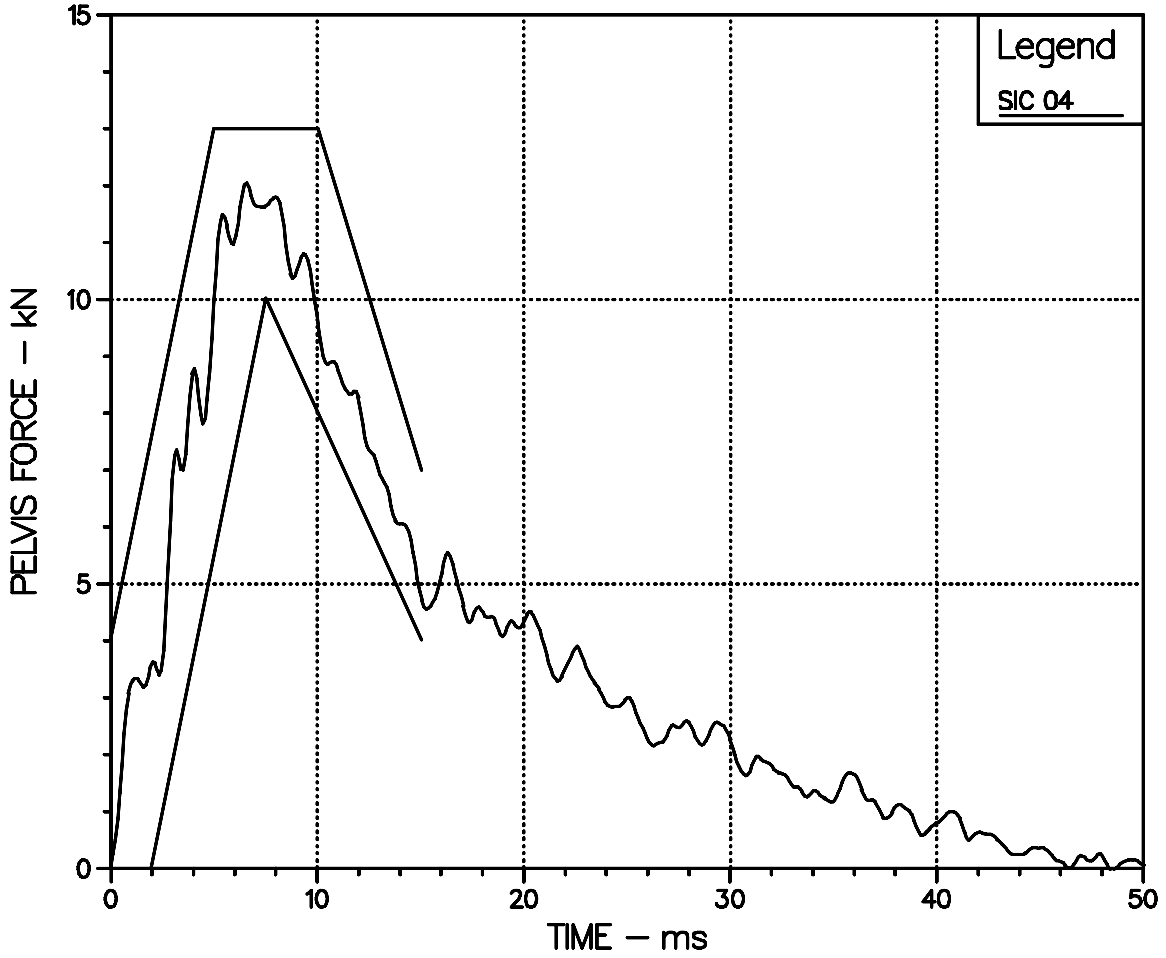


Figure R.7 — Normalized Pelvic impact surface force versus time histories and proposed response corridor for a 8,9 m/s rigid wall impact

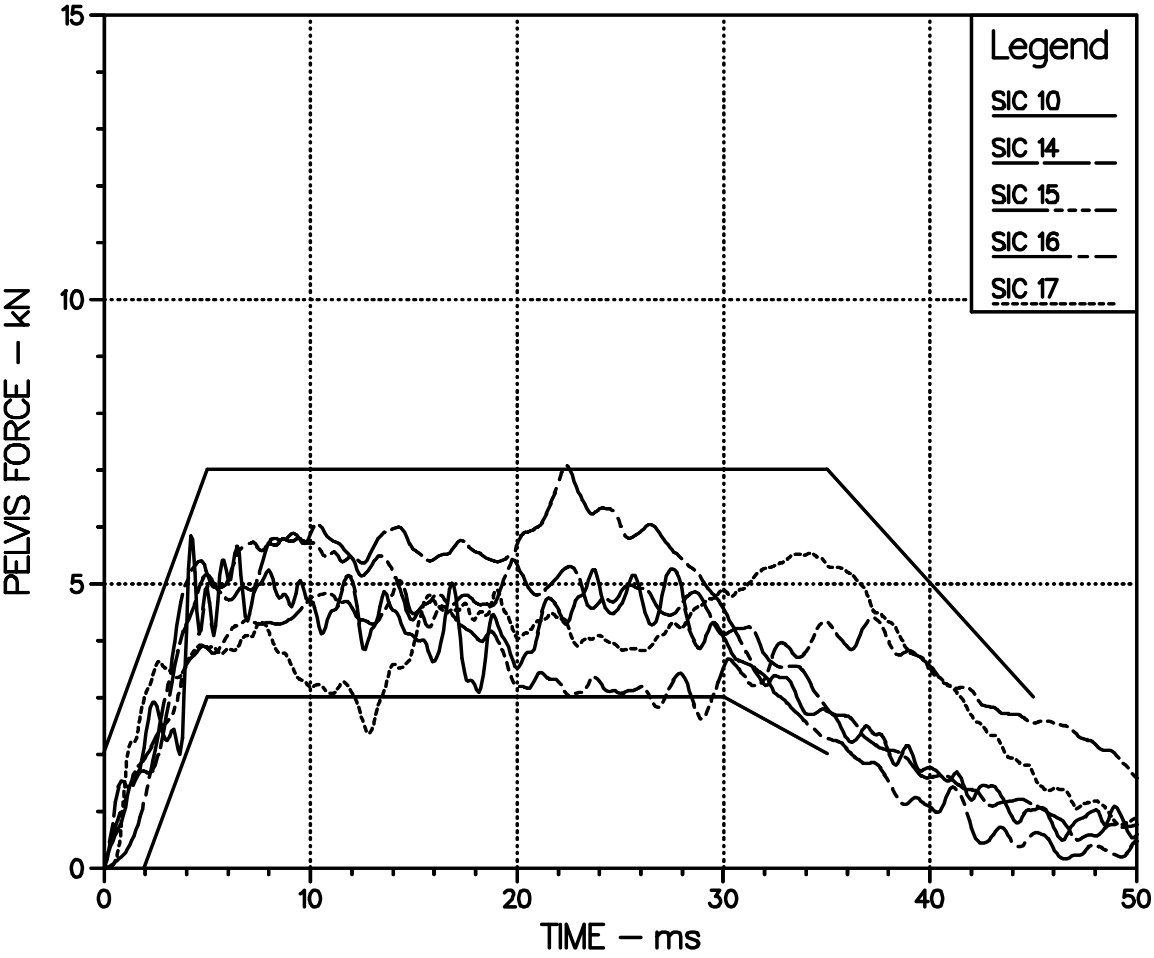


Figure R.8 — Normalized Pelvic impact surface force versus time histories and proposed response corridor for a 8,9 m/s padded wall impact

Annex S

Weighting factors for the body regions, impact conditions and responses

This annex gives the weighting factors for the body regions, impact conditions and response measurements for the tests described in this document. The weighting factors given here are an average of the values obtained from a poll of the ISO/TC22/SC12/WG5 experts.

Table S.1 — Weighting Factors for Body Regions, U_i

Body Regions	Weighting Factors
Head	$U_1 = 7$
Neck	$U_2 = 6$
Shoulder	$U_3 = 5$
Thorax	$U_4 = 10$
Abdomen	$U_5 = 8$
Pelvis	$U_6 = 8$

Table S.2 — Weighting Factors for Impact Conditions and Responses Defined for the Head

Impact Condition	Weighting Factors $V_{1,j}$	Response Measurements	Weighting Factors $W_{1,j,k}$
Head Test 1 200 mm Rigid Drop	$V_{1,1} = 8$	Peak Resultant Acceleration at a Point on the Non-impacted Side of the Head	$W_{1,1,1} = 9$
Head Test 2 1200 mm Padded Drop	$V_{1,2} = 4$	Peak Resultant Head Acceleration at the C.G.	$W_{1,2,1} = 9$

Table S.3 — Weighting factors for impact conditions and responses defined for the neck

Impact Condition	Weighting Factors $V_{2,j}$	Response Measurements	Weighting Factors $W_{2,j,k}$
Neck Test 1 7,2 G Sled Impact	$V_{2,1} = 7$	Peak Horizontal Acceleration of T1	$W_{2,1,1} = 5$
		Peak Horizontal Displacement of T1 Relative to the Sled	$W_{2,1,2} = 5$
		Peak Horizontal Displacement of the Head C.G. Relative to T1	$W_{2,1,3} = 8$
		Peak Vertical Displacement of the Head C.G. Relative to T1	$W_{2,1,4} = 6$
		Time of Peak Head Excursion	$W_{2,1,5} = 5$
		Peak Lateral Acceleration of the Head	$W_{2,1,6} = 5$
		Peak Vertical Acceleration of the Head	$W_{2,1,7} = 5$
		Peak Flexion Angle	$W_{2,1,8} = 7$
		Peak Twist Angle	$W_{2,1,9} = 4$
Neck Test 2 6,7 G Sled Impact	$V_{2,2} = 6$	Peak Flexion Angle	$W_{2,2,1} = 7$
		Peak Bending Moment about A-P Axis at Occipital Condyles	$W_{2,2,2} = 7$
		Peak Bending Moment about R-L Axis at Occipital Condyles	$W_{2,2,3} = 3$
		Peak Twist Moment	$W_{2,2,4} = 4$
		Peak Shear Force at Occipital Condyles	$W_{2,2,5} = 7$
		Peak Tension Force at Occipital Condyles	$W_{2,2,6} = 6$
		Peak P-A Shear Force	$W_{2,2,7} = 3$
		Peak Resultant Head Acceleration	$W_{2,2,8} = 4$
Neck Test 3 12,2 G Sled Impact	$V_{2,3} = 3$	Peak Lateral Acceleration of T1	$W_{2,3,1} = 5$
		Peak Lateral Acceleration of the Head C.G.	$W_{2,3,2} = 5$
		Peak Horizontal Displacement of the Head C.G. Relative to the Sled	$W_{2,3,3} = 8$
		Peak Flexion Angle	$W_{2,3,4} = 7$
		Peak Twist Angle	$W_{2,3,5} = 4$

Table S.4 — Weighting Factors for Impact Conditions and Responses Defined for the Shoulder

Impact Condition	Weighting Factors $V_{3,j}$	Response Measurements	Weighting Factors $W_{3,j,k}$
Shoulder Test 1 4,5 m/s Pendulum	$V_{3,1} = 6$	Pendulum Force	$W_{3,1,1} = 8$
		Peak Shoulder Deflection	$W_{3,1,2} = 6$
Shoulder Test 2 7,2 G Sled Impact	$V_{3,2} = 5$	Peak Horizontal Acceleration of T1	$W_{3,2,1} = 6$
		Peak Horizontal Displacement of T1 Relative to the Sled	$W_{3,2,2} = 6$
Shoulder Test 3 12,2 G Sled Impact	$V_{3,3} = 3$	Peak Lateral Acceleration of T1	$W_{3,3,1} = 6$
Shoulder Test 4 8,9 m/s Padded Sled	$V_{3,4} = 7$	Shoulder + Thoracic Plate Force	$W_{3,4,1} = 9$
		Peak Lateral Displacement of T1	$W_{3,4,2} = 5$

Table S.5 — Weighting Factors for Impact Conditions and Responses Defined for the Thorax

Impact Condition	Weighting Factors $V_{4,j}$	Response Measurements	Weighting Factors $W_{4,j,k}$
Thorax Test 1 4,3 m/s Pendulum	$V_{4,1} = 9$	Pendulum Force	$W_{4,1,1} = 9$
		Upper Spine Lateral Acceleration	$W_{4,1,2} = 7$
Thorax Test 2 6,7 m/s Pendulum	$V_{4,2} = 9$	Pendulum Force	$W_{4,2,1} = 9$
Thorax Test 3 1,0 m Rigid Drop	$V_{4,3} = 6$	Thorax Plate Force	$W_{4,3,1} = 8$
		Peak Deflection of the Impacted Rib	$W_{4,3,2} = 8$
Thorax Test 4 2,0 m Padded Drop	$V_{4,4} = 5$	Thorax Plate Force	$W_{4,4,1} = 8$
		Peak Deflection of the Impacted Rib	$W_{4,4,2} = 7$
Thorax Test 5 6,8 m/s Rigid Sled	$V_{4,5} = 7$	Thorax Plate Force	$W_{4,5,1} = 8$
		Peak Lateral Acceleration of the Upper Spine	$W_{4,5,2} = 7$
		Peak Lateral Acceleration of the Lower Spine	$W_{4,5,3} = 7$
		Peak Lateral Acceleration of the Impacted Rib (corresponding to the 4th rib of adult male)	$W_{4,5,4} = 6$
Thorax Test 6 8,9 m/s Padded Sled	$V_{4,6} = 7$	Shoulder + Thoracic Plate Force	$W_{4,6,1} = 9$
		Peak Lateral Displacement of T12	$W_{4,6,2} = 5$

Table S.6 — Weighting Factors for Impact Conditions and Responses Defined for the Abdomen

Impact Condition	Weighting Factors $V_{5,j}$	Response Measurements	Weighting Factors $W_{5,j,k}$
Abdomen Test 1 1 m Rigid Drop	$V_{5,1} = 7$	Armrest Force	$W_{5,1,1} = 9$
		Peak Acceleration of the Lower Spine	$W_{5,1,2} = 6$
		Peak Acceleration of the Impacted Rib	$W_{5,1,3} = 4$
		Peak Abdomen Penetration	$W_{5,1,4} = 9$
Abdomen Test 2 2 m Rigid Drop	$V_{5,2} = 6$	Armrest Force	$W_{5,2,1} = 9$
		Peak Acceleration of the Lower Spine	$W_{5,2,2} = 6$
		Peak Acceleration of the Impacted Rib	$W_{5,2,3} = 4$
		Peak Abdominal Penetration	$W_{5,2,4} = 9$
Abdomen Test 3 6,8 m/s Rigid Sled	$V_{5,3} = 3$	Abdominal Plate Force	$W_{5,3,1} = 9$
Abdomen Test 4 8,9 m/s Rigid Sled	$V_{5,4} = 3$	Abdominal Plate Force	$W_{5,4,1} = 9$
Abdomen Test 5 8,9 m/s Padded Sled	$V_{5,5} = 7$	Abdominal Plate Force	$W_{5,5,1} = 9$

Table S.7 — Weighting Factors for Impact Conditions and Responses Defined for the Pelvis

Impact Condition	Weighting Factors $V_{6,j}$	Response Measurements	Weighting Factors $W_{6,j,k}$
Pelvis Test 1 6,0 m/s Pendulum Impact	$V_{6,1} = 8$	Pendulum Force	$W_{6,1,1} = 9$
Pelvis Test 2 10,0 m/s Pendulum Impact	$V_{6,2} = 9$	Pendulum Force	$W_{6,2,1} = 9$
Pelvis Test 3 0,5 m Rigid Drop	$V_{6,3} = 4$	Peak Pelvic Acceleration	$W_{6,3,1} = 7$
Pelvis Test 4 1,0 m Rigid Drop	$V_{6,4} = 4$	Peak Pelvic Acceleration	$W_{6,4,1} = 7$
Pelvis Test 5 2,0 m Padded Drop	$V_{6,5} = 3$	Peak Pelvic Acceleration	$W_{6,5,1} = 7$
Pelvis Test 6 3,0 m Padded Drop	$V_{6,6} = 5$	Peak Pelvic Acceleration	$W_{6,6,1} = 7$
Pelvis Test 7 6,8 m/s Rigid Sled	$V_{6,7} = 8$	Peak Pelvic Force	$W_{6,7,1} = 9$
		Peak Pelvic Acceleration	$W_{6,7,2} = 7$
Pelvis Test 8 8,9 m/s Rigid Sled	$V_{6,8} = 7$	Peak Pelvic Force	$W_{6,8,1} = 8$
		Peak Pelvic Acceleration	$W_{6,8,2} = 7$
Pelvis Test 9 8,9 m/s Padded Sled	$V_{6,9} = 8$	Peak Pelvic Force	$W_{6,9,1} = 9$
		Peak Pelvic Acceleration	$W_{6,9,2} = 8$
Pelvis Test 10 6,8 m/s Rigid Sled	$V_{6,10} = 3$	Pelvic Plate Force	$W_{6,10,1} = 9$
		Peak Lateral Pelvic Acceleration	$W_{6,10,2} = 7$
Pelvis Test 11 8,9 m/s Rigid Sled	$V_{6,11} = 3$	Pelvic Plate Force	$W_{6,11,1} = 9$
		Peak Lateral Pelvic Acceleration	$W_{6,11,2} = 7$
Pelvis Test 12 8,9 m/s 15 psi Padded Sled	$V_{6,12} = 3$	Pelvic Plate Force	$W_{6,12,1} = 9$
		Peak Lateral Pelvic Acceleration	W6,12,2 = 7
Pelvis Test 13 8,9 m/s 23 psi Padded Sled	$V_{6,1}3 = 7$	Pelvic Plate Force	$W_{6,13,1} = 9$
		Peak Lateral Pelvic Acceleration	$W_{6,13,2} = 7$

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