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REVIEW OF DUMMY DESIGN AND USE

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16. Abstract

This report addresses various aspects of current anthropometric test device (ATD), or dummy, design and use. It includes the results of an international survey of dummy users, an evaluation of two current dummies from the standpoints of manufacturability and cost, a summary of repeatability and reproducibility assessment techniques, a review of anthropometric data available for dummy design, a demonstration biomechanical-response simulation for use in dummy design, and a review and evaluation of the major ATDs with emphasis on biofidelity, measurement capability, directionality, and impact testing performance. The overall conclusions are that current ATDs are deficient in many important areas, but that sufficient experience, data, and technology exists to make substantial improvements in dummy design, with associated benefits for their users.

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PREFACE

This report addresses various aspects of current anthropometric test device, or dummy, design and use. It includes the results of an international survey of dummy users, an evaluation of two current dummies from the standpoints of manufacturability and cost, a summary of repeatability and reproducibility assessment techniques, a review of anthropometric data available for dummy design, a demonstration biomechanical-response simulation for use in dummy design, and a review and evaluation of the major ATDs with emphasis on biofidelity, measurement capability, directionality, and impact testing performance. The overall conclusions are that current ATDs are deficient in many important areas, but that sufficient experience, data, and technology exists to make substantial improvements in dummy design, with associated benefits for their users.

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CHAPTER 1

DUMMY USER SURVEY RESULTS

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INTRODUCTION

A survey of users of the Part 572 and Hybrid III dummies was taken to determine the problems these users have encountered and their preferences for changes and improvements in dummy design. The questionnaire itself was developed primarily by G.W. Nyquist, Wayne State University, and was made available to a wide audience through NHTSA, SAE, ISO, and various individual contacts.

Responses were received from thirty-eight individuals representing twenty-nine organizations. The affiliation of the thirty-eight respondents can be categorized as follows:

7	U.S. vehicle industry
9	Foreign vehicle industry
12	U.S. government
4	Foreign government
2	Dummy manufacturing
4	Independent research

See Appendix A for a complete list.

This report summarizes the responses of these thirty-eight dummy users. Although the categories above are not represented equally in numbers, care is taken to present each viewpoint fairly within the context of the user community as a whole, while emphasizing those opinions expressed by more than one or two respondents. When significant differences of opinion are apparent among user categories, these differences are indicated.

This report follows the organization of the questionnaire and includes the following sections:

- Mechanical Design
- Serviceability and Maintenance
- Durability
- Certification
- Repeatability and Reproducibility
- Ease of Use

Each response summary is headed by the original question number and a brief indication of the question topic. (The full text of the questions themselves is given in Appendix B.) Finally, there is a summary of the general lessons to be learned from the experiences of these dummy users and what the indications are for the design and development of an AATD.

SURVEY

MECHANICAL DESIGN

1.1 Crash Environment. The primary environmental factors addressed by respondents were directionality and restraint conditions. Because of skepticism that an omnidirectional dummy was possible and/or that it could be as good as separate frontal and lateral dummies, industry and foreign government respondents favored the latter 2 to 1. U.S. government, dummy manufacturer, and independent research respondents favored the former almost unanimously. All agreed that the dummy should be able to respond under any restraint condition, including unrestrained, but there was support for the inclusion of pedestrian capabilities only among the government and the foreign industry respondents. Two specifically mentioned motorcyclists. There was special concern about the shoulder, thorax, and pelvis relative to dummy kinematics, and knee impacts were also highlighted. A respondent involved with aircraft applications also mentioned an interest in upward accelerations and helmeted-head impacts.

1.2 Feasibility and Tradeoffs Regarding Directionality, Biofidelity, and Repeatability. Industry and foreign government respondents again took the conservative approach that a frontal/lateral convertible dummy was the most feasible and thus the best approach at this time. U.S. government respondents tempered their enthusiasm for omnidirectional dummies, however, by acknowledging that a single- or two-directional dummy would likely be more repeatable and thus preferable for compliance testing. Although several among all types of respondents commented that repeatability and durability were more important than omnidirectionality, and even biofidelity, the majority responded that avoiding compromises in dummy performance was desirable but not essential in order to accommodate a multidirectional or omnidirectional dummy. U.S. industry and government respondents were less willing than other respondents to compromise repeatability and durability for omnidirectionality.

One respondent made a distinction between kinematic and kinetic fidelity, the former possibly being more important. Shoulder kinematics were identified as being of particular importance in both frontal and lateral impacts.

The question of frontal versus lateral performance was generally summarized by "Don't compromise frontal for lateral," so concentrate on frontal if both cannot be done. A few dissenters among U.S. respondents took the approach that there is already an adequate frontal dummy (Hybrid III), so work should focus on a separate lateral dummy or conversion kit. No foreign respondent mentioned the Hybrid III, and one even commented that there was an "urgent need" for a frontal dummy other than the Part 572.

Several respondents chose to define what "frontal" and "lateral" should include. For frontal, both $0^\circ \pm 20^\circ$ and $0^\circ \pm 30^\circ$ were used. Lateral was defined variously as $90^\circ \pm 30^\circ$, $90^\circ \pm 20^\circ$, and $90^\circ + 20, -10^\circ$.

1.3 Clothing and Shoes. There were pros and cons expressed for the use of actual clothing. While it provided a realistic frictional interaction between restraint and dummy and protected the dummy from wear, it made accurate targeting and film analysis difficult. Only the foreign industry respondents thought it could be dispensed with, favoring instead that the dummy surface be made to perform like clothing. U.S. respondents, however, would prefer a realistic skin/soft-tissue on the dummy and use tight-fitting clothing for frictional and protective effects. One respondent suggested that the targeting problem could be addressed by permanent points on the dummy to which targets could be attached through the surface clothing.

Regarding shoes, it was generally agreed that the extra height and frictional characteristics of the sole were necessary, but several suggested that this could be accomplished best through a permanent molded "shoe" on the dummy foot.

Clothing and shoes were said to have a certain value for the public relations function in which test films are often used.

1.4 Skin Color and Anatomical Landmarks. White (or off-white) and yellow were the colors most frequently mentioned, followed by flesh or tan. Orange, light blue, and light green were also suggested. Those who mentioned surface finish all emphasized that it not be reflective. A few suggested different colors for different body parts or for the right and left sides. Others wanted an option to order dummies in different colors to distinguish between two in the same test.

In general, major body segment centers-of-gravity and major joint pivot points were identified as desired landmarks. These included CGs of the head, thorax, pelvis, upper leg, and lower leg and pivot points of the hip, knee, shoulder, elbow, and ankle joints. It was recognized that H-point and hip pivot point were not necessarily the same thing. Also mentioned by at least two respondents were C_1, C_7 or clavicle, T_1, T_{12}, anterior-superior iliac spine (ASIS), and hand. Some respondents indicated a need for additional targets on the head, pelvis, etc., for use in rotational analysis and as back-up when the primary target is obscured.

Comments indicated that targets should be made of high-contrast or reflecting material and should be rigidly attached to the skeleton, not the skin. For assistance in rotational and belt slippage analysis, some suggested a checkerboard pattern on selected surfaces.

1.5 Non-Metallic Skeleton for Humanlike Mass Distribution. Although nearly all respondents indicated that they favored the idea, most mentioned at least one of several potential problems. The primary concern was for durability and the related problem of repairability in terms of feasibility, cost, time, and potential toxicity. Sensitivity to temperature, aging effects, and the possible difficulties in attaching transducers and targets were also often mentioned. There seemed to be some doubt that non-metallic materials could in fact be as repeatable and reproducible as metallic ones, especially if actual bone shapes were produced. Although some mechanical resonance and "ringing" problems might be eliminated, new problems related to different resonant frequencies might occur. Another advantage would be the potential for making "bones" flexible, such as in the pelvis, which could be achieved with glass-fiber/epoxy or other composite materials. It was also suggested that, if the skeleton was accurate in mass distribution, the "flesh" would then have to be solid rather than the current foam material, but that this should be achievable.

1.6 Acceptability of Frangible Parts. The majority responded that frangible parts would either not be acceptable at all or at least not in some test circumstances. Even those accepting the concept often qualified it by emphasizing the "if" regarding moderate replacement cost, enhanced performance, and direct load-severity measurement capabilities. The most acceptable approach, particularly among industry respondents, would be the provision of optional frangible parts for research purposes and/or for testing the response of specific body regions under limited impact conditions. The primary complaint regarding such parts was the pass/fail nature of the results. It was considered crucial by many that the dummy show the extent of the failure or how close the test was to the point of failure. One respondent, however, suggested that such a pass/fail system might in fact be appropriate for certification purposes.

1.7 Joint Stiffness and Degrees of Freedom. A large majority of the respondents approved of the concept of progressive-resistance joint-stops, indicating that the hard bump-stops were the source of durability problems as well as spurious signals. Caution was expressed, however, regarding repeatability and maintainability, one respondent noting that these problems have precluded such designs for past dummies. There was virtually no support for a remote control capability for changing joint stiffness during impact.

Very few comments were made regarding degrees of freedom. Two mentioned that current hip joints were too limited; one said a complex shoulder was unnecessary; another wanted the thorax to rotate about the 2-axis relative to the pelvis; and a few said that ankle, wrist, toe, and finger joints were not needed.

1.8 Arms Versus No Arms. Although those favoring arms under all conditions were in the clear majority, several respondents, representing all respondent groups, did indicate advantages for an armless dummy during side impact as well as in configurations in which the arms obscured the view of optical measures. It was also indicated that dummies simulating pedestrians did not need arms. In contrast, those commenting in favor of arms indicated that they did affect dummy kinematics and response under all impact conditions and thus could not be omitted even if this would be more convenient.

1.9 Functional Hands. Although the voting was fairly even for and against this concept, and several respondents were indifferent, the comments indicated an actual preference against this type of complexity. Those in favor indicated it would be nice if a simple grasping and break-free system were devised, while those opposed said it would definitely not be worth the trouble. One respondent thought that the current system of taping the hands was adequate, and two who liked the idea of a grasping hand added that the controlled break-free feature was not needed.

1.10 Attachable and Break-Free Feet. There was very little support for this idea. The consensus of those who commented was that some friction is needed for initial positioning, but that this could be provided by the shoe/foot sole.

1.11 SI Metric Units. Metric units were definitely favored by all foreign respondents and several U.S. respondents. What little opposition there was came from U.S. respondents. The question may have come as a surprise to many who answered as though it would be ludicrous to do otherwise.

1.12 Muscle Tension. There was a problem of definition of terms. Four respondents favoring "intermediate" tension and two favoring "relaxed" defined their choice as the current 1-G requirement. It was clear from several comments that the dummy must, at a minimum, be able to hold an initial set-up position, and this required a degree of tension somewhat greater than "relaxed." Beyond this, several suggested that the actual degree of tension be determined from field accident experience. Those few who supported a "tensed" dummy assumed that this was in fact the most likely real-world situation. Two favoring a "relaxed" state said this would represent the worst case. Several respondents suggested that ideally the dummy would be adjustable to simulate a range of muscle tension, especially for research purposes.

1.13 Structural Failure Versus Continuous Response Beyond Acceptable Injury Range. Among those who answered this long and complex question, the vast majority favored the continuous response approach beyond the point at which an actual human structure might fail. Reasons given were similar to those for non-frangible parts. Dummy users wanted to keep replacement and repair costs to a minimum, they believed that durable structures were more repeatable, and they needed to know how far beyond a "safe" level the tested systems were. These factors could not be outweighed by the potentially improved kinematics or the realism of organ damage offered by a dummy that mimicked human structural failure.

1.14 Injury Types and AIS Ranges for Each Body Region that the Dummy Should Sense. The most succinct response to this question was "yes." Another said, "Wow! What a question . . . and so little space to answer." Some pointed out that dummies could not and should not indicate an AIS level directly and gave instead the types of response measurements to be made in various body regions. Some did attempt to answer the question in the detail requested, but most answered a range of AIS for all body regions that was typically 2 through 6. A few went down to AIS–1 and some had an upper limit of AIS–4, but it was not clear that everyone interpreted the question in the same manner. Only two gave details of injury types of interest, but nothing unexpected was included, except perhaps an emphasis on joint damage and socket injury. It was also suggested that the answer might be different depending on whether the dummy was used for compliance or research.

1.15 Facial Features. The issue was clouded by the fact that the question equated the Hybrid III with "featureless." Four respondents pointed out that this was not the case, and six others indicated that, by featureless, they were referring to the Hybrid III style of semi-featureless face. It was not clear, therefore, how many of the twenty who merely indicated "featureless" were actually thinking of the Hybrid III style rather than a completely smooth face. In general, the preference for a smooth or semi-featureless face was justified on the basis of improved repeatability. The minority in favor of full features, however, said that facial contact was more easily determined and that there was a public relations benefit to a humanlike face. One respondent said ears would be useful.

1.16 Other Mechanical Design Issues. Many issues raised here were covered elsewhere in the survey, particularly in the Serviceability and Maintenance area. Other design suggestions included a flexible thoracic spine, spherical shoulder joints, a more realistic lumbar/pelvic region, a better-shaped chest for better belt fit, shoulder padding to prevent belt entrapment between the shoulder and upper arm, the avoidance of temperature sensitivity, indicators of vehicle interior contact and duration of contact, more injury indicators including facial laceration, and a range of dummy complexity from a simple version for compliance testing to a more complex dummy for research purposes.

SERVICEABILITY AND MAINTENANCE

2.1 Access to Instrumentation in Vehicle-Seated Position. The overwhelming response was that accessibility to instrumentation, once the dummy was seated for a test, would be desirable but not essential. Comments indicated that there should be no trade-off with durability, fidelity, or optimal transducer location to achieve this convenience.

2.2 Specified Storage Fixture and Attachment Points. The vast majority approved of this concept without comment. A significant minority among U.S. respondents, however, said that attachment points should be provided but that the actual storage fixture should be locally devised. A few of those voting "no" indicated that they hoped the AATD would not be sensitive to mode of storage. One respondent indicated that the head eyebolt system was not acceptable. Two respondents contributed designs using a seated configuration, torso anchors, and wheels for transport.

2.3 Joint Adjustment Access through Skin Holes. Nearly all respondents who had an opinion had minor or intermediate difficulty with joint adjustment access. In particular, the holes were considered too small. Two suggested that a set of tools be provided with the dummy, and that the number needed be kept to a minimum. Different joints seemed to cause problems for different respondents, with the shoulder receiving the most notice. Also mentioned were the elbow, knee, and hip joints, and the access holes to the femur load cell.

2.4, 2.5 Service and Maintenance Difficulties. Responses are grouped by body region. All comments relate to the Part 572 dummy unless otherwise noted.

Head. The poor fit between head-skin and skull was most often cited, making the skin difficult to put on and take off. The skin on the head-back was said to have the opposite problem and tended to come loose at the edge and even fall off. The vertical bolts holding the head accelerometer mount and connecting the head to the neck were difficult to install, and the necessity of removing the instrumentation package in order to remove the head from the neck was considered inconvenient. The inaccessibility of the Hybrid III head attachment bolt was also cited. These problems were rated as minor to intermediate.

Neck. The neck was considered quite difficult to inspect because of the skin covering it. This was rated as an intermediate to severe problem. Another intermediate difficulty was the tendency of the lower neck attachment screws to loosen due to shrinkage of the leather bib. One respondent referred to a suggested redesign of the neck bracket, described in an ISO document (WG5, N12), that allows mounting and removal from the top rather than through the thorax. One comment on the Hybrid III neck was that it had too many parts and was thus hard to assemble.

Shoulder. Access to and adjustment of the shoulder was considered very difficult, and disassembly could take an hour. Therefore, inspection or replacement of the clavicle and/or its "bump stops" was a major task. These joint stops were said to not be worth the effort to try to set. These problems were rated intermediate to severe. Assembly and disassembly of the Hybrid III shoulder was considered similarly difficult.

Thorax. Several commented that removal of the skin/flesh jacket was difficult because removal of the arms was required. A means of inspecting the ribs without removing the skin would be welcome. Zipper replacement was also time-consuming. The bib was said to be difficult to install, because it had to be "shoved" between the foam and the ribs, and the upper screws of the sternum were hard to reach and install. The most severe problem cited was the inability to inspect the bonding of the rib damping material because it was obscured by the shrink tubing. There were also complaints about the lack of a gauge to quantify permanent rib deformation. Access to accelerometers was considered difficult, and the cable often became pinched. Most of these problems were rated severe. It was suggested that the accelerometer mount for the chest should be identical to the one for the head. On the Hybrid III, accelerometers and transducers were also considered difficult to access and service, requiring that the dummy be split between the lumbar and thoracic spines.

Lumbar Spine. The most severe problem was the costly replacement after cracks in the rubber developed, although the effect of these cracks was not known. Other comments related to difficulties with installation, height adjustment, access, and removal. A screw slot in the cable was suggested to facilitate its installation, adjustment, and removal. These problems were rated at intermediate severity. Access to and adjustment of the Hybrid III lumbar spine was also said to be difficult.

Pelvis. The non-removable pelvic foam presented severe problems to several respondents in that it broke down, developed a permanent compression affecting dummy seated height and could not be repaired or replaced. Difficulties in setting pelvic angle, a critical factor in submarining behavior, also affected seated height, which in turn affected test repeatability. Another severe problem was that the access holes to the hip joint were considered too small for adjusting joint clearance or for easily reaching the femur retainer screws. It was thus difficult to replace the femur ball. Other comments were that the screws were too small in the instrument cavity and that threaded inserts were needed. Also, the pelvic flesh tended to interfere with hip joint movement, symmetry of the skin tended to shift with use, and damage to the abdominal insert was difficult to check and repair.

Upper Extremities. Respondents said that removable flesh would be desirable for the arms, that the skin overlap at the elbow interfered with joint movement, and that the skin on the hands easily tore at the palm and thumb and was difficult to repair.

Lower Extremities. Severe problems identified were inadequate means of attaching the ball to the femur and the femur to ends of the load cell. There was too much play in the latter, and thus excess tightening of the bolts was required. The knee casting was considered difficult to replace, and replacement of the knee skin required removal of the leg and adjustment bolt, which could cause the clutches to shift out of alignment. This was a severe problem. The knee not being sealed allowed it to get dirty, making it difficult to adjust and calibrate, and the flesh again interfered with joint motion. Respondents would prefer removable flesh on the lower leg as well. Problems with the foot were that shoes did not fit well and that the flesh was easily cut.

Joints. Numerous comments were made about the severe problem of joint adjustment. It was considered difficult, if not impossible, to set the joints to 1 G and have this maintained through the full range of motion. In general, service holes were considered too small, finer threads were needed, and loose friction washers were troublesome. It was suggested that these should be attached to the joint surface. Rust was also mentioned as an occasional but severe problem.

Skin. In general, the skin presented severe problems because it was porous and tacky, making cleaning and target adherence difficult. It also tore easily and was difficult to repair. Skin closures, i.e., zippers, could have an improved means of attachment to the skin, and closures for removable limb skin would be welcome.

Documentation. Written information concerning the handling and maintenance of the Part 572 dummy was considered inadequate for training personnel and for dealing with everyday problems. A handbook giving repair and adjustment procedures, including "tricks of the trade" was requested.

General. Respondents expressed a need for better access to and interchangeability of parts to facilitate inspection and replacement.

DURABILITY

3.1, 3.2, 3.7 Component Durability and Resistance to Wear. Responses are grouped by body region. All comments relate to the Part 572 dummy unless otherwise noted.

Head. The head seemed to be free of durability problems except for one mention of head-skin tearing.

Neck. The neck was not considered very durable in that the rubber would crack, the bond between the rubber and the metal plate often failed, and the neck bracket would bend, changing the angle between the neck and the torso. Such failures were said to occur in frontal tests of belt systems and in head/neck pendulum tests. The neck was also said to stiffen with age. It was pointed out that the original welded version of the neck bracket was known to break, but that the alternate cast version had not. Failures of the Hybrid III neck bracket had also been experienced under severe unrestrained test conditions.

Shoulder. Clavicles were reported to be the most frequently broken dummy component, especially under test conditions in which the arms were free to flail and rotate. This was also mentioned as a problem with the Hybrid III. There was some difference of opinion, however, as to whether the breakage on the Part 572 dummy was most common on the shoulder-belt side or the opposite side during three-point restraint tests. It was pointed out that the use of steel has improved clavicle durability, but weight distribution was affected. Regarding the shoulder assembly, the bump stops were said to tear too easily and the washers to fail so regularly that they almost had to be changed after every test. The vinyl covering on the clavicles was said to separate and the skin on the shoulder to abrade from belt use.

Thorax. The skin/flesh jacket was particularly susceptible to tearing at the underarms and the abdominal flap. The zipper bonding to the jacket also regularly failed under normal use and, less frequently, the zipper itself. The sternum was also considered to have inadequate durability in that the leather would deteriorate and tear and the metal strips would break. The padding was also said to break down and shift, due to a lack of underlying structure, leaving a cavity and changing the shoulder belt location. The bending and permanent set of the ribs under severe impact conditions and the cracking and separation of the damping material were cited by several respondents. Problems with screw heads popping off and hexagonal socket holes rounding were also mentioned. Rib bending and damping material separation were also problems on the Hybrid III.

Lumbar Spine. One respondent commented that this component softened with age.

Pelvis. Foam breakdown on the sitting dummy surface, affecting seated height, was again cited as a severe problem under normal storage and use. This problem was also mentioned for the Hybrid III. Other failures identified with the Part 572 included the hip joint limit screws shearing off during extreme joint articulation and "snapping" of the ball joint during rear impact. Tearing of the pelvic skin from belts was also mentioned.

Upper Extremities. Respondents said that bones have rusted under non-removable flesh and that fingers have been cut off on impact with an instrument panel. A "mitten" hand was suggested. Arm breakage was only reported under severe unrestrained conditions using the Hybrid III.

Lower Extremities. The femur shafts were said to bend excessively during unrestrained tests. The hole for the roll-pin connecting the ball to the shaft also tended to enlarge with use, creating a loose joint. The knee skin was said to be particularly susceptible to tearing during direct impact, and the knees as well as the ankle castings often broke under torsion loads and side impacts. The foot has also bent during severe impact.

Joints. All joints were said to degrade over time, making maintenance of proper joint adjustments difficult. Friction washers were particularly cited as quickly wearing out and leading to unstable performance conditions. On the Hybrid III, rubber joint-stops were said to wear and harden with age.

Skin. Respondents again remarked that the skin wore and tore easily, especially at belt locations on the shoulder and pelvis and at contact areas such as the knees. Flesh foam was also said to separate from the skin, and both suffered from aging deterioration.

3.3 Overdesigned Components. Several respondents said that anything not mentioned in the previous section could be considered "overdesigned," but others cautioned against this approach. In general, the head, thoracic spine, pelvis, and arm and leg bones were considered too heavy and/or rigid. It was suggested that mass could be reduced and biofidelity improved with the use of different materials.

3.4 Zippers and Alternatives for Chest-Skin Closure. The majority responded that zipper failure was a frequent occurrence. Some pointed out that it was not the zipper itself as much as the bonding between the zipper and the skin jacket. Several suggested that both problems could be solved by using heavier zippers, by sewing the zippers with reinforcing strips on the skin, and by making a skin jacket that fit better.

Lacing was not considered desirable due to the time involved and the potential for variability. Approximately a third of the respondents suggested Velcro or a zipper/Velcro combination. Others said that innovative closure methods, perhaps unknown in the dummy industry, should be investigated. The space program was suggested as a source of ideas.

3.5 Damage Due to Extreme Temperature and/or Humidity. The vast majority responded that this was not a problem, primarily because testing was done in a controlled environment. The one effect mentioned most often was rusting, but some admitted that the dummies in question had been needlessly exposed to humid conditions. The only other effect mentioned was the drying, brittleness, or tackiness of the skin after exposure to high or low temperatures.

3.6 Impact Severity Level and Number of Tests Expected Without Catastrophic Failure. Responses fell into two groups. One group was based on injury severity and the other on impact severity. The first group ranged from 100 tests achieving injury severity levels 50 percent greater than maximum human tolerance to 50 tests at three times human tolerance levels. The second group was more conservative regarding number of tests, with 20 being most frequently mentioned. The impact conditions were given in terms of either acceleration or velocity, but rarely both. In general, 30 to 40 mph and 30 G were favored for frontal, unrestrained tests; 20 to 30 mph and 20 G for lateral tests; and 40 to 45 mph for restrained tests. A respondent interested in aircraft applications suggested 50 G for tests using five-point harnesses. Several did not answer the question.

CERTIFICATION

4.1, 4.2 Certification Concerns and Alternatives. Responses are grouped by body region. All comments relate to the Part 572 dummy unless otherwise noted.

Head. There was much skepticism about the realism and validity of the head drop test, because it was done with the head detached from the dummy, it addressed only one small spot on the forehead, and it was highly sensitive to the frictional characteristics between the skin and skull. Respondents thought that the use of lubricants to reduce the peak acceleration should be neither necessary nor allowed. It was also noted that the skull surface finish and curvature as well as skin thickness were not fully specified on the drawings, and that the center of gravity of the head could be affected by a replacement skin. Suggested alternatives were that the head be certified while attached to the dummy using a transfer pendulum test, that the skin be bonded to the skull with designed-in relative movement, that a test for skin aging be developed, and that certification include a non-impact moderate-acceleration test.

Neck. This test was primarily criticized for its lack of repeatability and for its potential for interlaboratory variation. The velocity range was said to be too wide, the deceleration pulse was said to be very difficult to obtain with the non-reusable aluminum honeycomb material, and different instrumentation for measuring chordal displacement and rotation could alter test results. Two alternate procedures were suggested that could be done while the head/neck was attached to the dummy. One method would be a static test of angle versus force in all directions. Another would be a dynamic test with a short input acceleration followed by measurement of the resulting damped oscillatory motion. It was further suggested that a static test would suffice until deterioration or delamination was suspected, and then a dynamic test would be needed. A lateral test was also requested by two respondents.

Thorax. Respondents questioned the need for two tests using different impact velocities, one respondent stating that no failures had occurred at the lower speed when a thorax passed at the higher speed. Respondents also wanted corridors rather than only upper limits on load and deflection. They also wanted tolerances to be specified for the impact velocities, acceleration measures to be made during the test, and instrumentation for measuring deflection to be standardized. Other suggestions included a more realistic impactor shape, a device to facilitate repeatable alignment of dummy and impactor, and a test for thoracic rotational characteristics related to diagonal shoulder belt restraints. Respondents disagreed as to whether the thoracic test should be independent of other components or whether a whole-dummy test was needed with response of other components, such as the head, included in the test results.

Lumbar Spine and Abdomen. Several respondents, from both government and industry, questioned the usefulness of the lumbar flexion and abdominal force-deflection tests, noting that there was little relationship to the crash test environment and that there were no corresponding tests for the Hybrid III. The lumbar test was also faulted for its dependence on the technician for rate of loading and on the interaction between the thoracic skin and the abdominal insert. Respondents stated a need for the lumbar spine to be tested in isolation from the abdomen and pelvis. Suggestions for the lumbar tests included lateral and rotational stiffness tests and, for aircraft applications, compression and bending/compression tests. An abdominal penetration test was considered desirable only if some measure of potential injury from penetration could be made with the device.

Limbs. Comments regarding the variability of the knee impact test related as much to the design of the leg, which was said to allow some "clatter" between rigid components, than to the certification procedure itself. Respondents seemed to prefer the procedure for the Hybrid III, in which the leg was mounted off the dummy. The three tests with different weight impactors for the Hybrid III, however, was considered excessive. One respondent said that the Part 572 impactor overdrove the knees. The same situation as on the head with regard to skin/casting friction was noted for the knee. Reducing this friction would lower the measured force but increase the duration of forces over 1000 lbs. Suggestions included a tibia test as well as specifications for torque and lateral force sensitivity for the femur load cell.

Transducers. One respondent suggested that blanks simulating transducer mass and inertial properties should be supplied with the dummy.

General. There was concern expressed that current certification tests were difficult and costly in terms of manpower and seemed to bear little relationship to crash test performance. The results tended to be influenced by second-order effects that could not be closely controlled. Another general concern was with the lack of specifications for the measuring instruments and in some cases the inadequacy of these instruments for making the measurements specified.

There were two schools of thought relative to component versus assembled dummy testing, but most respondents in fact did not indicate a theoretical preference. The compromise position was that the smallest possible components should be tested in isolation at specified intervals (perhaps six months to a year) with more frequent tests of major regions using an assembled dummy. It was further suggested by government respondents that the overall certification test should be supplemented by tests for particular impact directions or restraint systems to obtain baseline performance for particular test modes. Regardless of the method chosen, however, industry respondents wanted the procedures to be thoroughly checked out at several different laboratories before they became final and fixed. A potential problem that was said to be currently overlooked was that different parameters might vary differently with temperature, making testing at two different temperatures advisable.

Respondents recommended reexamining the entire philosophy behind certification procedures, as to just what was being checked and how it was being done, with an aim toward utility, realism, and simplification. One approach would be to test the dummy in the same way in which the biomechanical tests were performed that had generated the dummy design data in the first place.

4.3 Whole-Dummy Certification Tests. There was little support for a whole-dummy certification test requirement, but the reasons came from two extremes. Some said the dummy should not need it if all the components were properly checked out, while others said a whole-dummy test would have too much variability. Many responded that they did not know. The few supporters of the idea came from nearly all respondent categories, with the U.S. government being the most frequent. The only rationale given, however, was to check for overall kinematics, especially under varying temperature/humidity conditions. Two respondents suggested a simple frontal restrained test, and two others referred to the tentative procedure developed but never adopted by SAE-HBSS.

4.4 Adjustable Components to Speed Certification. Respondents from all groups were generally in favor of this approach, provided the adjustments themselves could be locked after certification and would not change during transportation or testing, thus creating a new source of variation. Those who were opposed to the idea raised the same issues but were pessimistic that such a system could be achieved.

4.5 Other Certification Issues. Among the several comments, two main issues were raised. First, there was support for a procedure in which components or modules could be tested and certified independently and set aside for future use. The necessity of having to test a component only in its installed environment increased dummy down-time. The second issue related to providing specifications for test fixtures, instrumentation, and sensors to increase test reproducibility among different laboratories.

REPEATABILITY AND REPRODUCIBILITY

5.1 Definitions. (See Appendix B.)

5.2 Dummy Positioning and Documentation Aids Used. Only one respondent had a special apparatus that could "lift, position, and push on the dummy according to the [FMVSS] 208 procedure." A few others used templates with probes to aid in positioning and documentation. Most, however, used a variety of linear and angular measurement devices while following the procedures specified by the standard.

5.3 Designed-In Positioning Aids Needed. Implicit in the responses to this question was criticism of the FMVSS 208 positioning procedures themselves, which were said not to guarantee a repeatable dummy position. It was noted that the same positioning procedure could result in H-point locations varying by six inches and pelvic angles by 30°. Individual laboratories have therefore devised their own targeting and measurement procedures to document dummy position in one test so that it can be duplicated in subsequent tests. The most-needed feature was the inclusion of targets rigidly related to skeletal structure on every body segment. H-point, centerlines, CG indicators, and targets visible from all directions were particularly mentioned. The next feature needed was an external indicator of chest and pelvic angle as well as a means of adjusting the pelvic angle using, for instance, a removable handle. Indicators for joint angles were also mentioned. The third feature requested was a means of repeatably locating the shoulder belt relative to the chest structure rather than the shifting skin. Finally, a "better" procedure for measuring dummy seated height was requested. Several respondents indicated that the standard positioning procedures needed to be revised to take advantage of these features.

5.4 Repeatability and Reproducibility Testing in Use. References were made by individual respondents to the Hybrid III test procedures, the SAE/HBSS Mechanical Human Simulation Task Force procedure, and EEC tests of side impact dummies. Those few who indicated actual test features mentioned strict temperature control and the use of hard seats. Others indicated they merely used procedures specified in Part 572.

The intent of the request for data manipulation techniques may not have been clear, as the responses were sparse and vague. Most merely indicated that standard analog-to-digital, chart recording, and visual methods were used. A current round-robin exercise among SAE committee members to process analog tapes was mentioned. A dummy manufacturer indicated that data on dummy variability was being computerized for user reference. The responses on statistical measures were also few and vague, with references made to "standard methods" and "standard deviations."

The tolerable coefficient of variation for primary response characteristics and injury criteria ranged from 3% to 10%, with a preference for the 3% to 5% range. These responses, however, came primarily from industry representatives, the other respondents tending to cite difficulties putting a number on acceptable variation or not responding at all. A 1977 survey (SAE 770263) found a 30 percent variation in injury criteria and calibration measures between two Part 572 dummies of different manufacture. One respondent suggested that a goal could be to reduce the variation currently experienced by 50%.

Few shortcomings of currently used R & R test procedures were volunteered, but the level of expertise of technicians doing the testing was considered critical. It was also acknowledged that all variation in Hybrid III tests was attributed to the dummy, rather than attempting to trace the variation to test procedures, instrumentation, and/or data processing.

5.5 Other Recommended R & R Test Techniques. Only two respondents contributed ideas. One referred to a test apparatus for a seated dummy that supplied gravity-fed impacts to a specified portion of the dummy. Although not directly related to the automobile impact environment, it was said to be a simple idea that could be developed further. Another suggested that a universal test procedure with baseline response parameters be established, and that dummies periodically be tested against the baseline, with a statistical statement of the variation given. A qualifier of "easier said than done" was also added.

5.6 Adequacy of SAE Channel Class Specifications. Although respondents were split fairly evenly on this topic, the reasons given along with the negative responses were more specific. Several others had no opinion. Generally, the current J211 specifications were said to allow too much variability from the wide tolerances as well as from different filtering methods allowed. The specification of both a phase response and a target response within the J211 corridor was recommended. Several recommended that the head filter be lowered from 1000 Hz to 600 Hz, and two suggested a steeper roll-off to as much as 30 to 40 dB per octave to prevent aliasing. One respondent recommended that data be collected and stored wide band, rather than filtered, and that different filters be carefully specified for each individual measurement.

5.7 Specification of Transducer Performance and Software for Digital Filtering. The respondents were again divided as to the desirability of such specifications, but those who commented tended to take a middle ground. Performance requirements and the filter algorithm should be specified, but specification of actual hardware or software would not be practical or appropriate. A few suggested that such specifications should remain the purview of SAE and ISO, but others thought such standardization within the dummy package was critical for repeatable and reproducible measurements.

5.8 Other R & R Issues. A Hybrid III user pointed out that reproducible results would be achievable only if the dummy were thoroughly dimensioned, toleranced, and otherwise specified such that it could be manufactured entirely from its documentation. Another suggested that temperature sensitivity should be charted, if the effects were found to be significant, e.g. rib temperature versus chest deflection. Others suggested that a standard R & R test be specified and that interlaboratory comparison tests be funded.

EASE OF USE

6.1 Lifting and Positioning Devices in Use to Assist Technicians. Three-quarters of those answering used some type of mobile or overhead hoist or crane with arms, chains, hooks, bars, or slings. One, however, said "Who has technicians these days?"

6.2 Standard Lifting and Positioning Attachment Points. Support for this idea was nearly unanimous with few comments. Some said the current eyebolt on the top of the head was adequate, particularly for sled testing, but others requested a means of lifting from the thorax and/or pelvis for testing in vehicles. One cautioned that use of the current head eyebolt might lead to damage to neck load-cells. Others indicated that compression of soft foam during storage could be reduced by making use of attachment points and associated hanging devices, and that a means of transporting the dummy in a seated position into the test fixture would be useful.

6.3 Transducer Wiring Harness and Umbilical Pin Connector. Half the responses were in favor of these features, with the ease of changing transducers at the last minute being the primary advantage. It was suggested that provision be made for adding other transducers and wiring, including an auxiliary pin connector, for special testing needs. Those who would find a wiring harness undesirable, including most of the U.S. industry respondents, cited primarily its lack of flexibility, and they indicated that provision for a cable pathway would be sufficient. There was concern that such a system would require use of particular transducers. Several respondents were ambivalent or indifferent.

6.4 Channel Capability by Late 1980s. The majority of those responding expected to be able to handle at least sixty channels, while nearly half indicated that at least 100 would be possible. A few of these said they could handle whatever was required. A few respondents from both industry and government, however, indicated numbers below sixty, and some did not give specific numbers.

6.5 On-the-Dummy Signal Processing. Although a third of the respondents supported the idea, even this support was hesitant. Comments on both sides of the issue indicated that such a system was certainly not high priority and might even be undesirable. Unless very high reliability could be guaranteed, the time delays associated with pre-test checks and repairs and the high risk of losing all data would be unacceptable. Durability of such a system subjected to a crash environment was also questioned. If these problems could be overcome for a necessarily complex system, it would likely be too expensive. In addition, if it compromised repeatability/reproducibility or biofidelity, this trade-off would be unacceptable. Several suggested that on-the-dummy signal processing might be an option for certain unrestrained test conditions, but, if such a system were the primary one, then an off-board option must be maintained.

6.6 On-the-Dummy Storage of Digital Data and Associated Time Durations. The majority responded that "this approach has merit," which is not necessarily to say that such a system was considered practical or preferable at this time. The same concerns expressed in the previous responses were echoed here, including the suggestion that it be an option. Regarding time durations, sled and vehicle impact tests required from 200 to 500 ms, while rollover tests required 4 to 5 seconds, with one respondent indicating a possible duration of 10 seconds. One respondent suggested that consideration be given to on-board but off-the-dummy systems.

6.7 Controllable Temperature and Humidity Ranges by Late 1980s. Temperature extremes cited were 20° and 130° F. The more controllable lows ranged from 50° to 70°, with 60° to 66° being the most typical. Reasonable highs ranged from 75° to 90°, with 75° to 80° being the most typical. The question on variability was understood and thus answered differently by different respondents, but close control of temperature seemed to be the exception rather than the rule. Many respondents said they tested outside or at least needed a wide range of temperature occasionally. Humidity ranged from 10% to 100%, with 10% to 90% commonly cited. Several indicated an ability to adjust but not control humidity with air conditioning systems, and several had no control whatever.

6.8 Other Ease-of-Use Issues. Respondents here cited the need for a high degree of stability in the instrumentation and mechanical components so that less frequent calibrations would be necessary. Provision should be made for a system check in the installed position just prior to testing, and removal of transducers should require minimum effort. One respondent, however, suggested that it might not be possible to design a dummy with all the necessary humanlike characteristics that was also easy to use.

7. Other User-Oriented Issues. Nearly all issues raised here were addressed directly or indirectly elsewhere in the questionnaire, and the comments have been integrated in appropriate places. Two topics remained. One respondent wanted assurance that specifications for the AATD would be set up in such a way that they could easily be used in computer models. Two mentioned the issue of price—that it be kept as low as possible and that, if the AATD was more expensive than current dummies, its advantages outweigh the additional cost.

SUMMARY AND CONCLUSIONS

Throughout the responses to this survey, a strong emphasis was placed on the need for a durable, stable, and repeatable test device, even at the expense of biofidelity. The lack of enthusiasm for an omnidirectional dummy, expressed by several respondents early in the survey, seemed to be based on an assumption that such a dummy could not be made to be as repeatable and reliable as a unidirectional test device, while retaining a suitable simplicity of design. Comments in later sections of the survey clearly indicated that considerable time and effort was required to prepare the Part 572 dummy for testing, and that between-test repair, replacement, adjustment, and recalibration were frequent necessities. As the survey proceeded from theoretical design to more hands-on issues, the number of respondents decreased, but the conviction and level of detail of responses increased.

Respondents were generous with their advice as to how life with an anthropomorphic test device could be made easier. Designed-in means were needed for holding on to various parts of the dummy for transporting, positioning, and storage and for holding them fixed in space for certification tests. Also needed were visible indicators of the dummy's internal structural configuration and segment centers of mass. Joints were singled out as the assemblies in particular need of redesign. In addition, it was made clear that the performance characteristics of a dummy must be built up from the smallest components, but that performance checks of components in their assembled state were also necessary.

After reviewing the responses of this international group of dummy users, the term "advanced" in AATD begins to take on a broader meaning. Not only is there an opportunity here to advance the state of the art with regard to humanlike response and innovative instrumentation techniques, but there is a necessity to make significant design and materials improvements that will result in a more durable, repeatable, and trouble-free dummy.

ACKNOWLEDGMENT

The AATD project staff and sponsor would like to thank all those individuals throughout the world who took the time and considerable effort to carefully and conscientiously respond to this questionnaire. Future dummy design will depend heavily on this input.

APPENDIX A:
AFFILIATION OF SURVEY RESPONDENTS

U.S. VEHICLE INDUSTRY

American Motors (2)
Chrysler
Ford (2)
General Motors
SAE Dummy Testing Equipment Working Group

FOREIGN VEHICLE INDUSTRY

Fuji Heavy Industries, Japan
Honda, Japan
Motor Industry Research Association, England
Normenausschuss Kraftfahrzeuge FAKRA, Germany F.R.
Peugeot S.A./Renault, France
Toyo Kogyo, Japan
Toyota, Japan
Volkswagen, Germany F.R.
Volvo, Sweden

U.S. GOVERNMENT

Federal Aviation Administration
Federal Highway Administration
National Highway Traffic Safety Administration (5)
NHTSA, Vehicle Research and Test Center (5)

FOREIGN GOVERNMENT

Canada, Department of National Defence
Canada, Road Safety and Motor Vehicle Regulation
England, Transport and Road Research Laboratory
Netherlands, Research Institute for Road Vehicles TNO

DUMMY MANUFACTURING

Alderson Research Laboratory, Inc.
Humanoid Systems

INDEPENDENT RESEARCH

Biokinetics
ENSCO
Insurance Institute for Highway Safety
Michigan State University, Biomechanics Department

APPENDIX B: DUMMY USER SURVEY QUESTIONNAIRE

1. MECHANICAL DESIGN

1.1 With what vehicle environments should the new dummy be designed to interact (e.g. belt restraint systems, rear-impact, etc.)? Also, should a pedestrian version be pursued?

1.2 Several design philosophies are possible regarding the advanced dummy performance characteristics (biofidelity, durability, etc.) as a function of impact direction. Design efforts could focus on only frontal impact, on frontal and lateral impact fidelity only by means of "converting" the dummy, true frontal and lateral impact fidelity in a single version of the dummy or, finally, omnidirectional fidelity. These four design philosophies are listed in order of decreasing technical feasibility. It follows that compromises in dummy performance might become progressively more significant. Which design philosophy should be pursued, and how strongly do you feel about your choice? If compromises in dummy performance are necessary in order to accommodate a multidirectional or omnidirectional design philosophy, should priority be given to "frontal" or "lateral" performance?

1.3 Should standardized clothing be specified for the new dummy, or would no clothing (with suitable buttocks, frictional characteristics, etc.) be preferable? Shoes desirable?

1.4 For best visibility in high-speed films, what dummy skin color would be most desirable? What anatomical landmarks should be considered for attachment of high-speed film targets?

1.5 Given that strength, stiffness, and stability requirements can be met, do you foresee any problems in utilizing a non-metallic skeletal structure in the new dummy, in order to achieve a more humanlike mass distribution?

1.6 Is it acceptable to have a limited number of frangible components on the new dummy (e.g. facial bones) if they are of moderate replacement cost, enhance the dynamic mechanical response of the dummy, and provide a direct measure of the severity of applied loads?

1.7 Based on your current understanding of the characteristics of human joints and how dummies are used, do you feel that some form of the following should be designed into an advanced dummy: (a) progressive-resistance joint-stops, or (b) provision for remotely changing joint stiffness during a dynamic test (to simulate muscle tensing)? Also, comments are solicited regarding which human joint degrees-of-freedom need *not* be designed into the dummy, and what the joint stiffness characteristics should be for joints included.

1.8 Are there test environments for which you believe it would be desirable that the dummy not have arms (assuming arm mass, etc. was accounted for in the design of the torso)?

1.9 Should dummy hands be functional rather than anthropometrically sound; that is, should they be capable of grasping a steering wheel (or other component) and breaking free at a predetermined load level?

1.10 Similar to the question of the hands discussed in Item 8 above, should dummy feet include provisions for attachment to a vehicle floorpan and/or pedals and break free at a predetermined load level?

1.11 Should the new dummy be designed using the SI metric system of units?

1.12 Should the new dummy be designed to represent a relaxed or tensed human, or some intermediate condition?

1.13 Given that the dynamic mechanical response characteristics (e.g. dynamic force-deflection) of the new dummy are humanlike into the injury range, up to the points where structural integrity begins to be compromised, there are two possible options regarding response in more severe impacts. The response characteristics could be patterned after those of the human that is experiencing structural failure, or they could be extrapolated outward in a continuous fashion from those of the intact human. The former approach tends to offer more realism of occupant dynamics in very high severity impact environments, whereas the latter approach tends to provide better insights into just how far a vehicle environment is from a design that will keep occupant loads below those leading to significant structural failure type injuries. The appropriate option needs to be selected for each body region of the new dummy. Recommendations, with supporting rationale, are solicited.

1.14 What injury types and ranges of injury severity (AIS scale) should each of the individual body areas of the new dummy be capable of sensing (e.g. lower leg:fractures, AIS 2–3; head:brain injury, AIS 2–6)? Please provide rationale.

1.15 Are detailed facial features necessary on the new dummy, or would a "featureless" face such as that of the Hybrid III be acceptable?

1.16 Other mechanical design issues, please describe.

2. SERVICEABILITY AND MAINTENANCE

2.1 Should the new dummy be designed to facilitate easy access to instrumentation (accelerometers, etc.) while it is normally seated in a vehicle?

2.2 Should a suitable dummy storage fixture and associated attachment points on the dummy be included as part of the advanced dummy specification, to preclude permanent set in flesh subjected to sustained loads during storage, etc.

2.3 For the Part 572 50th percentile male dummy, are the adjustment access holes through the skin/flesh problematical as a result of skin/flesh shifting relative to the structure beneath? Indicate severity of the problem.

2.4 Describe servicing and maintenance operations that are unnecessarily difficult for the Part 572 50th percentile male dummy as a consequence of its design.

2.5 Other serviceability and maintenance issues, please describe.

3. DURABILITY

3.1 What components of the Part 572 50th percentile male dummy have insufficient maximum strength?

3.2 What components of the Part 572 50th percentile male dummy have insufficient wear characteristics?

3.3 What components of the Part 572 50th percentile male dummy appear to be over-designed from the standpoint of strength or wear resistance?

3.4 Do you find dummy torso skin/flesh zippers to fail frequently? Would lacing be a superior closure method? Other recommended techniques (please describe).

3.5 Have temperature and/or humidity extremes ever been responsible for damage to one of your dummies?

3.6 What impact severities should the new dummy be capable of withstanding without catastrophic failures, and for how many exposures? (Respondents are encouraged to address specific restraint types and impact directions.)

3.7 Other durability issues, please describe.

4. CERTIFICATION

4.1 Please provide an overview of your concerns with the Part 572 50th percentile male dummy certification testing requirements.

4.2 What alternative tests or modifications do you recommend?

4.3 Should one or more whole-dummy certification tests be required for the new dummy? If yes, please describe any test environment that you can recommend.

4.4 Consideration is being given to the inclusion of adjustable elements within the new dummy to speed the certification process. If you foresee benefits or possible problems with this approach, please elaborate.

4.5 Other certification issues, please describe.

5. REPEATABILITY AND REPRODUCIBILITY (R & R)

5.1 Definitions:

Repeatability: A qualitative term used in referring to the variability of a dummy's mechanical response in replicated exposures to an invariant stimulus.

Reproducibility: A qualitative term used in referring to the variability among the mechanical responses of dummies of the same design that are each exposed to identical stimuli.

5.2 What apparatus, system or technique do you currently utilize to assist positioning dummies pre-test and/or to document dummy position?

5.3 Describe design features any new dummy should have that would be helpful in connection with pre-test positioning.

5.4 Please describe any standardized test environments you utilize for assessing R & R, both for the whole dummy and for components:
  5.4.1 Test description
  5.4.2 Data reduction manipulations
  5.4.3 Statistical measures of R & R
  5.4.4 How much variability do you feel can be tolerated for an objective test device?
  5.4.5 What shortcomings do you associate with your technique?

5.5 Relative to Items 5.4.1 through 5.4.4, what techniques do you recommend if you have none currently, or if you are unsatisfied with your existing methods?

5.6 Do you feel that SAE Channel Class specifications are sufficiently stringent for crash test dummy data? Please elaborate.

5.7 Should transducer performance specifications and digital filter computer software be incorporated as part of the new dummy specifications?

5.8 Other R & R issues, please describe.

6. EASE OF USE

6.1 Do you currently utilize any type of device to assist technicians in lifting and positioning dummies within vehicles? If yes, please describe.

6.2 Would it be desirable to provide standardized attachment points on the new dummy for accommodating a lifting/positioning assist device?

6.3 Would it be desirable for the new dummy to include an internal wiring harness for all transducers and a standardized, suitably placed pin connector for any umbilical cord?

6.4 How many channels of Wheatstone bridge type electronic instrumentation do you anticipate your laboratory will be able to handle without undue hardship by the late 1980s?

6.5 Would you favor onboard (within dummy) signal processing for the advanced dummy?

6.6 The desirability and feasibility of onboard (in-dummy) storage of digital data are being investigated for the new dummy. Do you feel that this technique has merits? If so, what time durations of signals should be adopted for the various types of tests you would expect the advanced dummy to be used in?

6.7 By the late 1980s, within what ranges of temperature and relative humidity do you anticipate you will be able to maintain specified values in your laboratory, and what variability about the selected values is anticipated?

6.8 Other ease-of-use issues. Please describe.

7. OTHER ISSUES

Please address other user-oriented issues judged to be of importance that are not covered elsewhere in this questionnaire.

CHAPTER 2

REVIEW OF DUMMY DESIGN, MANUFACTURING, AND COST CONSIDERATIONS

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The purpose of this review is to provide information concerning design features, manufacturing techniques, and their cost effectiveness in the production of existing dummies. Both the Part 572 and the Hybrid III are reviewed in detail.

PART 572 DUMMY

Head and Head-Back Skin (ATD-7175 & 7176). These parts are cast-molded in pigmented vinyl plastisol, with a durometer hardness (Shore Type-A) of 34 ±10%. The forehead skin thickness has a tolerance of ±0.025 in. All other dimensions are ±1/32 in. External features are formed by the internal contours of an aluminum mold. The internal skin contours are formed by an aluminum mold insert, which is a modified skull casting. These components are relatively simple in design, and all features and dimensions remain as cast.

Materials such as vinyl plastisol and polyurethane are easily cast. Sorbothane, a type of polyurethane, has some unique properties that are usually associated with a viscous liquid. The material distorts easily, has a good delayed recovery (the recovery rate is a function of the hardness), and has a good memory. The material has the ability to stand up to high levels of repeated impact without significant loss of efficiency. Unlike vinyl plastisol, which is heat-sealable, Sorbothane can only be bonded using uncured Sorbothane as the bonding agent. Sorbo, Inc., is the only company that makes this material; the casting process is also proprietary. We experienced no difficulties having head skins cast in our mold. The comparative costs of cast components in vinyl plastisol and Sorbothane are about the same. Should Sorbothane not be accepted as the AATD flesh material, perhaps it could be used as padding in selected impact areas. It has real potential in terms of improving biofidelity.

Vinyl plastisol is cured in ovens at temperatures around 375°F to insure uniform cure of molded parts. Molds have to be preheated until all surfaces of the mold, including mold inserts, are uniformly heated to approximately 325°F. Molds are made of very high quality aluminum sand castings to minimize minute surface porosity, which, as a result of entrapped gases, may cause blistering on the molded part surface. Aluminum is used because of its good thermal conductivity and durability. High-temperature plastic molds (called soft tooling), although less expensive to make and easier to modify, do not have those properties. Using the aluminum molds and the molding method mentioned above, vinyl plastisol parts can be molded easily. Polyurethane casting can be done with low cost tooling and at low temperatures.

Present head skin thickness tolerances, especially in impact areas, permit large variations between different head skins and between different areas of the same head skin. Closer tolerances can be produced by the casting process without additional costs.

Skull and Skull Back (ATD-7147 A & B). These components are cast in no. 356 aluminum alloy and heat treated to condition T-6. Both are sand cast as one piece and machined to 125-microinch surface roughness (MSR). All tapped holes are fitted with corrosion resistant heli-coil inserts. The surface roughness on the skull forehead (frontal impact area) is not specified. As an ARL manufacturing option, the skull forehead is polished to 16-MSR. This is done to achieve the same skin-spreading effect and thus the same skull-to-skull impact characteristics among different dummy heads. All machining dimensions are toleranced to ±0.005 in.

The design is simple and functional, but the head center-of-gravity location holes should be included in the skull. The sand-mold casting process used lends itself to the formation of integral components with strength and rigidity frequently obtainable by no other method of fabrication. At present, it is the most cost-efficient method for producing a metal skull. The use of "keenserts" in place of "heli-coil" inserts is recommended. They install with standard taps, have positive mechanical lock against rotation, and are easier to install and replace.

Manufacturing tolerances of ±0.005 in. and surface roughness values of 125 MSR are adequate, since mating surfaces have no motion. The high polishing of the skull impact-area could be eliminated if a matching texture were molded into the inside of the skin and the surface of the skull to lock the skin in place and preclude the skin-spreading phenomenon. In considering alternative materials, it is possible that a fiber/epoxy composite would improve the biofidelity but would probably add considerably to the cost.

Rubber neck and Lumbar Spine (ATD-7101 & ATD 7102). These are molded of butyl rubber, to SAE specification J200D. The top and bottom flanges are made of AISI-1117 steel and bonded to the rubber during the molding process. Occasional bond (rubber to metal) failures occur.

Design is simple and structurally sound. The strength of bonded joints, however, could be increased in the following ways: (1) the bonding surface area could be increased by machining concentric "V" grooves on the flange surface, and (2) the flange bonding surface should be sand blasted. Present drawings do not include specifications for the type of adhesive or the type of metal surface preparation to be used. Proper preparation of the surfaces of the material to be bonded is one of the most important factors influencing adhesion in any bonding process. Drawings calling out the bonding process should specify type of adhesive and method of metal surface preparation. (Having obtained an optimum surface condition, it is also important to maintain it until it has fully served its purpose.)

To eliminate twisting of the lumbar spine cable assembly when tightening the cable nut, the threaded sleeve-end of the cable assembly and the top flange of the lumbar spine should have mating hexagon surfaces. Manufacturing tolerances of ±0.010 in. on molded rubber components, although obtainable, are not very practical. A tolerance of ±0.020 in. would improve cost effectiveness.

Neck Bracket Assembly (ATD-7111). The component specified for the Part 572 dummy is made up of five pieces (6061 aluminum), then heli-arc welded, heat treated to condition T-6, machined, and anodized per MIL-A-8625. ARL also offers an alternative part that is sand cast in no. 356 aluminum alloy, heat treated to condition T-5, and then machined.

The cost of producing the welded (Part 572) assembly exceeds that of the cast (ARL) bracket by approximately two to one. Further, the casting process forms an integral component with more strength and rigidity.

Tolerances on the welded assembly are too great: ±0.02 in. on details, ±0.01 in. on assembly drawings, and ±1° on angles. In addition, the relationship between the neck mounting surface and holes and the thoracic mounting surface and holes is not specified. This situation and the accumulation of tolerances to either the extreme high or low limits on related surfaces can cause an undesirable condition, such that the forehead in relation to the frontal plane of two dummies could differ by as much as 1/2 inch. Also the height of two dummies could vary by as much as 1/4 inch. To avoid such unsatisfactory conditions, it may be necessary to choose closer tolerances or to use a drilling-machining fixture, as does ARL.

Upper Thorax Padding and Cover (ATD-7153 & 7120). Three layers of padding, each cut to a different contour from one-inch-thick Ensolite Type AL, are bonded together with Uniroyal adhesive #6154. The thorax padding cover is made from 1/8-inch-thick oak tan leather contoured to a similar shape as the top layer of the padding assembly.

These parts are simple. The padding (Ensolite) contours are cut by means of a knife blade on a bandsaw with a corresponding template. The holes are transfer-located and cut with tubular cutters using the same template. The thorax padding covers are die-cut. The original tolerances of ±1/64 in. were unnecessarily close and difficult to hold when cutting Ensolite and were changed to ±1/16 in. The materials are suitable, but the leather costs 1.5 to 2 times as much as polyurethane, which would be just as suitable.

Sternum-Thoracic Assembly (ATD-3838). This assembly is comprised of 17 different steel (AISI-1018) parts that were welded together to form a relatively light and strong structure, which, in final assembly, supports the head/neck assembly, the rib-cage assembly, and shoulder/arm assemblies.

Of the seventeen parts, nine are easily machined from stock sizes, three are sheared, and five are stamped. A welding fixture is used. Because light gage steel is used throughout, hardened steel "clinch fasteners" are used to form strong thread engagements where necessary. The finished assembly receives a black oxide treatment. The design and fabrication methods are very cost-effective. For the finish, however, a cadmium plating, which is a corrosion preventive for steels, is recommended.

The manufacturing tolerances (±0.005 in. to ±0.03 in.) represent the minimum degree of accuracy necessary to meet the functional requirements of each detailed part and the entire assembly.

Thoracic to Lumbar Adaptors (ATD-7130 & 7123). These steel components comprise the joint assembly between the upper and lower thorax. The "female" adaptor (ATD-7130) includes upper thorax weight distribution ballast.

The "female" adaptor, originally machined out of one solid piece is now made up of three separate pieces machined from nominal stock sizes and welded to form an assembly. The "male" adaptor is a one-piece machined part. A sand-casting process would make it more cost-effective, provided quantities would be large enough to justify the tooling cost, namely the casting patterns. The "female" adaptor could be an integral part of the sternum-thoracic assembly, and the "male" adaptor likewise a part of the top lumbar spine flange. As designed, the mating surfaces of both adaptors require a high degree of accuracy to meet the functional requirements, i.e., a close sliding fit to prevent any play in the joint that would cause unrealistic ringing in the system. A "male/split-female" (clamp type) design would not require a high degree of accuracy, would form a positive (play free) joint that would facilitate assembly, and would result in lower fabricating costs.

Sterno-Clavicular Links (ATD-3052-1 & 2). These parts form the link between the sternum-thoracic assembly and the clavicles. They control motion (elevation and depression) for the shoulder girdle with respect to the torso. The links are investment cast in AISI-4140 steel and heat treated to RC28-32. Cast dimensions are held to tolerances of ±0.015 in. and machined dimension tolerances range from ±0.0015 in. to ±0.003 in. Four surfaces are machined to 62 MSR and all other surfaces to 125 MSR.

Considering the small size of these parts, the intricate contours with necessary accuracy, and the hardness of the material, the investment casting process is the most economical method of fabrication. These links cannot be readily machined. They are subject to very high stresses, but, with AISI-4140 steel, a broad range of strength and toughness is attainable. The designed-in degree of accuracy is compatible with the functional requirements.

Clavicle (ATD-3061-1 & 2). The clavicle is investment-cast in no. 356 aluminum alloy, heat treated to condition T−6, and machined to 125 MSR. The clavicle area (the anatomical shape in contact with the chest flesh) is dip-coated with vinyl plastisol to a thickness of 1/16 in.

This highly stressed component is the weakest link in the shoulder system. Its complex contours do not contribute much to biofidelity or strength. A simpler two-piece design using stronger materials, such as AISI−4140 steel for the mechanical section joined to a fiber/epoxy composite for a separate simplified section representing the anatomical contours, would result in a stronger component of approximately the same weight. The vinyl plastisol coating was added to protect the chest flesh in that area. A better surface finish would accomplish the same thing at lower cost.

The manufacturing tolerance of the shoulder yoke mating bore is +0.005 in., −0 in., which is too large for a running fit where minimum play is desirable. The surface roughness for the bore should be 62 MSR instead of 125 MSR. For this part, the investment-casting process is a very suitable method of fabrication.

Shoulder Yoke Assembly (ATD-3056-1 & 2). This steel weldment is comprised of two lugs that form a clevis for the attachment of the upper arm and a shaft that connects to the clavicle.

The lugs are 1/4-in.-thick C1018 steel with full radii at one end. These kinds of parts lend themselves to the stamping process. The shaft is turned from a standard nominal-size square AISI-4140 steel stock. Lugs are welded onto two opposing sides of the nominal size square, eliminating machining. The cylindrical end is machined to 1.435 +0 in., −0.003 in., and the mating part is dimensioned 1.437 in., +0.005 in., −0 in. This can cause a radial clearance of 0.005 in.

Shoulder Cylinder Assembly (ATD-7149). This assembly provides damping for shoulder motion in the elevation and depression direction. It is a relatively simple unit.

Shoulder Cylinder Pivot Shaft (ATD-3110). This shaft connects the shoulder cylinder to the clavicle at one end and to the bottom thoracic assembly at the other end.

The use of grip arc-rings instead of truarc-rings would eliminate the need for truarc-ring grooves and bevels.

Rib Assembly No. 1 thru No. 6 (ATD–3003 thru 3007). The ribs are formed from 1/8–in.-thick x 3/4–in.-wide C1075 spring steel and heat treated to Rockwell C45–48. A strip of damping material (1/4–in.-thick x 3/4–in.–wide) is bonded onto the inside of each rib, and the unit is enveloped by heat shrinkable flexible tubing.

Of the six pairs of ribs, only two pairs are identical. Cutting down on the number of different ribs would lower production costs. The heat-shrinkable tube covering does not serve any purpose—it only conceals imperfect bond areas. Drawings do not specify the type of surface preparation or maintenance of such surfaces prior to bonding (see comment on rubber neck and lumbar spine above). A possible alternative for the present rib design would be a fiber/epoxy composite wound around a damping material in the form of a rib. There are many variables in the choice of fibers and resins currently available, and strength and other factors are directly dependent on winding angle(s). It is this combination of material and technology that could be tailored to fit the application.

Sternum Assembly (ATD–3710). The sternum is made of 1/4-in.–thick leather (oak tan) plate with holes for rib attachments and three aluminum bars for stiffeners. The plate is first die-cut and then bevels are machined. Stiffeners are machined and bolted to the plate. This assembly could be replaced with a cast-molded part with molded-in stiffeners.

Chest Flesh Assembly (ATD–3151–6). This consists of a one-piece skin and foam chest-molding with a heavy-duty zipper in the back for quick access to the internal structures. This section can be removed only after disassembling the arms. The skin is slush cast in vinyl plastisol, with the foam becoming an integral part of the skin. The frontal chest area (approximately 6 in. by 8 in.) thickness is controlled to a tolerance of ±0.06 in.

Slush casting is a cost-effective method, and closer flesh-thickness tolerances can be achieved at no additional costs. Due to mold heating and cooling times, daily production for this and similar parts is one or at most two a day. Generally, the same comments as under **Head and Head-Back Skin** apply here.

Friction Washers (ATD–3051). These washers, used on sternoclavicular, shoulder, and elbow joints, are machined from glass melamine fiber or fiberglass reinforced epoxy to a thickness of 0.060 in. and 0.120 in., with surfaces parallel to within 0.004 in.

Originally, glass melamine fiber was chosen to produce a tense condition in clevis type joints. Because of its highly abrasive characteristics, machining and grinding of this material is an expensive operation. A tolerance of ±0.002 in. for parallelism is too large to produce a uniform motion resistance in the joints. There are more suitable materials, the choice depending on the type of joint friction desired. One is Delrin 100ST, a tough polymer with a low coefficient of friction, high impact resistance, injection moldability, and excellent machinability. Another is Kevlar, also a tough material with a high coefficient of friction, high tensile strength, and high resistance to wear, as well as being non-abrasive.

Chest Accelerometer Mount Assembly (ATD–3283). This assembly is a 6061-T6 aluminum weldment with mounting provisions for three Endevco accelerometers (series no. 2260) at the upper thorax center-of-gravity. It is comprised of seven different details that are welded and then machined to dimensions with tolerances of ±0.005 in. All other dimensions are ±0.015 in. A far more cost-effective method of fabrication would be the sand casting process, which would result in the formation of an integral component with the kind of strength and rigidity required. The chest accelerometer mount for the Part 572 dummy is too complex and provides little rigidity.

Pelvic Structure and Flesh Assembly (ATD-3703). This is a one-piece seated-form pelvic assembly. The skin and flesh are integrally molded about a human-shaped pelvic structure that is not removable. An abdominal skirt extends upward from the pelvic molding to shield the abdominal insert, protecting against intrusion of seat lap belts into the junction between the pelvic and the abdominal flesh. The seated-form pelvic molding eliminates such intrusions in the groin areas. Space is provided in the sacral region for accelerometers, which are accessible by removing a shaped flesh-plug in the back of the pelvic molding.

The pelvic structure is cast in aluminum alloy no. 355. The lumbar-sacral interface and femoral ball sockets are machined to 125 and 62 MSR respectively. Machining tolerances range from ±0.001 in. (femoral ball sockets) to ±0.015 in. Mounting holes are located within ±0.005 in. Dimensioning, tolerancing, and surface finishes are functional and reflect good standard shop practice. To assure reproducibility and cost effectiveness, however, drilling and machining fixtures are necessary. The sand casting process provides mechanical integrity and a low-cost fabricating method. The spatial geometry of the pelvic structure is representative of the human pelvis with the exception of the anterior-superior iliac spines, which are deficient in anatomical definition as well as in left-right symmetry. The latter deficiency also applies to femoral sockets.

The specific gravity (approximately 2.7) of the aluminum structure is twice that of human pelvic bone, which is approximately 1.3. Fiber/epoxy composites, which are 10% lighter than standard magnesium and with more human-like load deflection properties, would be an ideal material except for two considerations. First, the highly stressed threaded holes in the structure would present design and fabrication problems. Second, its lack of heat conductivity would prevent the build-up and curing of vinyl plastisol adjacent to the structure. Should vinyl plastisol be used as the material for the skin and flesh, then magnesium would make a choice material for improving the pelvic structure's mass-distribution.

Abdominal Insert (ATD-3250-2). This abdominal sac floats between the chest and pelvic moldings. The vinyl plastisol skin is slush-cast to a thickness of approximately 3/32 in., which brings the skin-as-molded weight to 2.3 lbs. +2 lbs., −0 lbs. Subsequently, the inside of this sac is filled with polyurethane foam, which brings the total weight to 3.0 lbs. ±0.2 lbs. (The effect of this weight on the mass-distribution of the upper and lower thorax should be considered.) Although presently cast in a three-piece mold, the shape of this insert could be simplified to allow a two-piece mold, which would eliminate some parting lines. This kind of change would cut down mold assembly and trimming time. A new Sorbothane of a lower density is currently under development at Sorbo, Inc. It could become a more suitable material for the abdominal insert.

Femur Assembly (ATD-3232-1 & 2). High-tensile manganese bronze castings are used for femurs and femur joint adjustment flanges, while precision aluminum-bronze balls are used for femur heads.

Manganese bronze is too heavy compared to human bone and too difficult to machine. Magnesium would more closely approximate the human bone in weight and would afford sufficient strength. A fiber/epoxy composite with high strength, low density, and an elasticity better approximating that of bone would be another choice. This, however, would require considerable effort in design, development, and fabrication.

The distance between the upper leg axis and the center of the femur ball in the left and right femur assembly, which is not specified on the drawings, differ by as much as 7/16 in. in both the sagittal and the transverse plane. This results in a lack of symmetry.

The femur ball has a machined slot in the transverse plane that engages a mating pin located in the corresponding socket at the H-point on the pelvic structure. This slot-pin combination controls leg adduction and abduction motions. It also prevents leg rotation at the hip pivot. This latter restriction of the rotational movement introduces a considerable amount of friction in the joint. The human hip joint is not restricted to vertical and horizontal motion, and therefore this design is questionable.

Specified dimensional tolerances on the femur-assembly drawing are adequate and practical. The surface roughness of 125 MSR on the leg rotation bore should be 62 MSR to produce a smoother motion. The surface roughness on the femur ball is about 4 MSR, sphericity is within 0.0002 in., and diameter is within 0.0002 to 0.001 in. This is more than adequate to assure a smooth, play-free joint. A better hip joint could be realized by using a Delrin liner in the pelvic hip socket, or a Delrin femur ball, to avoid metal-to-metal contact. This or a similar approach should be considered for all joints.

Upper Leg Bone (ATD-7131-1 & 2). This component is a steel weldment terminating in a split-sleeve clamp (for retention of the upper-leg load-cell) at one end and the upper-leg rotation shaft at the other end. A cylindrical housing is welded around one end of the shaft to hold Cerrobase weight distribution ballast. One side of the weldment (lateral border of the upper leg) has two threaded holes for attachment of external film targets.

The cost of Cerrobase is $4.50 to $6.50 per pound, while lead costs $0.45 per pound. Eight pounds of Cerrobase are required per dummy. With a minor design change and the substitution of lead, at least $33.00 could be saved. The steel weldment forms a strong, although rigid, skeletal member and is relatively economical to produce. A magnesium casting or a fiber/epoxy composite are feasible alternatives. One of these together with a higher density flesh simulation could result in a more human-like leg segment. Manufacturing tolerances, including weight criteria, are consistent with the functional requirements of the assembly.

Knee Joint Assembly (ATD-3774). This consists of a multiple disc clutch, housed in an aluminum casting with an external geometric, rather than anatomical, shape to produce a higher knee-impact repeatability. The impact area is part of the upper leg to eliminate the transference of load through the knee joint.

The complexity of the knee joint assembly is due to the multiple disc clutch. All disc plates are machined to very close tolerances to achieve maximum friction and minimum backlash. The knee cap, which also houses the clutch assembly, is made of cast aluminum because of weight limitations. However, careful design along with generous fillets and radii and minimum machining have produced a highly durable and cost-efficient part. Tolerances meet the functional requirements and facilitate assembly.

Thigh Flesh (ATD-3800) and Knee Flesh (ATD-3801). These parts, comprising the upper leg flesh, are designed for simple access to the femur load cell. Removal of one screw permits access to the load cell without the need to disturb any joint adjustment. This flesh-skin removability is a desirable feature. It facilitates servicing and replacements as well as molding, because the upper leg skeletal parts are not required in the molding process.

Lower Leg Assembly (ATD-3738). This is a steel weldment with a tube for the tibia and fibula, an ankle-rotation shaft at one end, and a clevis-type knee-joint attachment at the other end. Skin and foam are molded around it. The calf part of the lower leg flesh has a molded-in cavity that allows for a compressible calf and this provides for 160° of lower-leg flexion.

With careful design, the present leg bone could be reshaped to allow for a removable skin/flesh. Manufacturing tolerances on the knee-joint part are close but necessary to achieve a play-free joint and to facilitate assembly. Fiber/epoxy tubing for the tibia and fibula and a strong aluminum alloy for the knee and ankle joints, which would clamp around the tubing, are possible alternatives. The concept of a compressible cavity could also be considered for elbow flexion.

Ankle Rotation Assembly (ATD-3199). This assembly is a steel weldment comprised of six pieces, with a total weight of one pound. Relative to its size and function, this assembly is much too heavy and complex. All parts are machined from C-1018 steel to manufacturing tolerances of ±1/64 in. with one exception of +0.003 in. and −0 in. Twenty-five machining operations are involved. This is certainly a good candidate for an aluminum investment casting.

Foot Assembly (ATD-3141). The foot is molded of solid vinyl plastisol around a five-piece steel weldment. A sand-casting, as opposed to a steel weldment, would produce a highly durable foot bone with a minimum of machining.

Upper Arm (Upper Part) Assembly (ATD-3255). The skin and foam of the upper arm flesh is integrally molded around the upper-arm (upper-part) steel weldment, which is removable. The steel weldment is relatively simple in design. Of the five details comprising the weldment, two are stamped, one is saw-cut from standard stock, and two are machined. Only the machined parts have close (decimal) tolerances. All others are fractional. Surface roughness is called out only on one part. This situation can produce a poor upper-arm rotation-joint in one area and higher machining costs elsewhere. The feasibility of a fiber/epoxy composite for the bone with aluminum fittings for the joints should be considered as possible alternatives.

Upper Arm (Lower Part) Assembly (ATD-3237). This is a clevis-type steel weldment providing upper arm rotation and elbow flexion. It is simple in design and has a strong and highly durable construction. The "design guideline" for this component, as well as many other Part 572 components, seems to have been "survival of the fittest." To decrease the weight of this steel part (1.5 pounds) a strong aluminum alloy would be a good substitute.

Forearm Assembly (ATD-3145). The forearm consists of a steel weldment using square tubing for the radius and ulna and terminating in a clamping sleeve for wrist rotation at one end and steel pads for elbow joint friction at the other end. Skin and foam form forearm flesh around the weldment, which is not removable. With minimal design changes, however, the forearm flesh could also be made removable. Manufacturing tolerances allow for easy assembly and meet the functional requirements. Fiber/epoxy composites should be considered for this component.

Wrist Assembly (MD-403). This steel weldment is comprised of two lugs forming a clevis for attachment of the hand and a shaft that connects to the forearm. It should instead be an investment casting.

Hand Assembly (ATD-3142). The hand is made of solid vinyl plastisol molded around the hand bone, a steel weldment. The shape of the hand bone is ideally suited for the investment-casting method.

Pivot Screws (ATD-3043). These parts are the various sizes of screws used in the arm and leg joints. These pivot screws, as well as other screws used on the Part 572 dummy, are hex-socket screws of low quality. The result is that sometimes threads get stripped, and more frequently the hex head sockets get stripped. Screws of higher quality, such as Allen Head (not "allens" or "Allen type"), are recommended.

HYBRID III DUMMY

Head Assembly (78051-61). This assembly includes the skull assembly (78051-77), skull cap (78051-220), head skin (78051-228), head-back skin (78051-229), accelerometer mount (78051-222), accelerometers with harness assembly (78051-223), transducer-neck (78051-300), and mounting hardware. The head and head-back skins are cast-molded in pigmented vinyl plastisol formulation Pt-4, as called out on drawing 78051-228/229 (skin Hybrid III), but no reference is made to drawing 78051-372 (vinyl skin formulation Hybrid III), which defines formulations Pt-1, −2, −3, and −4. Formulations Pt-1, −2, and −3 correspond to the original ARL Pt-1, −2, and −3 formulations dated March 28, 1973. The Pt-4 formulation, however, does not correspond to the original ARL Pt-4 formulation dated March 18, 1976. The formulation designated Pt-4 on drawing 78051-372 corresponds to the Part 572 head skin formulation and should have a different designation to avoid any confusion.

Physical properties (i.e., shore hardness, tear strength, etc.) of vinyl plastisol can be influenced by variations in molding procedures and should be specified on drawing 78051-228.

The cranium part of the head skin is 0.441 inches thick with a tolerance of ±0.031 inch. The maximum permissible variation of 0.062 inch is controlled only along two lines, one described by the midsagittal plane (forehead to back of head) and the other by the coronal (ear to ear) plan. There is no skin thickness control outside of those two lines. Closer skin thickness tolerances and more inspection points to control such tolerances would be desirable in the frontal impact area as well as in the left- and right-side impact areas.

The skull assembly and cap-rear skull are cast as a one-piece aluminum casting, in no. (AA) 3570 aluminum alloy. All tapped holes are fitted with "keenserts," providing permanent wear-resistance threads with positive lock against rotation. All machined surfaces have a finish of 63 MSR maximum. On mating surfaces not involving motion, 125 MSR should be sufficient. The frontal and the left and right sides of the skull have no requirement for controlled surface texture, which, during impact, affects the head skin-spreading phenomenon. In the test procedure for head impact response specifications (drawing 79051-62), it is suggested that the application of silicon grease (Dow Corning compound No. 4 or equivalent) between the skull and vinyl skin be used as a means to adjust the hard-surface impact response. Any new skull drawing should instead reflect the MSR necessary for optimum function, without regard to casting practices and lubricating methods.

On most drawings, a circular zone tolerancing system is used, a system used primarily in mass production industry. Other drawings in the set reflect the use of a rectangular system of tolerancing, which is more often used in prototype or low-volume manufacturing. While there are advantages for each, a single system should be chosen and used.

The head ballasting overview of head assembly drawing no. 78051-61 refers to "head targets" as part no. 78051-227. The parts list does not include this number, although the parts list index does, and no drawing exists. The same overview states that all of the parts included on the head assembly drawing 78051-61 are to be included in the weight and center-of-gravity location determination, but no reference is made to the chart (drawing no. 78051-338, sheet 1 of 2) that lists the parts groupings for making such determinations. These types of information gaps are frustrating and time-consuming for the user.

The head ballasting procedure requires calculations for determining ballast location. It appears that the skull-cavity surface-contours and the matching ballast contours do not make positional adjustment possible. The head skin is molded over the skull/skull-cap mold insert. This method provides for uniform and easy skin replacement but does not assure perfect fit between skin and skull. This is because skull/skull-cap castings may differ due to variations in castings as a result of different shrinkages.

The head assembly has good design features, simple facial details, a highly durable skull designed to minimize "ringing" and resultant noisy instrument reading, minimal machining, and easy access to instrumentation. With some exceptions the assembly is well documented.

Neck Assembly, Complete (78051-90). The neck consists of a nodding-joint neck assembly (78051-297), nodding block (78051-351), neck molded assembly (78051-336), and cable (78051-301).

The nodding-joint neck assembly is machined from 7075-T6 aluminum with a maximum MSR of 63 on all surfaces. Only on two of the nine surface features is surface texture a functional requirement. With careful design considerations and choice of material, this part could be investment cast. The neck molded assembly is an excellent example of a good simple design. The requirement for mold parting line surfaces to blend within ±0.002 inch is superfluous and costly. The actual width on existing necks (as seen on three different specimens) is ±0.007 inch to 0.010 inch. (The molded lumbar spine assembly drawing 78051-66 has no parting line specifications at all.) Some of the revisions (i.e., Rev. C and E) seem to reflect the result in dimensional differences "as designed," as opposed to actual molded parts after shrinkage. Information in regard to such changes would be of benefit to a moldmaker trying to duplicate molded features whose controlling dimensions are subject to change. All rubber bumpers (i.e., elbow stops) deteriorate with time and use and require periodic (at least every six months) replacement. This is especially true for neck nodding blocks, which affect the head/neck dynamics.

The overall length of the neck cable has a tolerance of ±0.01 inch. The neck assembly design allows for at least ±0.60 inch. The overall length of the cable should be measured from the end of the threaded stud to the center of the ball fitting rather than to its end, because the center of the ball fitting is used as a dimensioning feature on the neck assembly. A screwdriver-slot or square wrench grip on the end of the threaded cable fittings would facilitate the application of torque to the cable nuts on the neck and lumbar spine cables. (Torque is specified for the lumbar spine cables but not for the neck cable.)

It has been noted that lifting of the dummy by its head as well as actual crash tests may cause a slippage of the end fittings on the cable. This slippage has to be monitored and cable replacement made when slippage has exceeded 0.015 inch.

Bracket Assembly—Neck Adjusting, Upper (78051-307) and Bracket Assembly—Neck Adjusting, Lower (78051-303). The unique design of these cast aluminum assemblies is simple and functional, resulting in components that are strong, compact, light, and relatively easy to manufacture. Experience has shown, however, that the neck adjustment capability is not used or needed (except in experimental situations) and that a one-piece neck base bracket would result in a stronger, more reliable, and more cost-effective part.

Thoracic Spine Assembly (78051-179). This assembly is made up of twelve machined parts, welded together, and resulting in a relatively light but rigid and strong structure. Seven of the several hole-locating dimensions on the front and back spine plates are toleranced at ±0.005 inch, but these dimensions are dependent on the welding process. Such close-toleranced machining should instead be accomplished after welding, and the casting method should also be considered as an alternative to welding.

Rib Assembly #1 through #6 (78051-36 through −40). The rib, rib damping material, and bonding procedures on the rib assembly drawings are well documented. The note on drawing 78051-17 through −22 (material, rib damping) specifies that the rib damping material thickness be determined for each new batch of material using a chest impact test method with a completely assembled dummy.

To ensure that the material is indeed uniform, each shipment supplied should be certified as all coming from one batch, and a simpler test for determining damping material thickness needs to be developed. As designed, the rib assembly performance is largely dependent on the damping material, which is very temperature sensitive and subject to flexural fatigue necessitating periodic rib replacement. Batch to batch damping material uniformity is difficult to obtain, and this results in a costly "tailor fit" type of manufacturing method.

Adaptor Machining Assembly, Instrumentation (78051-78). Greater accuracy, more rigidity, and better manufacturing economy could be attained if this instrument mounting adaptor were a casting instead of a weldment. Better yet, with some careful design modification, the instrumentation could be mounted directly on the thoracic spine assembly. This would eliminate the present costly instrumentation mounting adaptor and the necessity to disassemble the dummy at the lumbar-spine/thoracic-spine assembly interface in order to access the instrument mounting adaptor. This would facilitate access through the back and side of the thoracic spine assembly and provide far more rigidity to the instrument mounting base.

Clavicular Link Assembly (78051-188 L.H. & 189 R.H.), Clavicle Assembly (78051-141 L.H. & 142 R.H), and Yoke Assembly (78051-360). The major components of these assemblies are cast. The clavicular link and clavicle are cast in (AA) 357.0 aluminum, and the yoke in 4130 steel.

These assemblies comprise the shoulder system and corresponding motion joints (with respect to the torso) for shoulder elevation, depression, and anterior-posterior excursion. The clevis-type joints used are superior to those in the Part 572 dummy, and should be more widely used. The yoke joint system provides flexion, hyperextension, adduction, and abduction motion for the upper arm. When all the above angular movements are combined in succession, the distal end of the limb (i.e., upper arm shoulder pivot) describes the surface of a cone, a movement called "circumduction." Smooth humanlike circumduction, however, can only be achieved with a ball and socket joint or a joint made of elastic material (i.e., urethane elastomer).

This refined design features friction washers and shaft bushings made of Delrin 500 acetal resin Dupont®, and provides outstanding characteristics as described above for the Part 572 dummy. These features provide uniform smooth motion, damping, and metal-to-metal insulation. Of particular interest are the nut (i.e., nut-shoulder yoke assembly part no. 78051-255) design features. The sliding action of this nut ensures accurate parallel engagement between opposing friction surfaces and results in uniform joint motion resistance through its entire range. Another feature is the multiple (three places) key system that is designed to prevent the sliding nut from rotating and developing backlash (the shifting of the clearance between a key or a gear tooth and its mating feature, the gap). In order to prevent the backlash phenomenon, the mating features must be controlled with a high degree of accuracy, as they are on the Hybrid III drawings. But no matter how accurately a key and its mating gap are controlled and meshed together, backlash is bound to creep in. For example, the wear from repeated use of a joint will result in backlash. It is quite impossible to eliminate backlash completely and still have a nut that will slide smoothly without binding. The addition of an antibacklash device is impractical because of space and weight limitations and undesirable complexity. One possible solution would be to considerably enlarge the gap between the key and its mating feature and fill the gap with urethane or some other elastomeric material. This would minimize and damp the backlash phenomenon, eliminate metal-to-metal contact, allow the high degree-of-accuracy requirement to be relaxed, and smooth the initial motion of the joint.

Upper Torso Assembly, Complete (78051-89). The chest accelerometers can be accessed only by separating the upper thorax from the lower thorax at the thoracic/lumbar-spine interface. The upper torso assembly is a relatively complex one, and the requirement that the intersection of the accelerometer seismic mass axes coincide with the upper torso center of gravity is complicated by the position of the sternum assembly (in its deflected position relative to upper torso CG location), the physical size of the accelerometers, and the upper torso CG location itself. The location of accelerometers in future dummy design should receive serious consideration.

The chest flesh arm holes are oval shaped, creating additional clearance on the aft side of the shoulder yoke. This unique feature allows for removal of the chest flesh assembly (with arms in a 90° flexed position) without the need to remove the arms when accessing the thoracic assembly.

The desirable joint torque adjusting and insulating features, which are used in the shoulder elevation-depression joints, are omitted from the shoulder fore and aft joints, where the need is just as important, if not more so.

Bracket Assembly—Molded Lumbar Spine (78051-53). This is a complex welded structure encased with 13 pounds of Cerrobase material. The drawing does not define the cast Cerrobase external features, but a note refers to SRDL mold no. 78051, sheets 322 through 326. Drawings with those numbers cover bushing, connectors, neck bracket, and screw. The welded assembly (78051-28) is made up of parts requiring substantial amount of machining. A casting would eliminate most of it.

Leg Assembly, Complete (78051-56 and −57). With the exception of friction-washer clutch design features in the knee joint, the leg assembly is similar to the Part 572 leg assembly. The upper leg rotation joint was eliminated from the upper leg structure, and it is the femur "ball and socket joint" that now provides upper leg rotation, resulting in better biofidelity. The knee impact area has a removable flesh insert molded of butyl rubber, durometer 45. This feature allows for periodic quick replacement and better control over knee impact characteristics.

Patterns for Molded Flesh Parts. Drawings for molded assemblies (i.e., lower arm assembly molded, 78051-194) call for the use of corresponding models for moldmaking. Master patterns are available only for the head and the abdominal insert. All other models are the actual molded parts. Master patterns have a built-in predetermined shrinkage factor to compensate for mold shrinkages occurring during the casting process and also for subsequent shrinkages that occur during post-molding operations.

Summary. The Hybrid III is well documented. For most parts and assemblies the drawings are clear, and the parts list and the parts list index are a great service to test dummy manufacturers as well as users. The head, neck, and lumbar spine are of simple and functional design. The clavicular, shoulder, elbow, and knee joint designs represent a significant improvement over the clevis-type joints on the Part 572 dummy. Other features representing advances in the state of the art with regard to dummy design are the six-axis neck transducer, the adjustable neck base, the designed-in chest deflection measuring device, the systems for mounting a mechanical pelvic angle gage and a chest target angle gage, and the removable insert in the knee impact area.

Manufacturing cost efficiencies could be realized by simplification of some of the complex shapes as well as by relaxing some of the dimensional tolerances and surface roughness value requirements, which would not affect the test dummy weight distribution or its dynamic performance.

GENERAL ISSUES

Dimensioning. By far the most important features of a part or assembly drawing are the dimensions. Their nature and format should even be considered in the design stage. Dimensions should be placed in an orderly and uncrowded arrangement on the drawing for ease of use, and their relationship to one another should reflect the part's engineering intent. In order to permit a variety of manufacturing methods, a drawing should only specify the desired result and not the process to be used in obtaining that result.

Tolerancing. The purpose of manufacturing tolerances is to assure that variations in the manufacturing process are controlled, but they should also permit the greatest economy of production consistent with the functional requirements of the part or assembly being produced.

The accumulation of tolerances and dimension limits is a potential problem. Because dimensions can vary from the extreme high to the extreme low on related parts, it is possible that an undesirable condition will be created upon assembly. The likelihood of such a condition can often be reduced if parts are dimensioned such that the minimum number of dimensions and thus tolerances are involved in each aggregation.

Standard Sizes. Stock sizes for finished parts should be selected whenever possible to reduce material, tooling, and machining costs. Although it is generally easier to hold an external diameter to a closer tolerance than an internal one, if a shaft can be made from standard stock without further machining, it may be more economical to use that stock and specially machine the sleeve or housing.

CHAPTER 3

REPEATABILITY AND REPRODUCIBILITY

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Assessment of the repeatability and reproducibility of candidate anthropomorphic test devices is an important element of this program. In this application, repeatability refers to the variance of replicate tests with the same test device, while reproducibility refers to the variance arising from different test devices. The objective of this chapter is to identify appropriate techniques for assessing repeatability and reproducibility where possible, and to identify areas requiring further development in Phase 2.

TYPES AND SOURCES OF ERROR

This section presents an overview of the types of error and sources of error in the environment in which the anthropomorphic test device will be used. Specification of dummy design objectives will be influenced by the magnitude of sources of error *apart* from the dummy, as well as sources of error inherent to the dummy. In a discussion of error, it is important to distinguish random errors from bias, or systematic, error. Although any error is undesirable, random error is the preferable of the two, since it has zero mean by definition. Consequently, statistical techniques can identify and measure random error, and estimates of the desired quantities can be made as accurate as one wants (if the necessary sample sizes are not impractical). However, bias error nearly always causes serious problems since, by its nature, it is not distinguishable from the desired response. Bias usually refers to a shift in the mean, or average value, measured as opposed to random fluctuations about a stable mean. An example of bias error is the gradual change in the response of a dummy component due to permanent deformation, or degradation, that altered the response characteristic for a given input.

An overview of sources of error is given below in relation to the measurement of dummy repeatability and reproducibility.

A. Repeatability

1. Variation in the Test
    - Type of test (vehicle, sled)
    - Type of seat (hard, soft)
    - Initial speed
    - Deceleration pulse
    - Signal processing
    - Positioning

2. Variation in the Dummy
    - Variation in the dynamic response (due to joint friction changes, etc.)
    - Transducer errors
    - Permanent damage, or deterioration

B. Reproducibility
    - Systematic differences in response from one dummy to another

An obvious point is that the error associated with repeatability will include any inherent variation in the test itself. Consequently, when measuring repeatability, one would like to use the most repeatable test procedure possible as long as the dummy is exercised in a manner that is representative of its intended use. Since errors combine as their square (variances), dummy repeatability cannot really be assessed unless variations in the test are small in comparison. Similarly, a practical design objective is to make the dummy variability comparable to that of its intended test application (soft seats, real vehicles)[1].

The NHTSA Crash Test Repeatability Program is addressing many aspects of the overall problem. As results become available, they should be incorporated in this program. The dummy certification procedures under development are an important element of the assessment of repeatability and reproducibility. Ideally, certification would be carried out in terms of the same responses used to assess repeatability and reproducibility. In this situation, multiple certification tests and statistical procedures would allow certification procedures that recognized the presence of random error and would be sensitive to its magnitude as well. In this way, certification would cover both the accuracy of the response and the variability. If different responses are used for certification and repeatability, then one must relate these measures so that the certification procedures are compatible with the repeatability desired. Other tasks in the NHTSA Crash Test Repeatability Program are relevant to this project. These include the Statistical Analysis of Vehicle Dummy Parameters, the Quantification of Specific Crash Parameters, Evaluation of Data System Acquisition Errors, and the Injury Criteria Analysis.

STATISTICAL TECHNIQUES

For this discussion, measurements obtained from the dummy are divided into time-independent and time-dependent measures. Time-independent measures are all those that result in a single number, regardless of how it may have been derived from the original time-history. Time-dependent measures are functions, or transformations, that retain time as an independent variable, including the original transducer signals. Statistical methods for the time-independent measures are straightforward, while comparison of the time-dependent measures is not. Consequently, the time-independent measures are

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[1] This assumes that the cost associated with reducing any particular source of error is equal; in which case, the minimum cost and minimum total error is achieved when each source is of equal magnitude. In the more realistic situation, in which the cost to reduce the error associated with different sources is different, then the square relationship should guide cost allocation. Consequently, one would be willing to allocate four times the cost for an incremental change in an error source that had double the magnitude of another. This procedure usually leads to fairly uniform variances, unless the relative costs are really disparate. In that case, the irreducible source of error effectively defines a level of error with little incentive to reduce other sources.

preferred from the standpoint of evaluation of repeatability and reproducibility. However, a test device with good repeatability for one injury criterion may not have good repeatability if a new criterion were introduced. A more stringent requirement is to compare the time-histories, but the cost required for this approach may be prohibitive. Statistical methods are discussed separately below for evaluating the repeatability and reproducibility of time-independent and time-dependent measures.

Analysis of variance techniques are the method of choice for evaluating the repeatability and reproducibility of time-independent measures. These techniques separate "within" and "between" variability. "Within" refers to the variability of individual dummies over replicate tests, and "between" refers to the variability that arises from the use of different dummies in replicate tests. The null hypothesis is that the variability from one dummy to another is not greater than the variability of an individual dummy. Sample size can be determined to identify a specified level of between variability given the magnitude of the within variability.

Time-dependent measures may compare either the magnitude or the phase relationship of the transducer time-history. Currently, the most attractive measure that has been proposed is the Normalized Integral Square Error (NISE) (Jovanovski 1981, Donnelly et al. 1983). This measure is derived from the autocorrelation functions. It is relatively easy to compute, and has the advantage of partitioning the error into that arising from phase differences, magnitude differences, and a remaining error that may be interpreted as waveform differences.

Donnelly et al. (1983) develop limits of acceptability for the NISE derived from the comparison of a single pair of time-histories based on an overall percent error criterion. However, methods for statistical hypothesis testing for this measure have not been developed. Such methods are needed to compare the distribution of the NISE obtained from several replicate runs as would be needed to assess repeatability. This work would seem to be a logical task for Phase 2.

REFERENCES

Jovanovski, J. (1981) *Crash data analysis and model validation techniques using correlational techniques*. SAE paper no. 810471.

Donnelly, B.R.; Morgan, R.M.; and Eppinger, R.H. (1983) *Durability, repeatability, and reproducibility of the NHTSA side impact dummy*. SAE paper no. 831624.

CHAPTER 4

ANTHROPOMETRIC DATA AND BIOMECHANICAL RESPONSE SIMULATION FOR AATD DESIGN

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This chapter presents a summary of the anthropometric data available for use in developing design specifications for an advanced anthropomorphic test device. It also demonstrates the use of these data in a limited simulation of dummy response using the CAL-3D crash victim simulation code. Parameters of particular interest in this stage of AATD development are those associated with spinal flexibility and shoulder mobility. It has been shown that spinal flexibility, beyond that presently included in existing dummy designs, such as Part 572 and Hybrid III, plays a major role in controlling torso and head motions and applied forces. It is expected that parameter studies of this type will be used to assist in determining the relative importance of various dummy design features during the next phase of AATD development.

STATUS OF DATA RESOURCES AND THEIR APPLICATION TO DESIGN CONCEPTS

Several data resources are available from the recently completed dummy anthropometry project on Contract no. DTNH22-80-C-07502. These include mass and inertial properties, body surface shape, seated posture, estimations for the location of the bony structure, joint locations, and range of motion at the various joint structures. These data are all static and are for a mid-sized male driver in an average vehicle-seated posture. In order to conduct a parameter study of AATD potential dynamic performance, it is also necessary to consider additional parameters describing crash events and the physical definition of the vehicle. These crash environment data are discussed at the end of this section.

Body Linkage and Segmentation. Mass and inertial properties are given in Robbins (1983) for a traditional linkage and segmentation of the body in the static seated posture. The mechanical term "linkage" implies that the available data are most applicable to dummies or simulations based primarily on rigid-body mechanical models. Considerable work has been done in reviewing a spectrum of linkages for use in the parameter study and for potential use in AATD design. The parameter study has been accomplished using a lumped-mass chain-linkage dynamic simulation software package consisting of rigid masses connected at joint structures. In other words, masses were lumped and flexibilities were lumped. For the head, arms, lower legs, and feet, the selection of linkage elements (distances between joints, such as knees, elbows, ankles, H-point, and L5/S1 connection) was straightforward. (This is arguable, especially for the case of the knee joint.) For the rest of the body, consisting of the shoulder mass and its joints, the torso and spine (from C1 through L5), and the upper leg masses, the selection of elements was more difficult.

The details of the linkage are summarized in Figure 4-1 as well as Tables 4-1 and 4-2. Figure 4-1 shows details of the occupant, including centers of gravity, joints, and principal axes of inertia. Table 4-1 shows how the thorax mass data developed by Robbins (1983) was divided to provide flexibility within the thoracic region including the shoulders. The percent of the total mass for each segment was estimated using the front and side skeletal drawings, MM-104 and MM-105 (see Robbins 1983). The region occupied by the tissue for each segment was outlined on the drawings. From these outlines, volume (mass) estimates were made. Table 4-2 shows the attachments (joints) between the various masses in the body. Details follow of the data sources and methods used to determine segmentation for specific regions.

TABLE 4-1

DIVISION OF RIGID THORAX INTO SEGMENTS

Segment	Percent of Total Mass	Mass (kg)
Upper Spine (T1T4)*	10	2.376
Middle Spine (T5T8)	20	4.753
Lower Spine (T9T12)	20	4.753
Right Shoulder (SHO)	10	2.376
Left Shoulder (SHO)	10	2.376
Rib Cage (THORAX)	30	7.129

*Quantities in parenthesis refer to labels used in Figure 4.–1.

Shoulder. The shoulder segments were modeled as entities separate from the chest due to their known mobility both in frontal and lateral impacts as observed in cadaver tests. Joints have been selected at the glenohumeral and sternoclavicular articulations. The scapula link, as defined by Dempster (1955), is lumped with the clavicle due to the paucity of mobility information other than that defining mobility of the humerus with respect to the chest. Most of the relevant usable data on forced shoulder girdle mobility has been developed by Engin at Ohio State University. Both published and unpublished data have been made available to the project.

Neck.[2] The neck has proven to be one of the easier segments to model due to the work of Bowman et al. (1984) and Wismans and Spenny (1984) who have independently worked on the Naval Biodynamics Laboratory (NBDL) data. They agree that a rigid link from the occipital condyles to the C7/T1 interface can be used to model dynamic response of the head with respect to the torso in frontal, lateral, and oblique impacts. This model is only valid, however, for non-contact dynamic response, as the NBDL test subjects were not subjected to direct head impact. Data of Bowman et al. (1984) are used in developing neck flexibility parameters.

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[2] In other AATD project reports, the neck has been treated as part of the spinal unit. In this work, however, the neck is considered separately from the thoracolumbar spine.

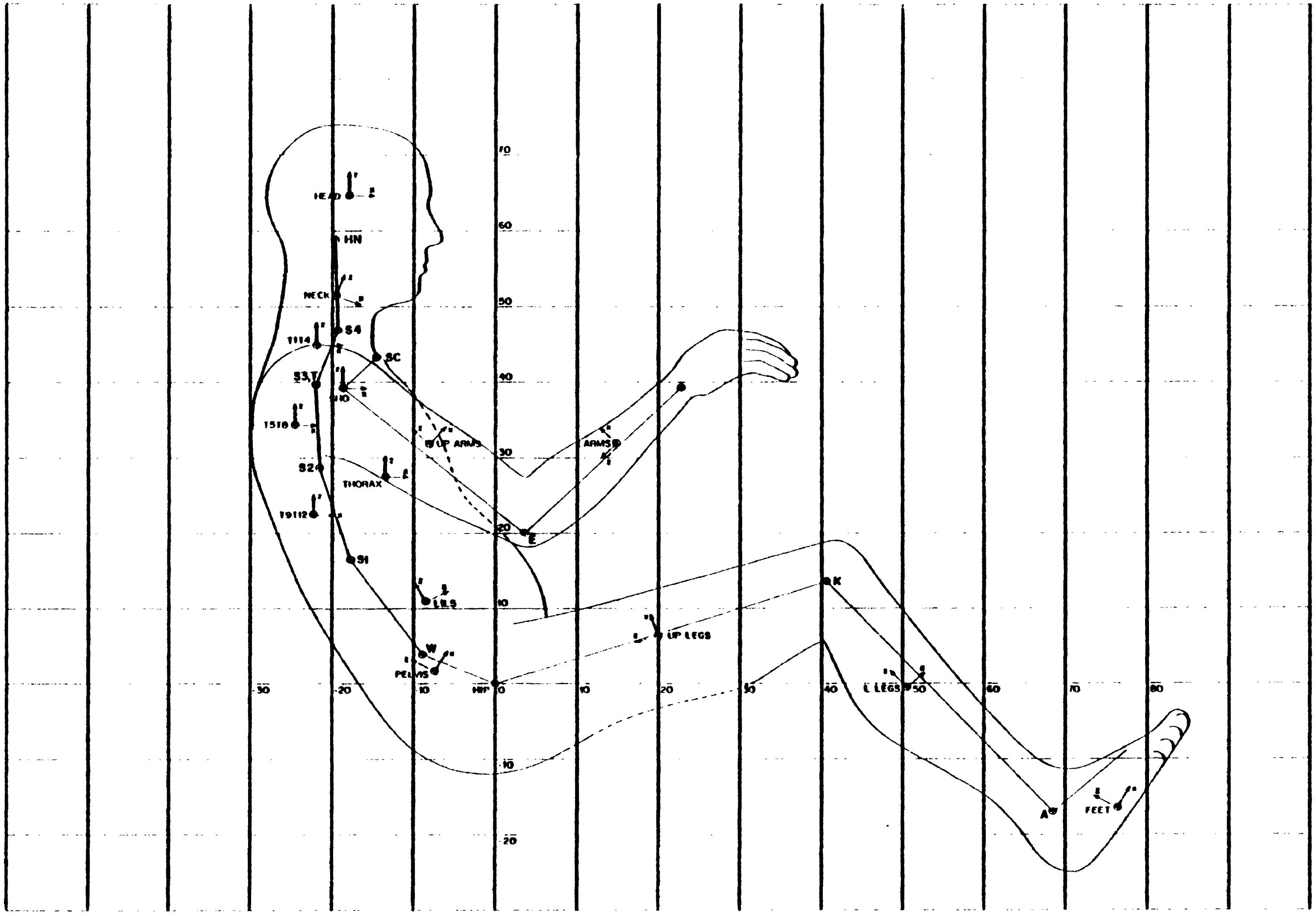

FIGURE 4-1. Seated occupant showing joints, masses, and inertial properties.

TABLE 4-2

BODY LINKAGE MODEL

Body Segment			Joint			Attached To		
Name	Fig 4-1 Code	Tab 4-3 Code	Name	Fig 4-1 Code	Tab 4-3 Code	Name	Fig 4-1 Code	Tab 4-3 Code
Head	HEAD	HEAD	Head-Neck	HN	HN	Neck	NECK	NECK
Neck	NECK	NECK	Head-Neck	HN	HN	Head	HEAD	HEAD
Neck	NECK	NECK	C7-T1	S4	S4	Upper Spine	T1T4	T1T4
Upper Spine	T1T4	T1T4	C7-T1	S4	S4	Neck	NECK	NECK
Upper Spine	T1T4	T1T4	T4-T5	S3	S3	Middle Spine	T5T8	T5T8
Middle Spine	T5T8	T5T8	T4-T5	S3	S3	Upper Spine	T1T4	T1T4
Middle Spine	T5T8	T5T8	Left Sterno-Clavicular	SC	LSC	Left Shoulder	SHO	LSHO
Middle Spine	T5T8	T5T8	Right Sterno-Clavicular	SC	RSC	Right Shoulder	SHO	RSHO
Middle Spine	T5T8	T5T8	Thorax	T	T	Thorax	THORAX	THOR
Middle Spine	T5T8	T5T8	T8-T9	S2	S2	Lower Spine	T9T12	T9T12
Left Shoulder	SHO	LSHO	Left Sterno-Clavicular	SC	LSC	Middle Spine	T5T8	T5T8
Left Shoulder	SHO	LSHO	Left Glenohumeral	SHO	LGH	Left Upper Arm	UP ARMS	LUAR
Left Upper Arm	UP ARMS	LUAR	Left Glenohumeral	SHO	LGH	Left Shoulder	SHO	LSHO
Left Upper Arm	UP ARMS	LUAR	Left Elbow	E	LE	Left Lower Arm	LARMS	LLAR
Left Lower Arm	LARMS	LLAR	Left Elbow	E	LE	Left Upper Arm	UP ARMS	LUAR
Right Shoulder	SHO	RSHO	Right Sterno-Clavicular	SC	RSC	Middle Spine	T5T8	T5T8
Right Shoulder	SHO	RSHO	Right Glenohumeral	SHO	RGH	Right Upper Arm	UP ARMS	RUAR
Right Upper Arm	UP ARMS	RUAR	Right Glenohumeral	SHO	RGH	Right Shoulder	SHO	RSHO
Right Upper Arm	UP ARMS	RUAR	Right Elbow	E	RE	Right Lower Arm	LARMS	RLAR
Right Lower Arm	LARMS	RLAR	Right Elbow	E	RE	Right Upper Arm	UP ARMS	RUAR
Thorax	THORAX	THOR	Thorax	T	T	Middle Spine	T5T8	T5T8
Lower Spine	T9T12	T9T12	T8-T9	S2	S2	Middle Spine	T5T8	T5T8
Lower Spine	T9T12	T9T12	T12-L1	S1	S1	Lumbar Spine	L1L5	L1L5
Lumbar Spine	L1L5	L1L5	T12-L1	S1	S1	Lower Spine	T9T12	T9T12
Lumbar Spine	L1L5	L1L5	Waist, L5-S1	W	W	Pelvis	PELVIS	PELV

TABLE 4-2 (Continued)

Body Segment			Joint			Attached To		
Name	Fig 4-1 Code	Tab 4-3 Code	Name	Fig 4-1 Code	Tab 4-3 Code	Name	Fig 4-1 Code	Tab 4-3 Code
Pelvis	PELVIS	PELV	Waist, L5-S1	W	W	Lumbar Spine	L1L5	L1L5
Pelvis	PELVIS	PELV	Left Hip	HIP	LHP	Left Upper Leg	UP LEGS	LULG
Pelvis	PELVIS	PELV	Right Hip	HIP	RHP	Right Upper Leg	UP LEGS	RULG
Left Upper Leg	UP LEGS	LULG	Left Hip	HIP	LHP	Pelvis	PELVIS	PELV
Left Upper Leg	UP LEGS	LULG	Left Knee	K	LKN	Left Lower Leg	L LEGS	LLLG
Left Lower Leg	L LEGS	LLLG	Left Knee	K	LKN	Left Upper Leg	UP LEGS	LULG
Left Lower Leg	L LEGS	LLLG	Left Ankle	A	LAKL	Left Foot	FEET	LFOT
Left Foot	FEET	LFOT	Left Ankle	A	LAKL	Left Lower Leg	L LEGS	LLLG
Right Upper Leg	UP LEGS	RULG	Right Hip	HIP	RHP	Pelvis	PELVIS	PELV
Right Upper Leg	UP LEGS	RULG	Right Knee	K	RKN	Right Lower Leg	L LEGS	RLLG
Right Lower Leg	LLEGS	RLLG	Right Knee	K	RKN	Right Upper Leg	UP LEGS	RULG
Right Lower Leg	LLEGS	RLLG	Right Ankle	A	RAKL	Right Foot	FEET	RFOT
Right Foot	FEET	RFOT	Right Ankle	A	RAKL	Right Lower Leg	LLEGS	RLLG

Thoracolumbar Spine. The thoracic and lumbar spine has proven to be the most difficult region of the body to segment. The present consensus between Nyquist, King, and Robbins is that the spine (excluding the neck) should ideally be divided into four links: T1-T4, T5-T8, T9-T12, L1-L5. This is based on a review of sled test data using cadavers obtained during NHTSA projects at both UMTRI and WSU. The major purpose of the T1-T4 and T9-T12 links, added to the thoracic spine, is to distribute spinal flexibility. The bulk of the thoracic mass is concentrated in the T5-T8 and thorax links.

Thorax. Modeling of the thorax, including the coupling of the rib cage to the spine, is difficult in that the rib cage is a major load-carrying structure. Depending on the direction and surface area of contact, the force-deformation characteristics and hence the mass mobility are known to be different. The problem, therefore, is to choose a single structural representation that is responsive to the various types of impact to which the chest is subjected. A complex representation that includes rib cage mobility and rotation has been developed. The objective was to choose linkage arrangements with a structure that would yield insight into possible hardware design configurations of mass, mobility, and compliance for the thorax. It is believed that frontal mobility and compliance as well as rotation about the side-to-side axis for frontal impact are necessary for the thoracic region to represent its loose coupling with the spinal column. This means that under frontal loading the front of the thorax should be able to move linearly toward the spine as the result of rotation about a left-right axis through the joint at the T4/T5 interspace.

In support of this work, a study of rib cage rotation with respect to the spinal column has been completed. It was concluded, based on an analysis of both three-point-belt (Test No. 76T008) and airbag/steering-column (Test No. 76T020) restrained cadaver test results gathered at UMTRI, that the rib cage rotates downward toward the spinal column by as much as 20 degrees. These peaks are reached at the time of maximum loadings to the thorax by the belt and column. This result is based on angle measurements of targets on T1 and on the eighth ribs. The same analysis yielded the result that the spine straightens out so that the lower part of the thoracic spine actually moves away from the rib cage. The angle change between T1 and T12 from the initial slouched position to the time of peak loading is about 15 degrees straightening for the belt case and almost 40 degrees for the column/airbag case. These kinematic results lead to the conclusion, previously based on intuition, that flexibility is needed in the thoracic spine and that a degree of freedom should be added to represent the rotation of the bony rib cage.

Segment Mobility and Range of Motion. Mobility and range of motion between segments is another area where quantitative data are in limited supply, but where analytical simulations can provide guidance in assessing the importance of these parameters to dummy dynamic response. Data for static mobility or voluntary range of motion are in fair supply. In other words, it is possible to estimate how far the segments can move with respect to each other before subjects say "ouch" or before outside forcing agents must be supplied to produce further motions. Similar quantitative data for dynamic mobility (dynamic motions voluntarily made or those that occur under the influence of an outside forcing agent, such as a deceleration device) are virtually nonexistent, except for the neck and, perhaps to a more limited extent, for the thoracic and lumbar spines. General dynamic torque data are not yet available for the thoracic and lumbar regions. Work is underway at the present time in an attempt to fill this gap. Earlier work by Cheng et al. (1979) as well as Nyquist and Murton (1975) is being used in the interim in constructing CAL 3-D data sets. Their work provided appropriate values for the first four joint-stop locations and linear flexion coefficients listed in Table 4–3. This information was supplemented by Robbins (1983) and Bowman et al. (1984) for the two neck joints.

Some limited static data are available to describe the resistance of most other body joint structures to forcible motion beyond the voluntary range. Some of this has been included in Robbins (1983), while new data for the shoulder has been provided by Engin (1983) during the current activity. These data as well as Dempster (1955) provided the linear flexion and joint-stop data for the glenohumeral and sternoclavicular joints given in Table 4–3.

TABLE 4–3

JOINT TORQUE PARAMETERS

Joint	Linear Flexion (N•m /deg)	Joint-Stop Location (deg)
Waist (lumbar-sacral)	6.43	±15
Thorax (T12/L1)	14.15	±10
Thorax (T8/T9)	14.15	±10
Thorax (T4/T5)	14.15	±10
Thorax (T1/C7)	1.60	±45
Head/Neck	2.50	±45
Glenohumeral (L and R)	2.45	±55
Sternoclavicular (L and R)	2.45	±22

It can be hypothesized that a general plot of torque versus relative angle between any two segments has the form shown in Figure 4–2. This plot shows that there are many possibilities for torque values given any particular relative angle. Conversely, there are many angle positions for a given torque. When it is not possible for a relative angle to be reached without exertion of torque, a limit is reached. Either flexion or extension torques must be generated to exceed this zero torque limit. Because self generation of torque is possible by the flexing of muscles, a range of motion larger than the zero torque limit can be generated voluntarily. When joints are forced beyond the voluntary limits by inertial or direct loadings, injuries can occur. In addition to range-of-motion limits, strength limits also are involved in defining the width of the torque versus relative angle curve. For any given relative angle, a different torque will resist motion in the flexion direction from that which will resist motion in the extension direction. This is the measure of static strength. It should also be noted that the maximum strength capability of the muscles (tetanus) exceeds voluntary static strength data. As indicated above, dynamic data are virtually nonexistent, but it can again be hypothesized that such data would produce curves with the same general shape as Figure 4–2.

A summary of key data developed for modeling of joint resistance is given in Table 4–3. Additional realistic quantities for torsion of the thoracolumbar spine need to be developed for use in lateral or oblique impact simulations. Some very limited data are available for developing these quantities.

Segment Force-Deformation Characteristics. There are few data sources appropriate for modeling the force-deformation properties of body regions under direct loading in a crash environment. For the thorax, however, Melvin et al. (1985) have concluded that the force-deflection response characteristics are different for different

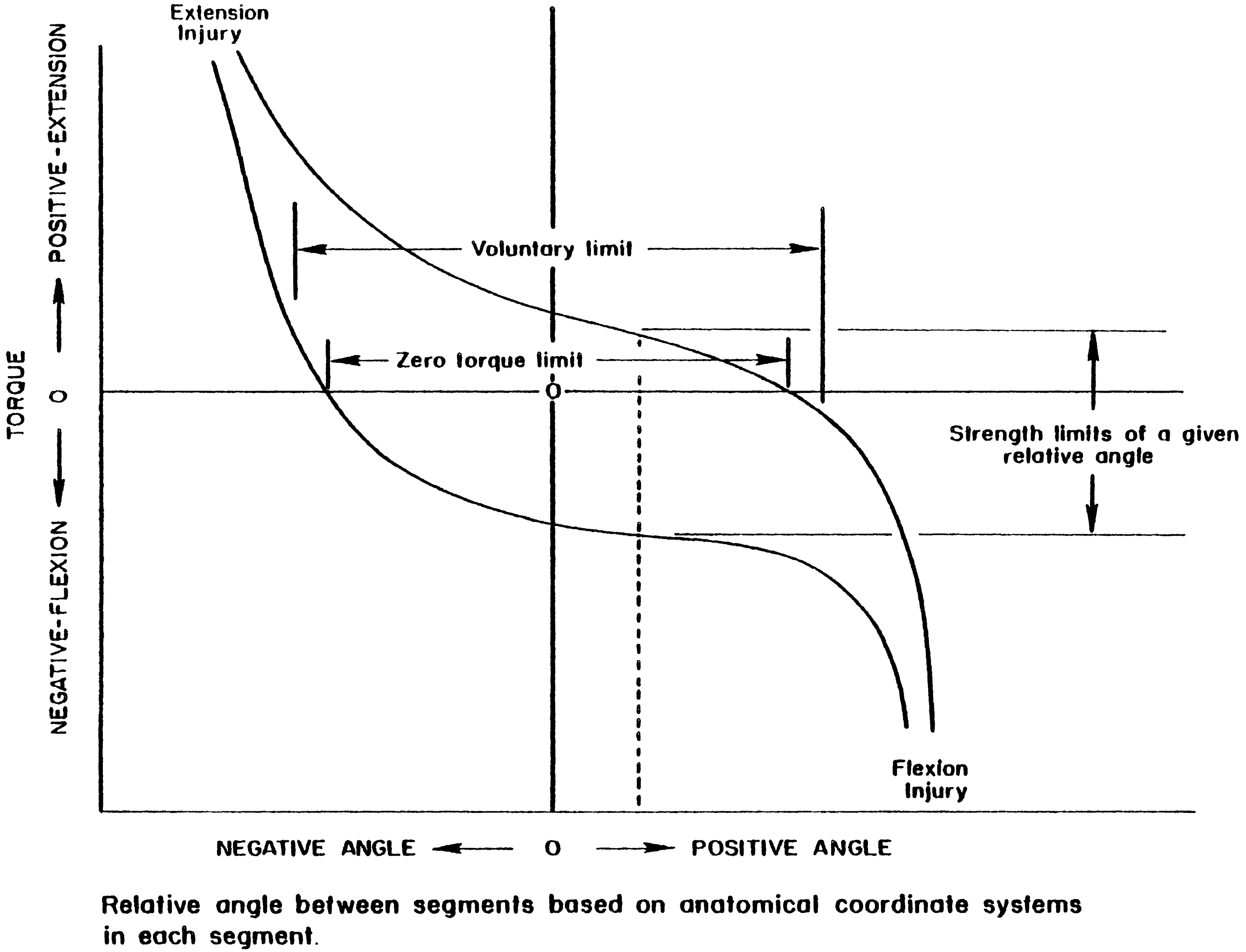

FIGURE 4-2. Hypothetical torque versus relative angle curve.

impact velocities and impact load distributions. Figure 4–3 shows idealized curves for belt and steering wheel impacts based on the Melvin et al. (1985) review.

The pelvis/lower-leg region is the major contact interface with the seat. On the basis of the results of Contract DTNH22–80-C–07502 presented by Robbins (1983), there are two or more inches of highly mobile tissue between the bony structures of the pelvis and upper legs and the seat. Due to the large seat interaction forces measured in the dynamic tests and predicted in crash victim simulations, the deformation characteristics of this region should be a major concern in the dummy design process due to the effect that these parameters can have on occupant dynamics, and particularly, on their effect on the pelvic angle.

Crash Environment Data. Data sources are divided into those dealing with the crash event and those describing vehicle characteristics.

Crash Event. A definition of the crash event is necessary to provide the forcing function to drive the dynamic simulation. The basis for this definition is a study of accident experience. The necessary data include a definition of the range of accident impact velocity vectors over which the AATD is expected to have reasonably humanlike responses. Based on the Injury Priority Analysis work of Carsten and O'Day (1984), it is clear that the majority of cases are frontal or near frontal as opposed to lateral and rear impact involvement. It can also be assumed that the majority of occupants are not impacted at exactly "12 o'clock" but that these impacts are slightly-or-more non-symmetric, due to occupant posture, vehicle rotation (a factor not really included in the accident velocity descriptions), and obliqueness of the major force vector. Also, the great majority of injuries occur at a velocity change (delta V) of 30 mph or less. The results point to the need for a three-dimensional device (or device with interchangeable components for use in impacts of various directions) that is capable of reasonably humanlike responses under a variety of different conditions. In planning for the parameter study, the assumption was made that three-dimensional simulation would be required.

Vehicle Characteristics. The crash deceleration profile, or other description of vehicle motions during the crash event, is required as input data for the simulations. This implies selection of a vehicle, or class of vehicles, as well as availability of vehicle crash acceleration data for the desired conditions to be modeled. For use in preliminary modeling studies of frontal impact, a 35-mph test involving a Ford Escort has been selected from the collection of crash pulses developed at the Transportation Systems Center (TSC) by Minneman and Hsia in 1982 (Test DOT 0206). Figure 4–4 shows vehicle deceleration as a function of time as used in the model.

The Escort also represents a vehicle for which interior geometric data are available. These geometric features have been used previously in studies both for NHTSA and the Motor Vehicle Manufacturers Association (MVMA). For the current study the following components are required:

Passenger and driver seats
Instrument panels
Steering wheel rim/column assemblies
A-pillar
Windshield
Side door including windows
Three-point-belt systems

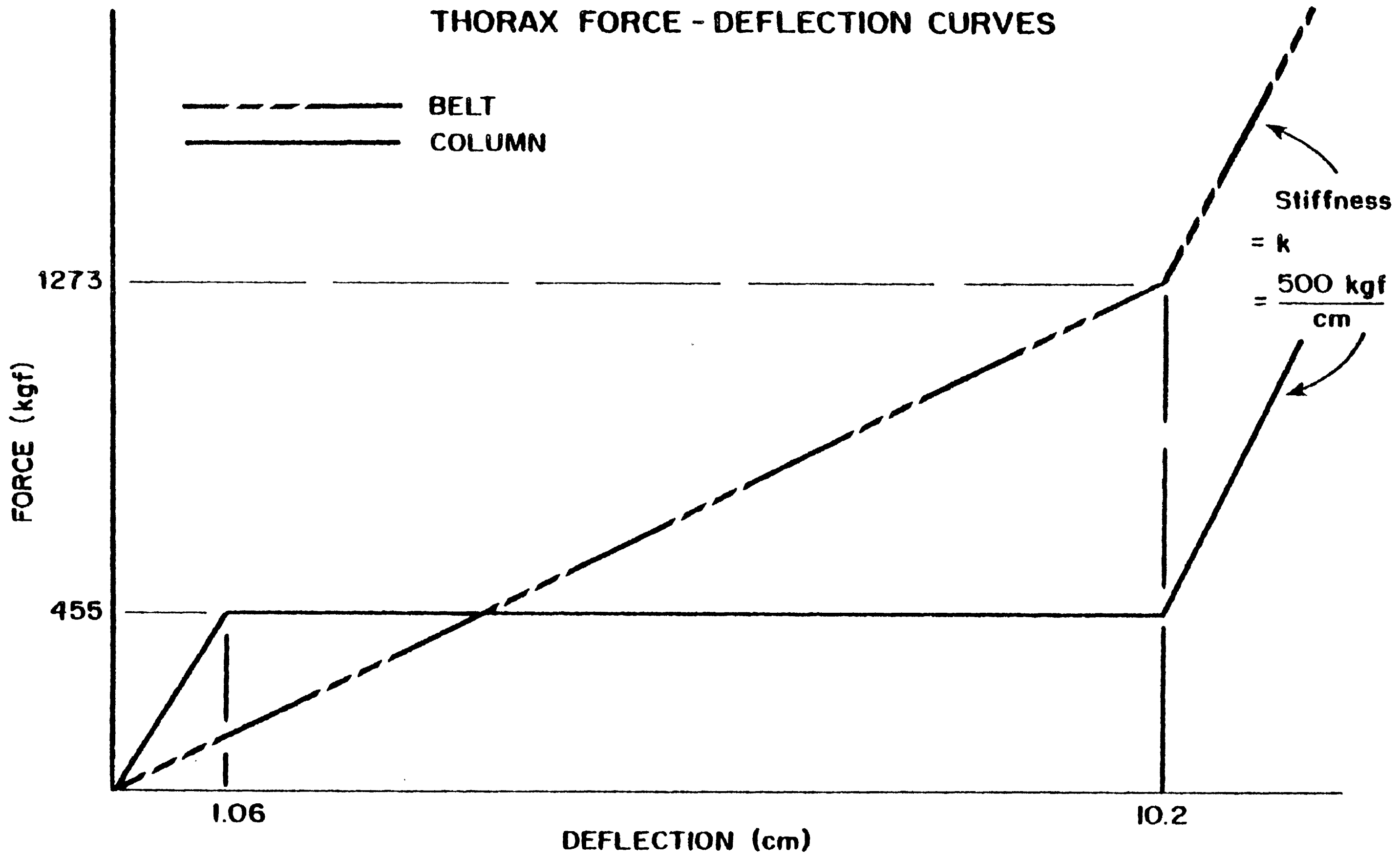

FIGURE 4-3. Thorax deflection curves.

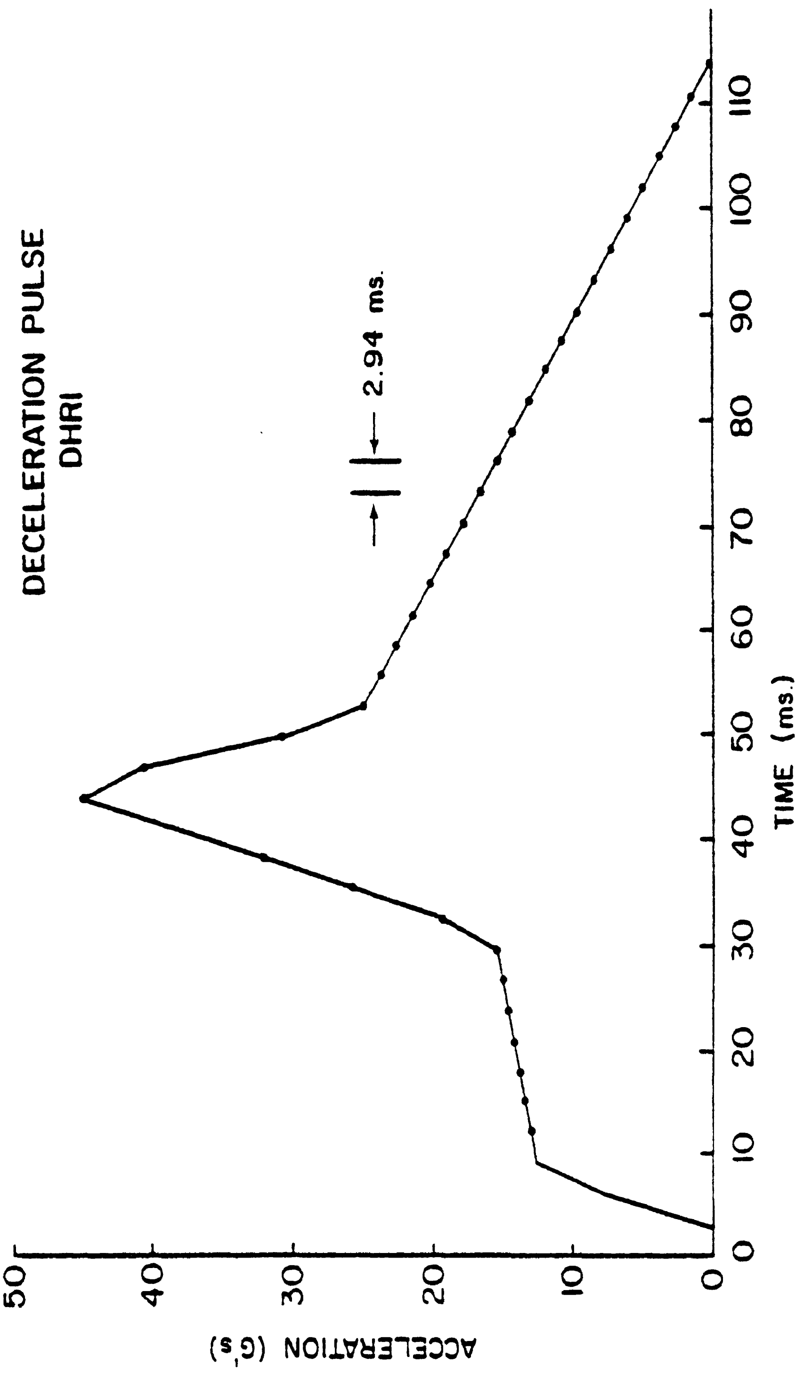

FIGURE 4-4. Ford Escort deceleration pulse (35 mph).

Each of these components requires two sets of physical parameters—geometry and location within the vehicle, as well as point-by-point force-deformation characteristics. The A-pillar and side door surfaces are not included in the current frontal exercises. Geometric data were obtained for the simulation exercises from the Escort drawing package.

BIOMECHANICAL RESPONSE SIMULATION

In order to demonstrate the utility of the CAL-3D CVS for the development and evaluation of AATD design concepts, a limited parameter study was undertaken. The thoracic spine and shoulder linkages were selected for study because of their importance to a tentative upper-torso design concept.

Data Set. The initial data set used for running the CAL-3D software is included as Table 4-4 of this report.[3] Four drawings supplement this data set. Figure 4-5 shows the vehicle interior contact surfaces for the small vehicle used. Figure 4-6 shows the occupant seated in the vehicle. Included are the ellipsoids that sense contact between the occupant and the vehicle. Special note should be taken of the thorax ellipsoid and a contact surface attached to the spine of the simulated occupant. The thorax is assumed to be inflexible, as it is modeled as a rigid body, and is attached to the T5-T8 segment by a transverse pin-joint. The thorax is then free to rotate toward the lower thoracic spine. The restraint of the thorax ellipsoid by the spine is modeled by the force-deflection curves given in Figure 4-3. It should be noted that, with the mass of the thorax in front of the contact surface, the inertia of the chest acts in addition to the force-deflection curve. Figure 4-7 is like Figure 4-6 but includes the outline of the seated surface form of the mid-sized male to show the way the data from the previous project has been incorporated. Figure 4-1 has already shown details of the occupant, including centers of gravity, joints, and principal axes of inertia.

The parameter study involved eight exercises as follows:

1. Baseline data set. Loose joints in spine and shoulder joints. No Coulomb restraint (belted and unbelted).
2. Same as no. 1 but with large Coulomb friction in spine and shoulder joints to simulate locked conditions or a stiff spine and shoulder complex (belted and unbelted).
3. Same as no. 2 but with zero Coulomb friction in shoulder joints to separate their effect from the torso (belted and unbelted).
4. Same as no. 1 but with small Coulomb friction in spine and shoulder joints (belted and unbelted).

Results. The purpose of this analysis was to study the effects of spinal and shoulder flexibility in the thorax on whole-body response. Degrees of freedom, discussed previously, which are not present in current test devices, such as the Part 572 and Hybrid III, have been added to the linkage model. Comparative results for stiff and flexible joints between the thorax components are presented for belted and unbelted occupants.

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[3] For reader convenience, this table and the remaining figures are placed at the end of the chapter.

Belted Occupants. For an occupant restrained by a three-point harness, Figure 4–8 shows four frames of occupant position at different times. The initiation of belt loading and contact with the knee bolsters occurs around 40 ms. By 70 ms, substantial chest loading due to the belts occurs. Also, the head is just beginning to pitch forward. By 110 ms, the forward motions are complete and rebound has begun. It should be noted that no attempt was made to model the detailed interactions of the belted dummy with the steering wheel even through its plane is shown in the graphic display.

Figure 4–9 compares a flexible three-link thoracic spine with a stiffer linkage closer to that used in current dummies. The solid lines show the position at 100 ms for the flexible case. The stiff thorax, represented by the dashed lines, does not allow as much forward excursion of the head.

Figure 4–10 shows the head movement for the four belted cases. Loose joints in the thorax and shoulders yield the greatest forward and downward motion of the head. The addition of low stiffness to all these joints, simulating partial tensing of the body, changes the results somewhat. The stiff joints restrict the downward motion of the head considerably by about 9 cm. If the degrees of freedom in the thoracic spine at the T4/T5- and T8/T9-interspaces were completely eliminated, this effect would be even more pronounced.

Figures 4–11, 4–12, and 4–13 show the belt forces exerted on the thorax as well as the thorax-segment and head accelerations. Because of the properties of the belts, the curve shapes are similar for the belt loads in Figure 4–11. As would be expected, the load reaches a peak more quickly for the stiff-joint case and drops off more quickly as well. The shapes of the curves of thorax-segment acceleration are generally similar. Peak values are earlier in time and about 10 percent higher in magnitude for the loose-joint case when compared with the stiffened thorax. It should be noted that these values are reported for the mobile rib cage (thorax) segment rather than for one of the spine segments. They may provide a more realistic idea of response in the region where load is applied to the thorax by the belts. The force in this region initiates reduction of the kinetic energy of the upper torso, neck, and head. Figure 4–13 shows the head G–levels. The spikes at the end are due to interactions with joint stops in the low-friction cases. For the stiff-joint cases, the spikes appear to be due to the effect of locking and unlocking of the joints in the model. Refinement of the data set, probably by the inclusion of damping, will alleviate this problem in any future design studies in order to produce better peak values.

Unbelted Occupants. For an unrestrained occupant, Figure 4–14 shows four frames of occupant position at different times. By 40 ms, there is initial contact with the knee bolster. By 80 ms, the chest has impacted the steering column. The column has been driven down considerably, and the thorax has been driven back toward the spine. By the end of the simulation at 110 ms, the head has pitched over the steering assembly to interact with the instrument panel structures.

Figure 4–15 compares the response for the flexible, three-link spine with the stiffer linkage. The drawing was made by superimposing the two cases at 90 milliseconds. Although lower torso motion was virtually identical in the two cases, the principal observation which can be made is that the thorax, neck, and head regions have moved farther forward for the stiff spine. This is probably due to the fact that the thorax and shoulder girdle loaded the column more as a single lumped mass than as a flexible, deformable body, as would be the case for a human.

Figure 4–16 presents the results of Figure 4–15 in a different context. The solid line represents the flexible spine case. The dotted line has been prepared by superimposing the abdomen ellipse for the two cases and then sketching the upper thorax, head, and neck positions for the stiff thorax case as dotted lines. This shows the effect of the spinal stiffening. Although the whole body went farther forward for the stiff-joint case, as was shown in Figure 4–15, the stiffening of the thoracic spine prevented the neck and head from moving forward as far as would be desirable. This is similar to the observation which was made for the belt-restrained subject.

Figure 4–17 shows the effect of shoulder girdle flexibility on occupant motions. The solid line in this figure is for the case where the thoracic spine is stiffened but the shoulder girdle and arm segments are loosely coupled to the thorax. The dotted line shows a case where all thoracic spine and shoulder girdle joints are stiffened. For the stiff-joint case, all upper torso segments are forward by more than a centimeter than is the case in which the shoulder girdle is loosely coupled. This reflects the added mass of the shoulder girdle in loading the column. It should be noted for the case of the flexible shoulder girdle that the shoulder circle has moved forward several centimeters due to the loose coupling. It is believed that this behavior more closely represents human response than does the rigid shoulder linkage found in current generation test devices.

Figure 4–18 shows head movement for the four cases of an unrestrained occupant. Although motions are generally similar, the head moves forward about 2 cm more for the case of the stiff thorax than for the case in which joints allow flexibility.

The force of interaction between the thorax and the steering wheel is shown in Figure 4–19. For the case of loose joints in the spine, the thorax contacts the steering wheel at the earliest point in time. The curve is almost the same for low-stiffness joints. There is a large spike at the end of the curve for the case of stiff joints. This is the result of the larger coupled mass of the spine, thorax, and shoulder girdle loading the column and bottoming it out. This effect is notably less for the case where the shoulder masses are uncoupled from the thorax. It can be concluded that the loose coupling of the shoulder complex with the thorax has a major effect on the interaction of the thorax with a steering column when compared with the rigid structures used in the current generation of test devices.

Figures 4–20 and 4–21 show the thorax-segment and head accelerations. The curves are generally similar in shape for chest accelerations. The higher initial reactions are observed for the loose-joint cases at the earlier part of the curve, whereas the bottoming out is reflected by the higher acceleration at the end of the stiff-joint case. The higher initial reactions for the loose-joint cases are probably due to the fact that lower, uncoupled masses are involved in the impact. The head acceleration curves are generally similar with high loadings occurring by 84 ms or so due to the interactions with the upper instrument panel. It is probable that the series of spikes which occurred for the loose-joint case would be attenuated by the addition of damping to the joint structures.

CONCLUSIONS AND RECOMMENDATIONS

The following comments can be made concerning the anthropometry data base:

1. The mass and postural data are available.

2. The body segmentation needs to be refined to include spinal and shoulder girdle masses.

3. The data base on joints needs to be expanded to provide torque on joints versus relative angle information in the form shown in Figure 4–2. The most pressing need is for additional information on spinal flexibility and torsion properties.

4. Decisions on coupling of soft tissue to the bony structures will have to be based on engineering judgment, as no data base exists. However, some basis exists for segmenting the thorax and shoulders from the spine. For the tissues in the abdomen and the musculature surrounding the pelvis and upper legs, little information exists.

The parameter study has yielded the following information:

1. Crash victim simulation software can be used to study the effects of changing important design parameters in the advanced anthropomorphic test device.

2. The addition of thoracic spinal flexibility has major effects on the motion of the body of the crash victim. This is particularly noticeable in head motion increases of several centimeters for the belted occupant.

3. The uncoupling of the shoulder masses from the thorax has a major effect on the interactions of a crash victim with vehicle structures forward of the occupant, such as the steering column and instrument panel.

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TABLE 4–4

CRASH VICTIM SIMULATION DATA SET FOR DUMMY PARAMETER STUDY

```
JUNE 1984                                                                              A 1.A
TYPIC      AL SMALL CAR FRONTAL IMPACT CRASH                                           A.1.B
                                                                                       A.1.C
  CM KGF SEC          0.0          0.0    -980.665                                     A.3
   6 110 0.00100 0.00025   0.0010.000025                                               A.4
 0 0 5 0 0 0 0 0 0 0 0 0 0 0 0 0 0 010 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0         A.5
   20    19           NEW DUMMY                                                        B.1
PELV A11.4141.0157.942381.1847   1.0   1.0   1.0   1.0   1.0   1.0   0   1 B.2.A
L1L5 B2.365 .16761.10656.25484   1.0   1.0   1.0   1.0   1.0   1.0   0   2 B.2.A
T912 C4.753 .91358.64452.60318   1.0   1.0   1.0   1.0   1.0   1.0   0   3 B.2.A
T5T8 D4.753 .91358.64452.60318   1.0   1.0   1.0   1.0   1.0   1.0   0   4 B.2.A
T1T4 E2.376 .45664.32226.30159   1.0   1.0   1.0   1.0   1.0   1.0   0   5 B.2.A
NECK F0.965 .01480.01846.02291   1.0   1.0   1.0   1.0   1.0   1.0   0   6 B.2.A
HEAD G4.137 .20027.22155.14455   1.0   1.0   1.0   1.0   1.0   1.0   0   7 B.2.A
RSHO H2.376 .45664.32226.30159   1.0   1.0   1.0   1.0   1.0   1.0   0   8 B.2.A
RUAR I1.769 .11247.12253.02312   1.0   1.0   1.0   1.0   1.0   1.0   0   9 B.2.A
RLAR J2.022 .31077.30925.02015   1.0   1.0   1.0   1.0   1.0   1.0   0  10 B.2.A
LSHO K2.376 .45664.32226.30159   1.0   1.0   1.0   1.0   1.0   1.0   0  11 B.2.A
LUAR L1.769 .11247.12253.02312   1.0   1.0   1.0   1.0   1.0   1.0   0  12 B.2.A
LLAR M2.022 .31077.30925.02015   1.0   1.0   1.0   1.0   1.0   1.0   0  13 B.2.A
THOR N7.129 1.3699.96678.90477   1.0   1.0   1.0   1.0   1.0   1.0   0  14 B.2.A
RULG O8.614 1.23091.3015.36712   1.0   1.0   1.0   1.0   1.0   1.0   0  15 B.2.A
RLLG P3.587 .52040.52834.06069   1.0   1.0   1.0   1.0   1.0   1.0   0  16 B.2.A
RFOT Q0.981 .00873.04297.04413   1.0   1.0   1.0   1.0   1.0   1.0   0  17 B.2.A
LULG R8.614 1.23091.3015.36712   1.0   1.0   1.0   1.0   1.0   1.0   0  18 B.2.A
LLLG S3.587 .52040.52834.06069   1.0   1.0   1.0   1.0   1.0   1.0   0  19 B.2.A
LFOT T0.981 .00873.04297.04413   1.0   1.0   1.0   1.0   1.0   1.0   0  20 B.2.A
W     1   1  -2   1.2   0.0   2.4  -3.7   0.0 -6.07                      1 B.3.A
                  0.0 26.12   0.0   0.0 -6.83   0.0                3 2 1 3 2 1
S1    2   2  -2  -5.5   0.0   9.2   4.4   0.0 -5.82                      2 B.3.A
                  0.0  10.8   0.0   0.0 -17.3   0.0                3 2 1 3 2 1          2 B.3.B
S2    3   3  -2   .36   0.0   6.1  3.05   0.0 -5.88                      3 B.3.A
                  0.0  -3.4   0.0   0.0  -3.4   0.0                3 2 1 3 2 1          3 B.3.B
S3    4   4  -2  2.52   0.0  5.11   0.0   0.0 -5.34                      4 B.3.A
                  0.0 20.56   0.0   0.0 20.56   0.0                3 2 1 3 2 1          4 B.3.B
S4    5   5  -2  2.67   0.0  2.21   1.8   0.0  -4.2                      5 B.3.A
                 00.0  1.45   0.0   0.0-22.14   0.0                3 2 1 3 2 1          5 B.3.B
HN    6   6  -2  -2.7   0.0   6.8  -2.1   0.0  -5.7                      6 B.3.A
                  0.0 -4.36   0.0   0.0 20.15   0.0                3 2 1 3 2 1          6 B.3.B
RSC   7   4  -2  10.1  -4.3   8.8   4.1   8.7   4.0                      7 B.3.A
                  0.0 -90.0 -76.0   0.0 -90.0 -76.0                3 2 1 3 2 1          7 B.3.B
RGH   8   8  -2   0.0  -4.3   0.0  -.45   0.3  13.0                      8 B.3.A
                 52.9 27.55 121.4 77.43 38.03184.47                3 2 1 3 2 1          8 B.3.B
RE    9   9  -1 -2.20   0.9 -16.5  -.48  -.19 16.76                      9 B.3.A
               173.52 67.61 178.0 206.3-16.02181.24                3 2 1 3 2 1          9 B.3.B
LSC   !   4  -2  10.1   4.3   8.8   4.1  -8.7   4.0                     10 B.3.A
                  0.0 -90.0  76.0   0.0 -90.0  76.0                3 2 1 3 2 1         10 B.3.B
LGH   "  11  -2   0.0   4.3   0.0  -.45  -0.3  13.0                     11 B.3.A
                127.1-27.55 121.4102.57-38.03184.47                3 2 1 3 2 1         11 B.3.B
LE    #  12  -1 -2.20  -0.9 -16.5  -.48   .19 16.76                     12 B.3.A
               186.48 67.61 182.0 153.7-16.02178.76                3 2 1 3 2 1         12 B.3.B
T     $   4   1   2.6   0.0   5.2  -8.5   0.0  12.2                     13 B.3.A
                  0.0   0.0   0.0   0.0   0.0   0.0                3 2 1 3 2 1         13 B.3.B
RHP   %   1  -2  2.08  -8.2 -7.27   0.7   5.7  20.7                     14 B.3.A
               174.6749.069166.59182.65.85947172.67                3 2 1 3 2 1         14 B.3.B
RKN   &  15  -1  -0.6  -1.5 -21.8   2.3   0.9  17.0                     15 B.3.A
               147.61-70.63210.49191.89 5.838178.17                3 2 1 3 2 1         15 B.3.B
RAKL  (  16  -2  1.19   2.0 -24.4 -4.71  1.46  6.42                     16 B.3.A
               141.39 87.62134.03192.16 71.42197.25                3 2 1 3 2 1         16 B.3.B
LHP   )   1  -2  2.08   8.2 -7.27   0.7  -5.7  20.7                     17 B.3.A
               185.3349.069193.41177.33-.8594187.33                3 2 1 3 2 1         17 B.3.B
LKN   *  18  -1  -0.6   1.5 -21.8   2.3  -0.9  17.0                     18 B.3.A
                32.39 70.63210.49-11.89 5.838178.17                3 2 1 3 2 1         18 B.3.B
LAKL  +  19  -2  1.19  -2.0 -24.4 -4.71 -1.46  6.42                     19 B.3.A
                38.61-87.62134.03-12.16-71.42197.25                3 2 1 3 2 1         19 B.3.B
   65.6  56.5   0.0   0.5  15.0       565.0  56.5   0.0   0.5  10.0      1 B.4.A
  144.3  56.5   0.0   0.5  10.0       565.0  56.5   0.0   0.5  10.0      2 B.4.A
  144.3  56.5   0.0   0.5  10.0       565.0  56.5   0.0   0.5  10.0      3 B.4.A
  144.3  56.5   0.0   0.5  10.0       565.0  56.5   0.0   0.5  10.0      4 B.4.A
   16.3  56.5   0.0   0.5  45.0       565.0  56.5   0.0   0.5  10.0      5 B.4.A
   25.5  56.5   0.0   0.5  45.0       565.0  56.5   0.0   0.5  10.0      6 B.4.A
   25.0  56.5   0.0   0.5  22.0       565.0  56.5   0.0   0.5  22.0      7 B.4.A
   25.0  56.5   0.0   0.5  55.0       565.0  56.5   0.0   0.5  55.0      8 B.4.A
    0.0 250.0   0.0  0.75  71.0         0.0   0.0   0.0   0.0   0.0      9 B.4.A
   25.0  56.5   0.0   0.5  22.0       565.0  56.5   0.0   0.5  22.0     10 B.4.A
   25.0  56.5   0.0   0.5  55.0       565.0  56.5   0.0   0.5  55.0     11 B.4.A
    0.0 250.0   0.0  0.75  71.0         0.0   0.0   0.0   0.0   0.0     12 B.4.A
    0.0   0.0   0.0   0.0   0.0         0.0   0.0   0.0   0.0   0.0     13 B.4.A
  565.0  56.5   0.0   0.5  40.0       565.0  56.5   0 0   0.5  40.0     14 B.4.A
    0.0  82.5   0.0  0.75  72.0         0.0   0.0   0.0   0.0   0.0     15 B.4.A
  565.0  56.5   0.0   0.5  30.0       565.0  56.5   0.0   0.5  40.0     16 B.4.A
  565.0  56.5   0.0  0.75  40.0       565.0  56.5   0.0   0.5  40.0     17 B.4.A
    0.0  82.5   0.0  0.75  72.0         0.0   0.0   0.0   0.0   0.0     18 B.4.A
  565.0  56.5   0.0  0.75  30.0       565.5  56.5   0.0   0.5  40.0     19 B.4.A
    0.0   0.0 100.0 300.0   0.0                     0.0   0.0            1 B.5.A
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TABLE 4–4 (Continued)

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86       0.0   0.0 100.0 300.0   0.0             0.0   0.0                      2 B.5.A
87       0.0   0.0 100.0 300.0   0.0             0.0   0.0                      3 B.5.A
88       0.0   0.0 100.0 300.0   0.0             0.0   0.0                      4 B.5.A
89       0.0   0.0 100.0 300.0   0.0             0.0   0.0                      5 B.5.A
90       0.0   0.0 100.0 300.0   0.0             0.0   0.0                      6 B.5.A
91       0.0   0.0 100.0 300.0   0.0             0.0   0.0                      7 B.5.A
92       0.0   0.0 100.0 300.0   0.0             0.0   0.0                      8 B.5.A
93       0.0 300.0 100.0 300.0   0.0             0.0   0.0                      9 B.5.A
94       0.0   0.0 100.0 300.0   0.0             0.0   0.0                     10 B.5.A
95       0.0   0.0 100.0 300.0   0.0             0.0   0.0                     11 B.5.A
96       0.0 300.0 100.0 300.0   0.0             0.0   0.0                     12 B.5.A
97       0.0   0.0 100.0   0.0   0.0             0.0   0.0                     13 B.5.A
98       0.0 300.0 100.0 300.0   0.0             0.0   0.0                     14 B.5.A
99       0.0 300.0 100.0 300.0   0.0             0.0   0.0                     15 B.5.A
100      0.0 300.0 100.0 300.0   0.0             0.0   0.0                     16 B.5.A
101      0.0 300.0 100.0 300.0   0.0             0.0   0.0                     17 B.5.A
102      0.0 300.0 100.0 300.0   0.0             0.0   0.0                     18 B.5.A
103      0.0 300.0 100.0 300.0   0.0             0.0   0.0                     19 B.5.A
104                                   00.1 00.10 00.10 00.01 00.01 00.01          B.6
105                                   00.1 00.10 00.1
106                                   00.1 00.10 00.10
107                                   00.1 00.10 00.10
108                                   00.1 00.10 00.10
109                                   00.1 00.10 00.10
110                                   00.1 00.10 00.10
111                                   00.1 00.10 00.10
112                                   00.1 00.10 00.10
113                                   00.1 00.10 00.10
114                                   00.1 00.10 00.10
115                                   00.1 00.10 00.10
116                                   00.1 00.1  00.1
117                                   00.1 00.1  00.1
118                                   00.1 00.1  00.1
119                                   00.1 00.1  00.1
120                                   00.1 00.1  00.1
121                                   00.1 00.1  00.1
122                                   00.1 00.1  00.1
123                                   00.1 00.1  00.1
124           SMALL CAR                                                           C.1
125   0     0     0     1569.2  0.00.0  0.0   0.0         39 0.0  .00294          C.2.A
126   0.0   7.8   12.5  12.9  13.3  13.7  14.1  14.5  14.9  15.3  19.0  25.5    1 C.3.A
127   32.0  38.5  45.0  40.5  30.5  24.6  23.4  22.2  21.0  19.8  18.6  17.4    2 C.3.A
128   16.2  15.0  13.8  12.6  11.4  10.2  9.0   7.8   6.6   5.4   4.2   3.0     3 C.3.A
129   1.8   0.6   0.0                                                           4 C.3 A
130      14     0     0    20     0     1                                         D.1
131       1    FLOOR                                                            1 D.2.A
132           25.91     127.00     -27.97                                       1 D.2.B
133           25.91    -127.00     -27.97                                       1 D.2 D
134           69.19     127.00     -27.97                                       1 D.2.C
135       2    TOEBOARD                                                         2 D.2.A
136           69.19     127.00     -27.97                                       2 D.2.B
137           69.19    -127.00     -27.97                                       2 D.2.D
138           78.99     127.00     -24.97                                       2 D.2.C
139       3    TOEPAN                                                           3 D.2.A
140           78.99     127.00     -24.97                                       3 D.2.B
141           78.99    -127.00     -24.97                                       3 D.2.D
142           87.48     127.00      -1.88                                       3 D.2.C
143       4    BOLSTERD                                                         4 D.2.A
144           48.97     127.00      23.04                                       4 D.2.B
145           81.08     127.00     -10.34                                       4 D.2.C
146           48.97    -127.00      23.04                                       4 D.2.D
147       5    MIDDLEDASH                                                       5 D.2.A
148           55.63     127.00      45.62                                       5 D.2.B
149           54.43     127.00      17.22                                       5 D.2.C
150           55.63    -127.00      45.62                                       5 D.2.D
151       6    UPPERDASH                                                        6 D.2.A
152           84.15     127.00      45.62                                       6 D.2.B
153           47.50     127 00      42.42                                       6 D.2.C
154           84.15    -127 00      45.62                                       6 D.2.D
155       7    WINDSHIELD                                                       7 D.2.A
156           36 42     127.00      76.63                                       7 D.2.B
157           93.04     127.00      42.42                                       7 D.2.C
158           36.42    -127.00      76.63                                       7 D.2.D
159       8    CUSHION                                                          8 D.2.A
160           42.16     127.00      -0.36                                       8 D.2.B
161          -13.72     127.00     -12.09                                       8 D.2.C
162           42.16    -127.00      -0.36                                       8 D.2.D
163       9    SEATBACK                                                         9 D.2.A
164          -13.72     127.00     -12.09                                       9 D.2.B
165          -43.94     127.00      55.91                                       9 D.2.C
166          -13.72    -127.00     -12.09                                       9 D.2.D
167      10    HEADER                                                          10 D.2.A
168           19.56     127.00      81.94                                      10 D.2.B
169           32.26     127.00      76.63                                      10 D.2.C
170           19.56    -127.00      81.94                                      10 D.2.D
171      11    ROOF                                                            11 D.2.A
172          -15.88     127.00      86.23                                      11 D.2.B
173           27.18     127.00      83.24                                      11 D.2.C
174          -15.80    -127.00      86.23                                      11 D.2.D
175      12    STEERINGWHEEL                                                   12 D.2.A
176           27.81     127.00      51.23                                      12 D.2.B
177           13.03     127.00      18.62                                      12 D.2.C
178           27.81    -127.00      51.23                                      12 D.2.D
```

TABLE 4-4 (Continued)

```
179     13    RIMTOP                                                         13 D.2.A
180           27.81        127.00        51.23                               13 D.2.B
181           27.81       -127.00        51.23                               13 D.2.D
182           25.70        127.00        46.52                               13 D.2.C
183     14    BACKBONE                                                       14 D.2.A
184            -7.1         -18.0         13.0                               14 D.2.B
185             1.0         -18.0         -8.4                               14 D.2.D
186            -7.1          18.0         13.0                               14 D.2.C
187        1  12.9  20.3   9.1  .846   0.0 -9.81    0.0  40.3    0.0          1 D.5.A
188        2   7.4  16.8  12.5   5.8   0.0 -0.76    0.0  -6.8    0.0          2 D.5.A
189        3   2.4  10.0 7.073 -2.67   0.0 -0.76    0.0-17.3     0.0          3 D.5.A
190        6 5.725   5.8 7.529   0.0   0.0   0.0    0.0-22.22    0.0          6 D.5.A
191        7 9.294   8.013.059 0.764   0.0-2.648    0.0-10.86    0.0          7 D.5.A
192        8   4.8   4.8   4.8   0.0  -4.3   0.0110.97 19.29237.13            8 D.5.A
193        9  14.2   4.3   5.0 -1.32  0.63  -4.2162.4786.96891.585            9 D.5.A
194       10  15.2   3.8   3.8  0.11 -0.21  -1.0-56.46  90.0 14.78           10 D.5.A
195       11   4.8   4.8   4.8   0.0   4.3   0.0 69.02-19.93237.13           11 D.5.A
196       12  14.2   4.3   5.0 -1.32 -0.63  -4.2197.5186.92591.612           12 D.5.A
197       13  15.2   3.8   3.8  0.11  0.21  -1.056.458  90.014.783           13 D.5.A
198       14  9.89  14.5 17.07-2.235   0.0   1.0    0.0 -20.8    0.0         14 D.5.A
199       15  20.3   8.0   8.0 -1.82  0.56 0.01260.35 80.36163.89            15 D.5.A
200       16  14.8   5.1   5.1  2.38  1.27 5.99135.11 87.86  23.1            16 D.5.A
201       17  10.3   6.0   6.0 -3.94 -0.45 3.06   0.0   0.0   0.0            17 D.5.A
202       18  20.3   8.0   8.0 -1.82 -0.56 0.01 99.65 80.36 16.11            18 D.5.A
203       19  14.8   5.1   5.1  2.38 -1.27 5.99224.89 87.86 156.9            19 D.5.A
204       20  10.3   6.0   6.0 -3.94  0.45 3.06   0.0   0.0   0.0            20 D.5.A
205       22   5.5   5.5   5.5 -0.58 -1.51-21.79-32.39 70.65 149.5           22 D.5.A
206       23   5.5   5.5   5.5 -0.58  1.51-21.79 32.39 70.65  30.5           23 D.5.A
207                                                                             D.7
208                                                                             D.7
209     3 14   0.    0.    0.   3.5    0.  -1.1  13.0 -500.    0.    0.    0.   D.8
210        1    DASHSTAT                                                      1 E.1
211   0             1000000.    0  .                                          1 E.2
212                 57.54       2.78         0.77                             1 E.3
213        2    CUSHIONSTAT                                                   2 E.1
214   0             1000000.    0                                             2 E.2
215                 26.25126    2.643656     -2.0616064  0.241544             2 E.3
216        3    SEATBACKSTAT                                                  3 E.1
217   0             1000000.    0                                             3 E.2
218                 13.92924    -4.598274    1.865632    -0.32046   0.0183629 3 E.3
219        4    FLOORSTAT                                                     4 E.1
220   0             1000000.    0                                             4 E.2
221                 142.864                                                   4 E.3
222        5    WINDSHSTAT                                                    5 E.1
223   0             1000000.    0                                             5 E.2
224                 357.16                                                    5 E.3
225        6    HEADERSTAT                                                    6 E.1
226   0             1000000.    0                                             6 E.2
227                 714.32                                                    6 E.3
228        7    BOLDSTERDSTAT                                                 7 E.1
229   0             -2449.399   0                                             7 E.2
230         2                                                                 7 E.4.A
231   0.0           0.0         15.24        2449.399                         7 E.4.B
232        8    STRWHLSTAT                                                    8 E.1
233   0             -4535.924                                                 8 E.2
234        10                                                                 8 E.4.A
235   0.0           0.0         0.254        708.511     1.245      850.486   8 E.4.B
236   1.295         1133.981    1.905        850.486     3.81       708.511   8 E.4.C
237   6.096         453.592     9.906        340.194     20.32      340.194   8 E.4.D
238   25.4          4535.924                                                  8 E.4.E
239        9    ROOFSTAT                                                      9 E 1
240   0             -5896.70                                                  9 E.2
241         3                                                                 9 E.4.A
242   0.0           0.0         5.08         907.185     7.62       5896.701  9 E.4.B
243       10    FRIC=0.1                                                        E.1
244   0.            0.          0.1                                             E 2
245       11    G=0. TO 0.95                                                    E.1
246   0.            -1000.      0.                                              E.2
247         4                                                                   E.4.A
248   0.            0.          0.5          0.          0.6        0.95        E.4.B
249   1000.         0.95                                                        E.4.B
250       12    R=1. TO 0.05                                                    E.1
251   0.            -1000.      0.                                              E.2
252         4                                                                   E 4.A
253   0.            1.          0.5          1.          0.6        0.05        E.4.B
254   1000.         0.05                                                        E.4.B
255       13    THORAXSTAT                                                      E.1
256   0.            -110.2      0.                                              E.2
257         4                                                                   E.4.A
258   0.            0.          1.06         455.        10.2       455.        E.4.B
259   110.2         43355.                                                      E.4.B
260      999    ENDFUCTINPUT                                                 10 E.1
261        2  2  2  4  4  1  1  3  1  0  0  3  0  1                           0 F.1.A
262        1 21 17 17  4  0 12 11 10                                          1 F.1.A
263        1 21 20 20  4  0 12 11 10                                          1 F.1.B
264        2 21 17 17  4  0 12 11 10                                          2 F.1.A
265        2 21 20 20  4  0 12 11 10                                          2 F.1.B
266        3 21 17 17  4  0 12 11 10                                          3 F.1.A
267        3 21 20 20  4  0 12 11 10                                          3 F.1.B
268        4 21 15 22  7  0 12 11 10                                          4 F.1.A
269        4 21 16 16  7  0 12 11 10                                          4 F.1.B
270        4 21 18 23  7  0 12 11 10                                          4 F 1.C
271        4 21 19 19  7  0 12 11 10                                          4 F.1.D
```

TABLE 4–4 (Continued)

```
272         5  21  10  10   1   0  12  11  10                                5 F.1.A
273         5  21  13  13   1   0  12  11  10                                5 F.1.B
274         5  21  15  22   1   0  12  11  10                                5 F.1.C
275         5  21  18  23   1   0  12  11  10                                5 F.1.D
276         6  21   7   7   1   0  12  11  10                                6 F.1.A
277         7  21   7   7   5   0  12  11  10                                7 F.1.A
278         8  21   1   1   2   0  12  11  10                                8 F.1.A
279         8  21  15  15   2   0  12  11  10                                8 F.1.B
280         8  21  18  18   2   0  12  11  10                                8 F.1.C
281         9  21   3   3   3   0  12  11  10                                9 F.1.A
282        12  21   2   2   8   0  12  11  10                               12 F.1.A
283        12  21   7   7   8   0  12  11  10                               12 F.1.B
284        12  21  14  14   8   0  12  11  10                               12 F.1.C
285        14   3  14  14  13   0  12  11  10                               14 F.1.A
286                                                                            F.3.A
287                                                                            F.3.B
288                                                                            F.4.A
289                                                                            F 4.B
290            0.0       0.0       0.0                                         G.1.A
291           -7.4       0.0       1.7                                       1 G.2.A
292            0.0   -61.045       0.0                       3  2  1         1 G.3.A
293            0.0   -28.099       0.0                       3  2  1         2 G.3.A
294            0.0       0.0       0.0                       3  2  1         3 G.3.A
295            0.0       0.0       0.0                       3  2  1         4 G.3.A
296            0.0       0.0       0.0                       3  2  1         5 G.3.A
297            0.0    20.793       0.0                       3  2  1         6 G.3.A
298            0.0    -3.859       0.0                       3  2  1         7 G.3.A
299            0.0       0.0       0.0                       3  2  1         8 G.3.A
300         23.910   -48.245   -25.489                       3  2  1         9 G.3.A
301        207.302   -45.890   171.889                       3  2  1        10 G.3.A
302            0.0       0.0       0.0                       3  2  1        11 G.3.A
303        -23.910   -48.245    25.489                       3  2  1        12 G.3.A
304        152.698   -45.890   188.111                       3  2  1        13 G.3.A
305            0.0       0.0       0.0                       3  2  1        14 G.3.A
306        196.876   -68.125   166.277                       3  2  1        15 G.3.A
307        -28.900   -37.734    23.094                       3  2  1        16 G.3.A
308        -21.762   -57.352    25.473                       3  2  1        17 G.3.A
309        163.124   -68.125   193.723                       3  2  1        18 G.3.A
310         28.900   -37.734   -23.094                       3  2  1        19 G.3.A
311         21.762   -57.352   -25.473                       3  2  1        20 G.3.A
312           0.    2000.      1.    0                                         H.0.1
313         1   2   3   4   5   6   7   8                                      H.0.2
314                                                                            H.0.3
315          20    1    -8.18            0.0        1.07                       H.1.A
316                2     -0.4            0.0       -2.42                       H.1.B
317                3      0.0            0.0         0.0                       H.1.C
318                4      0.0            0.0         0.0                       H.1.D
319                5      0.0            0.0                                   H.1.E
320                6      0.0            0.0         0.0                       H.1.F
321                7     0.84            0.0         0.0                       H.1.G
322                8      0.0            0.0         0.0                       H.1.H
323                9     1.65            3.0       -17.2                       H.1.I
324               10     -1.0            3.5       -16.6                       H.1.J
325               11      0.0            0.0         0.0                       H.1.K
326               12     1.65           -3.0       -17.2                       H.1.L
327               13      -1.0          -3.5       -16.6                       H.1.M
328               14      0.0            0.0         0.0                       H.1.N
329               15      0.6            6.6       -20.0                       H.1.O
330               16    -1.19           -5.7       -14.9                       H.1.P
331               17    -7.69          -0.06       -0.62                       H.1.Q
332               18      0.6           -6.6       -20.0                       H.1.R
333               19    -1.19            5.7       -14.9                       H.1.S
334               20    -7.69           0.06       -0.62                       H.1.T
335                                                                            H.2
336          20    1    -8.18            0.0        1.07                       H.3.A
337                2     -0.4            0.0       -2.42                       H.3.B
338                3      0.0            0.0         0.0                       H.3.C
339                4      0.0            0.0         0.0                       H.3.D
340                5      0.0            0.0         0.0                       H.3.E
341                6      0.0            0.0         0.0                       H.3.F
342                7     0.84            0.0         0.0                       H.3.G
343                8      0.0            0.0         0.0                       H.3.H
344                9     1.65            3.0       -17.2                       H.3.I
345               10     -1.0            3.5       -16.6                       H.3.J
346               11      0.0            0.0         0.0                       H.3.K
347               12     1.65           -3.0       -17.2                       H.3.L
348               13      -1.0          -3.5       -16.6                       H.3.M
349               14      0.0            0.0         0.0                       H.3.N
350               15      0.6            6.6       -20.0                       H.3.O
351               16    -1.19           -5.7       -14.9                       H.3.P
352               17    -7.69          -0.06       -0.62                       H.3.Q
353               18      0.6           -6.6       -20.0                       H.3.R
354               19    -1 19            5.7       -14.9                       H.3.S
355               20    -7.69           0.06       -0.62                       H.3.T
356                                                                            H.4
357                                                                            H.5
358          20    1     2     3     4     5     6     7     8     9    10    11   H 6
359               12    13    14    15    16    17    18    19    20               H.6
360          19    1     2     3     4     5     6     7     8     9    10    11 1 H.7
361               12    13    14    15    16    17    18    19                   2 H.7
362                                                                            H.8
363         1   1                                                              I.1 1
```

TABLE 4-4 (Continued)

```
364        23   0  23   4                                                     I.2.1
365        12           0      120      7.5      8.5
366        16           0      160       10       11                          I.4.1
367         9    TIME (MS)
368        12    ACCEL. (G'S)
369        23    RESULTANT LINEAR ACCEL.
370        21    OF HEAD SEG. VS. TIME
371      0 0 1 1 0 1 0 0
372           0.      .110    .010
373           1.       0.      0.
374           0.       1.      0.
375           0.       0.      1.
376           .5       .5      11.      8.5
377           .5       .5      10.       7.
378      -94.,-53.,236.,165.,1.0
379      X-Z
```

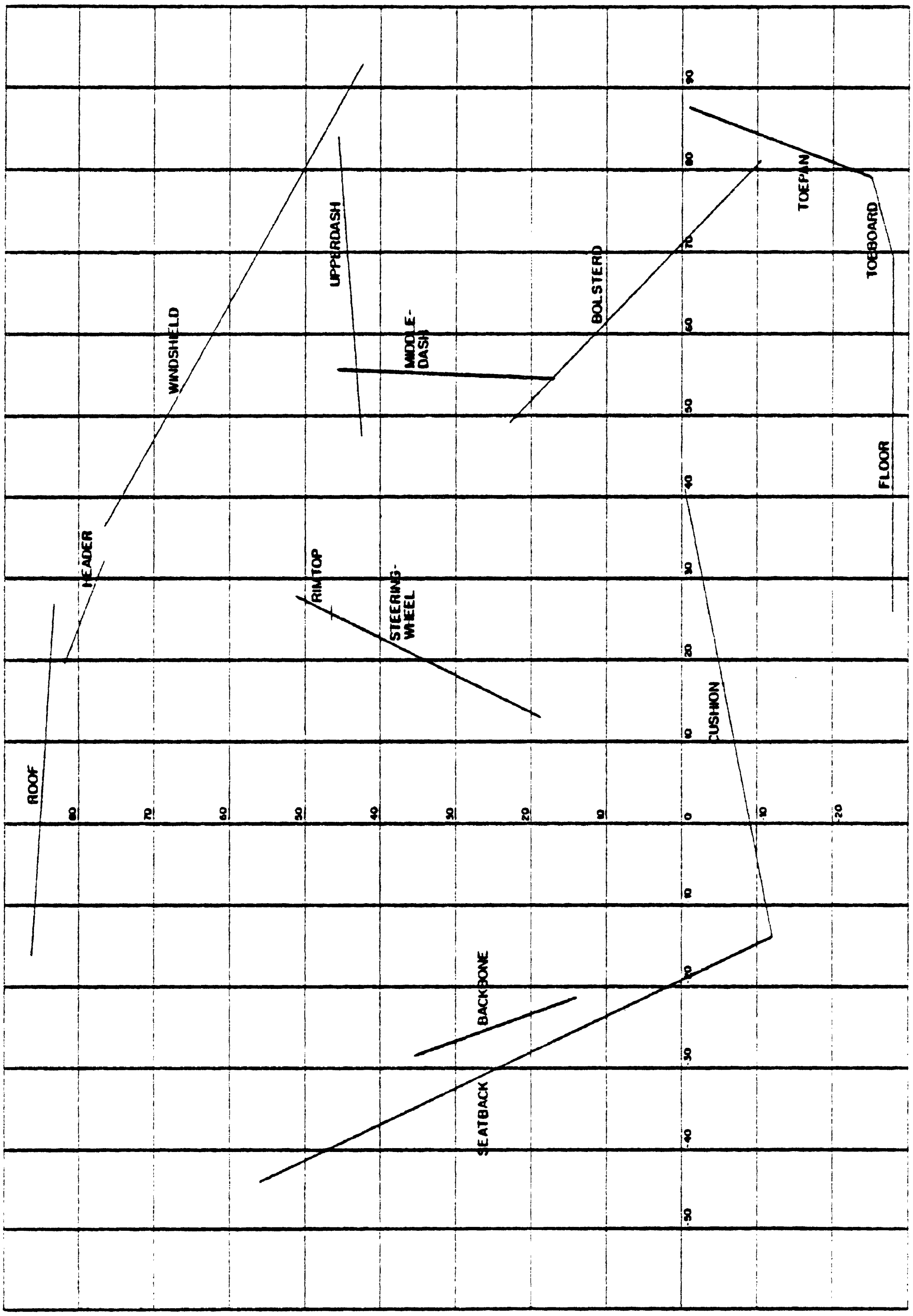

FIGURE 4-5. Vehicle interior contact surfaces.

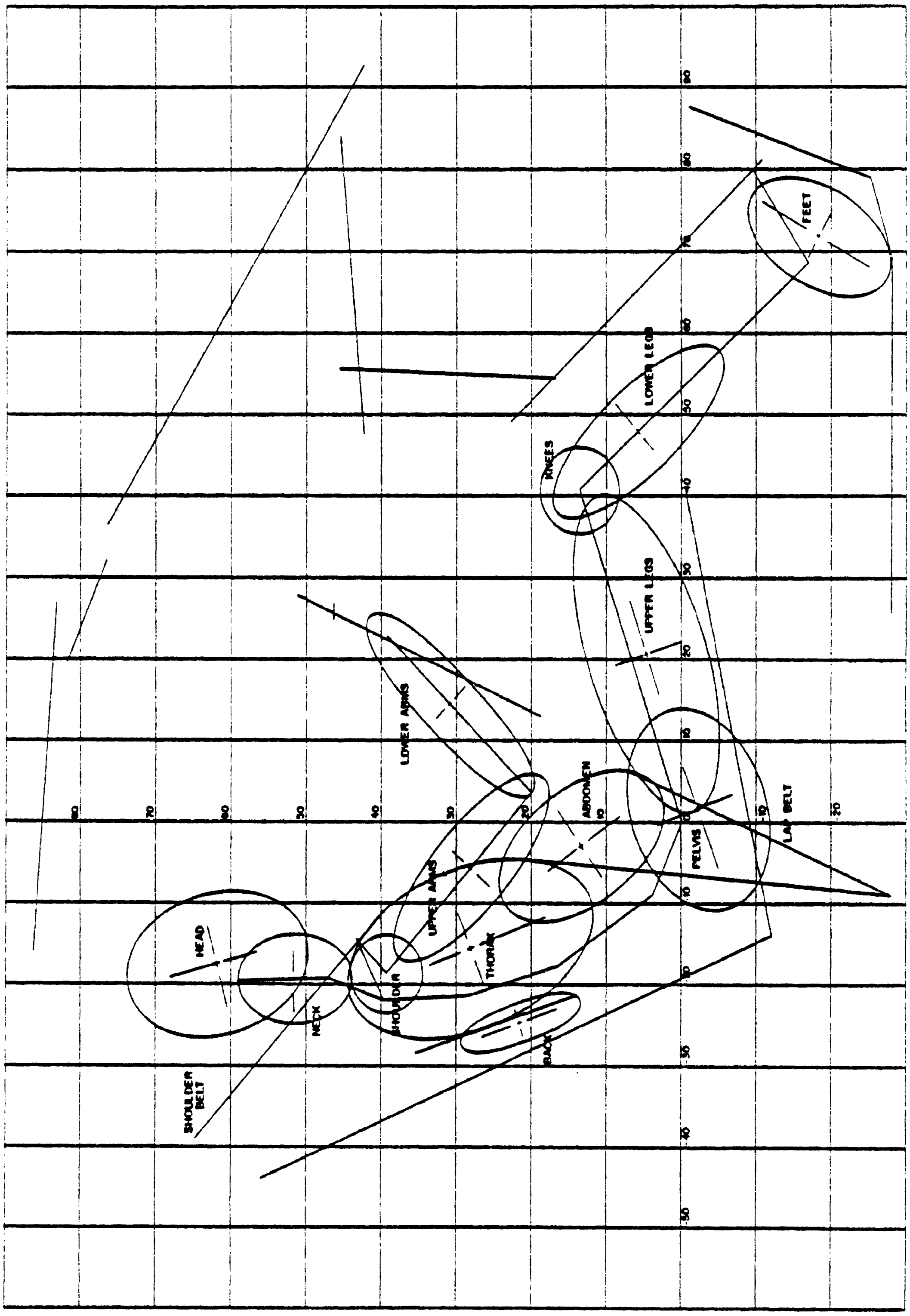

FIGURE 4-6. Occupant scaled in vehicle showing contact ellipses.

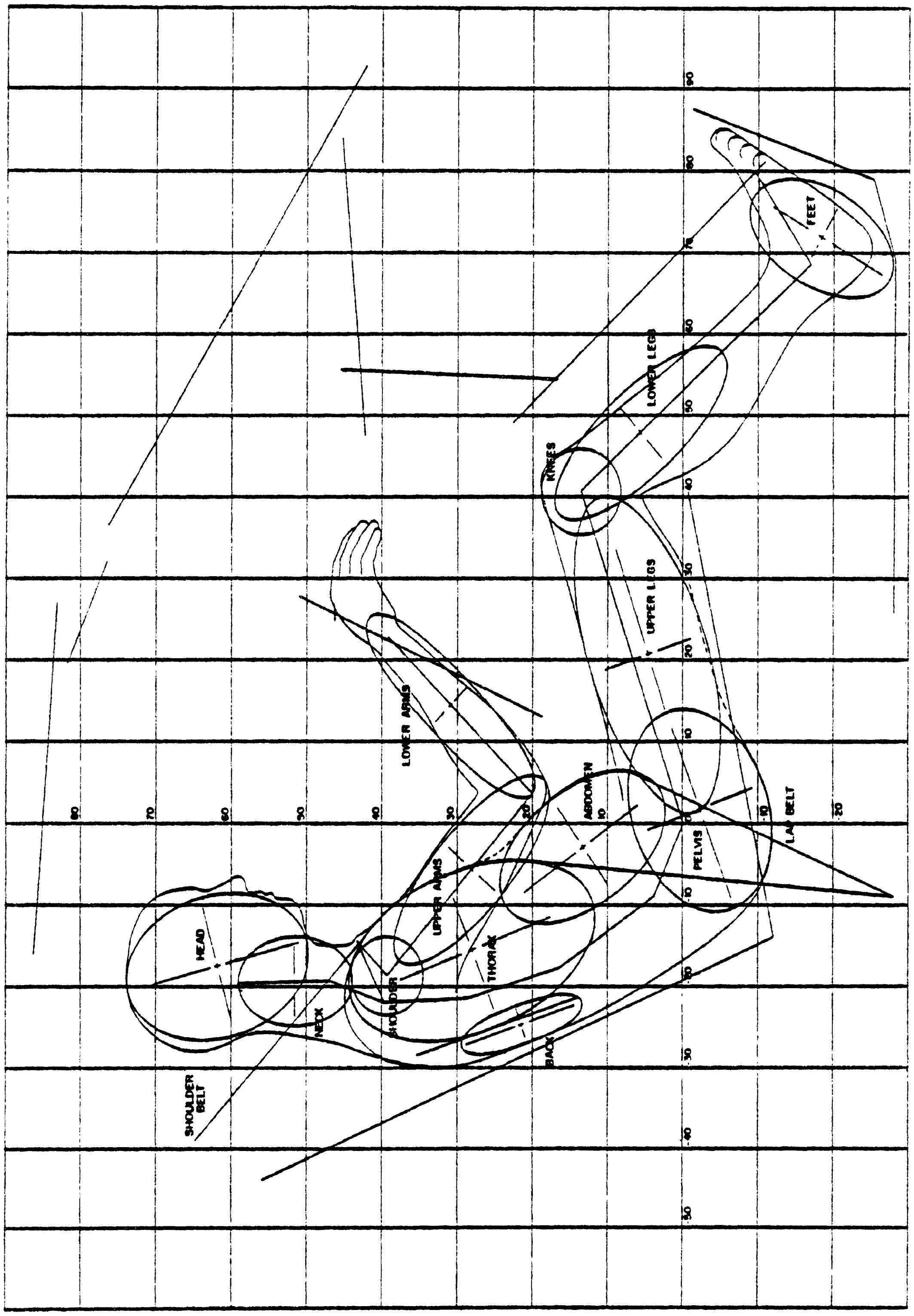

FIGURE 4-7. Seated occupant showing outline of seated surface form.

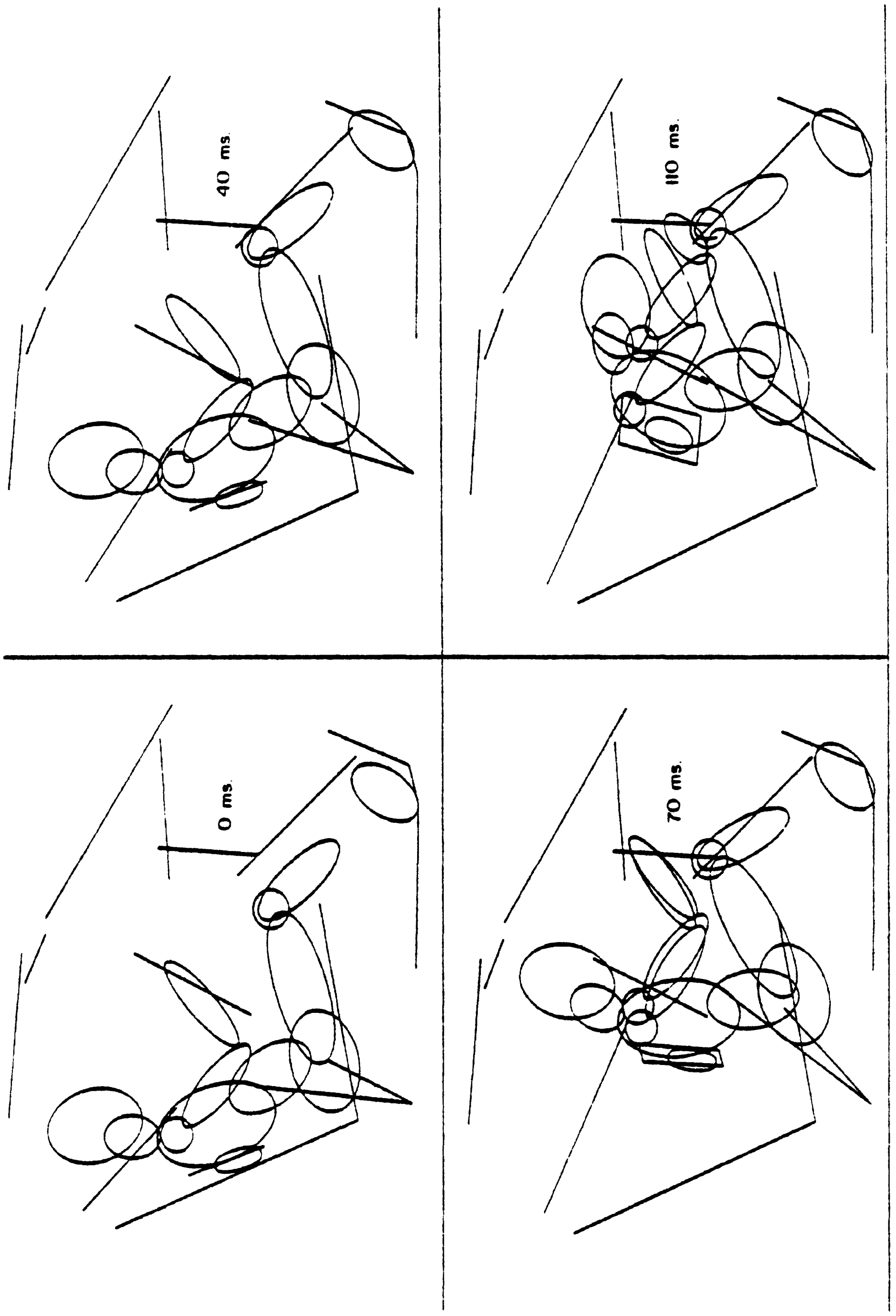

FIGURE 4-8. Occupant motion: restrained case.

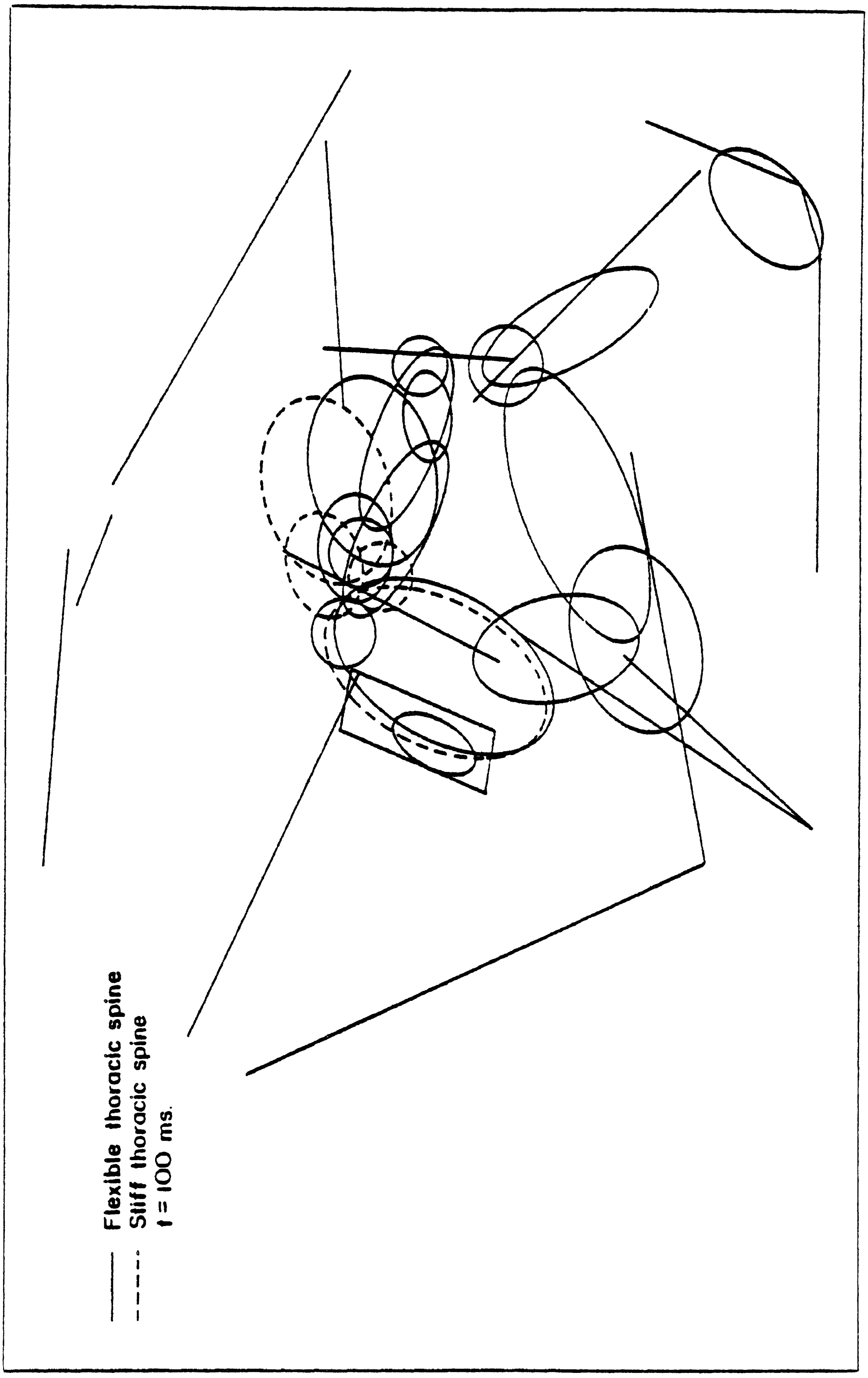

FIGURE 4-9. Effect of thoracic spine flexibility: belted case.

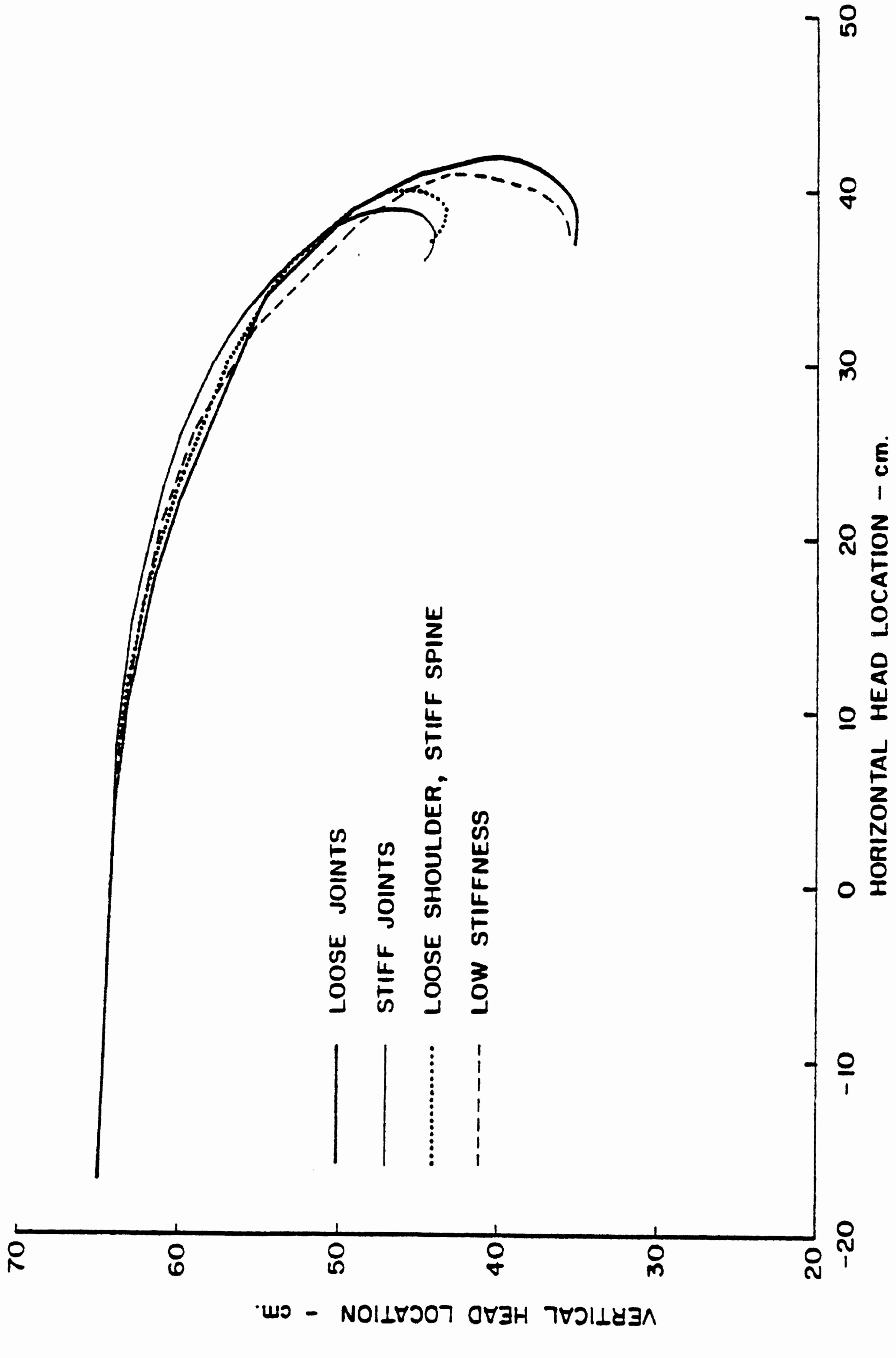

FIGURE 4-10. Head movement: belted case.

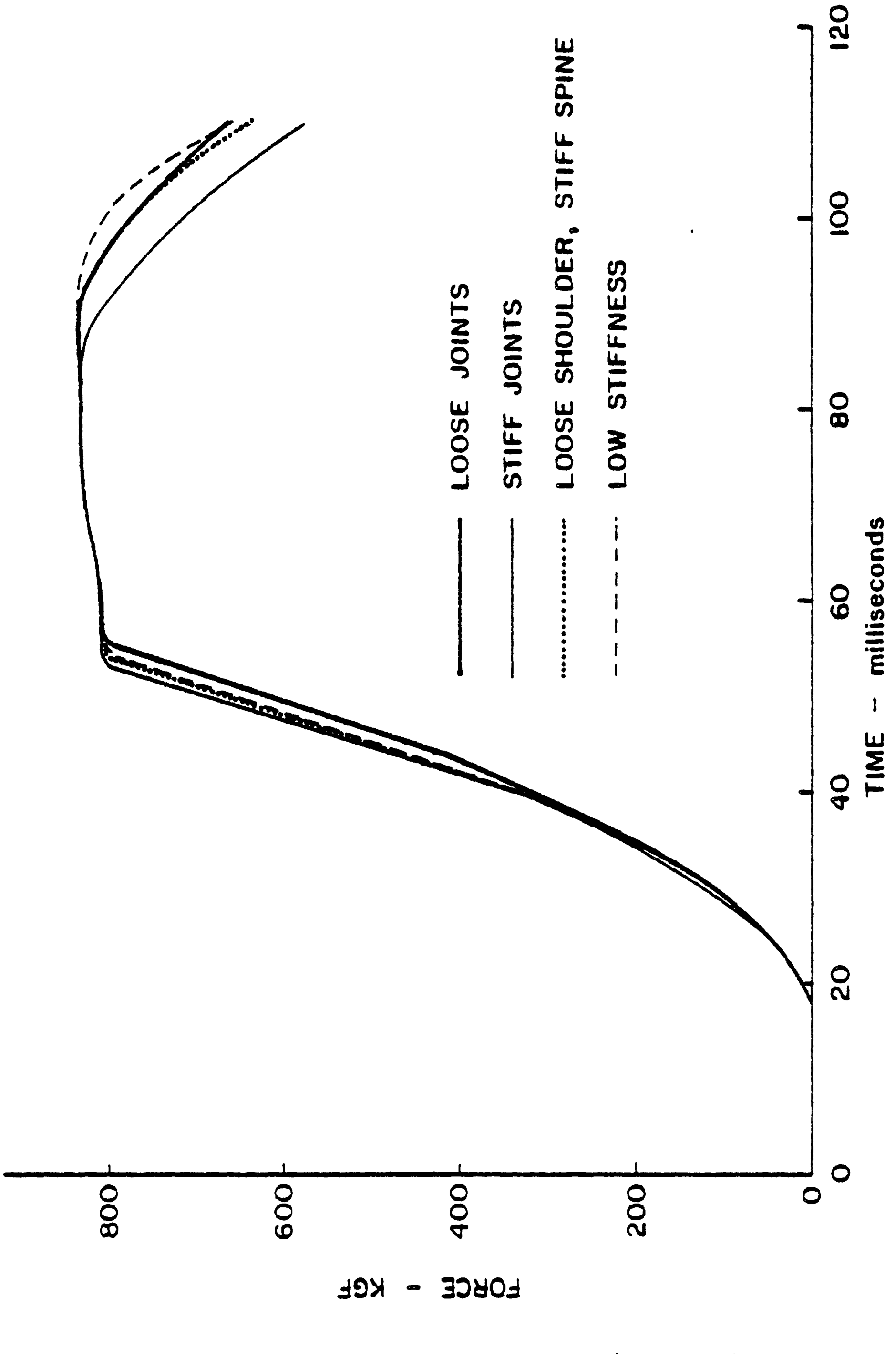

FIGURE 4-11. Force in shoulder belts.

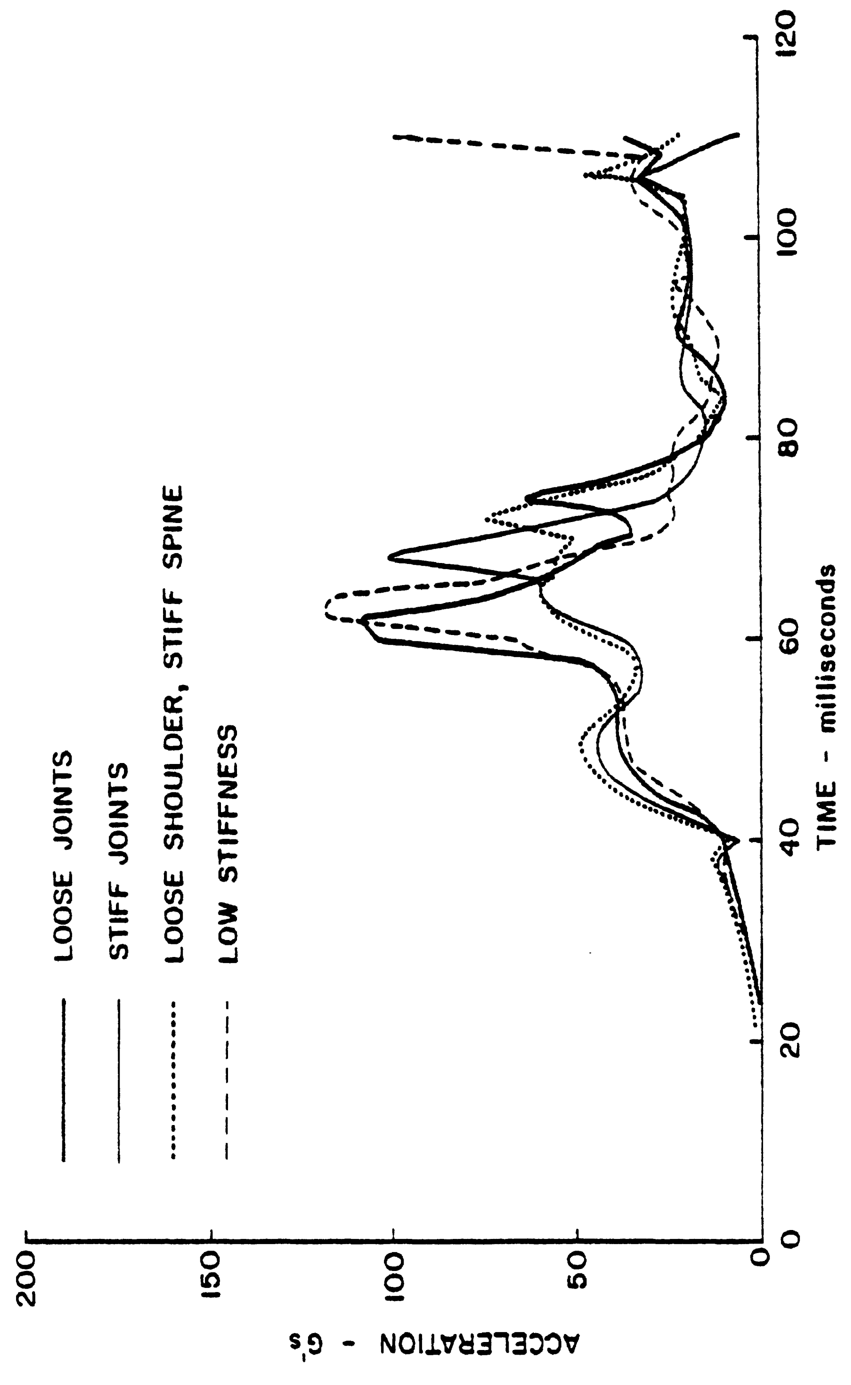

FIGURE 4-12. Thorax segment acceleration: belted case.

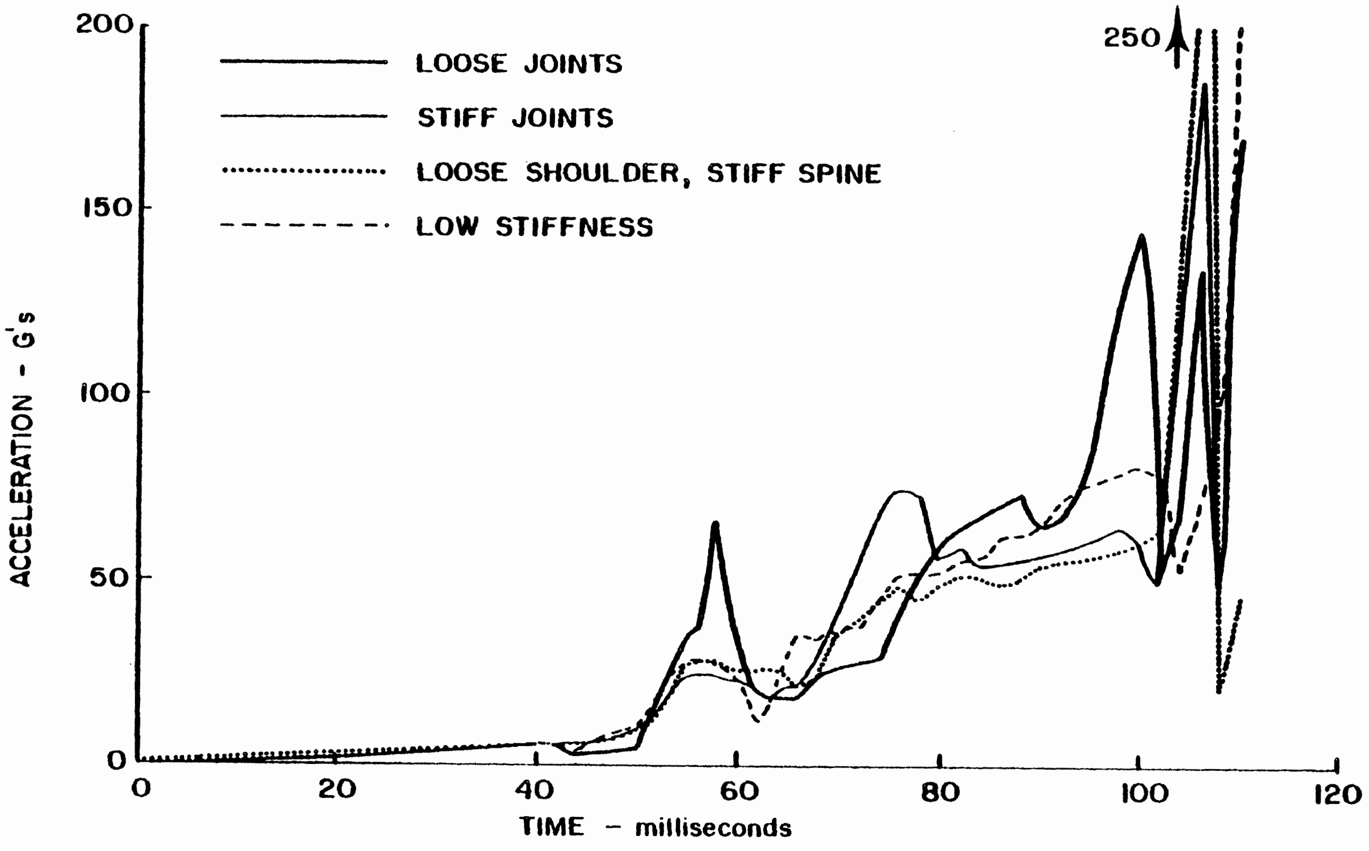

FIGURE 4-13. Head acceleration: belted case.

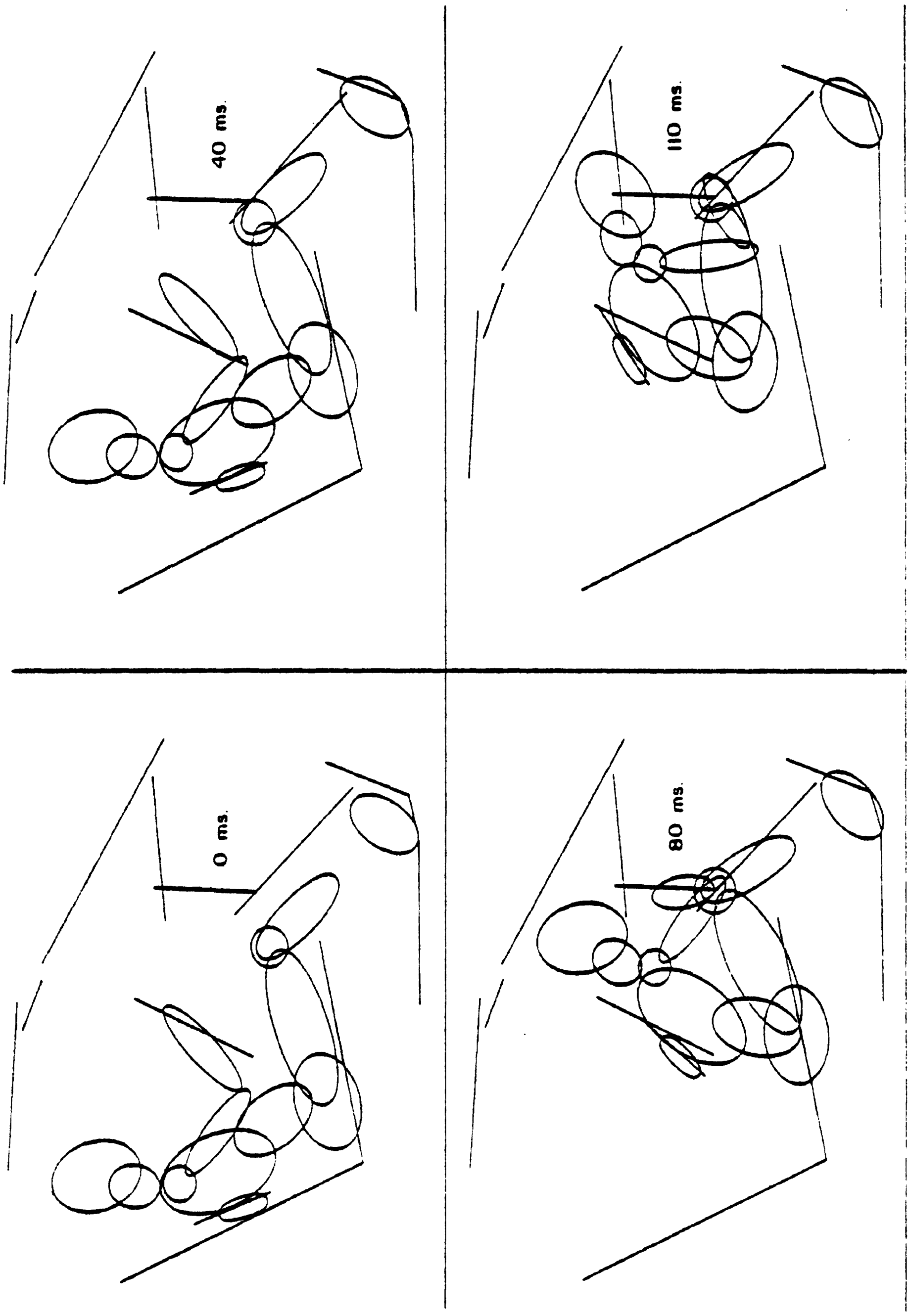

FIGURE 4-14. Occupant motion: unrestrained case.

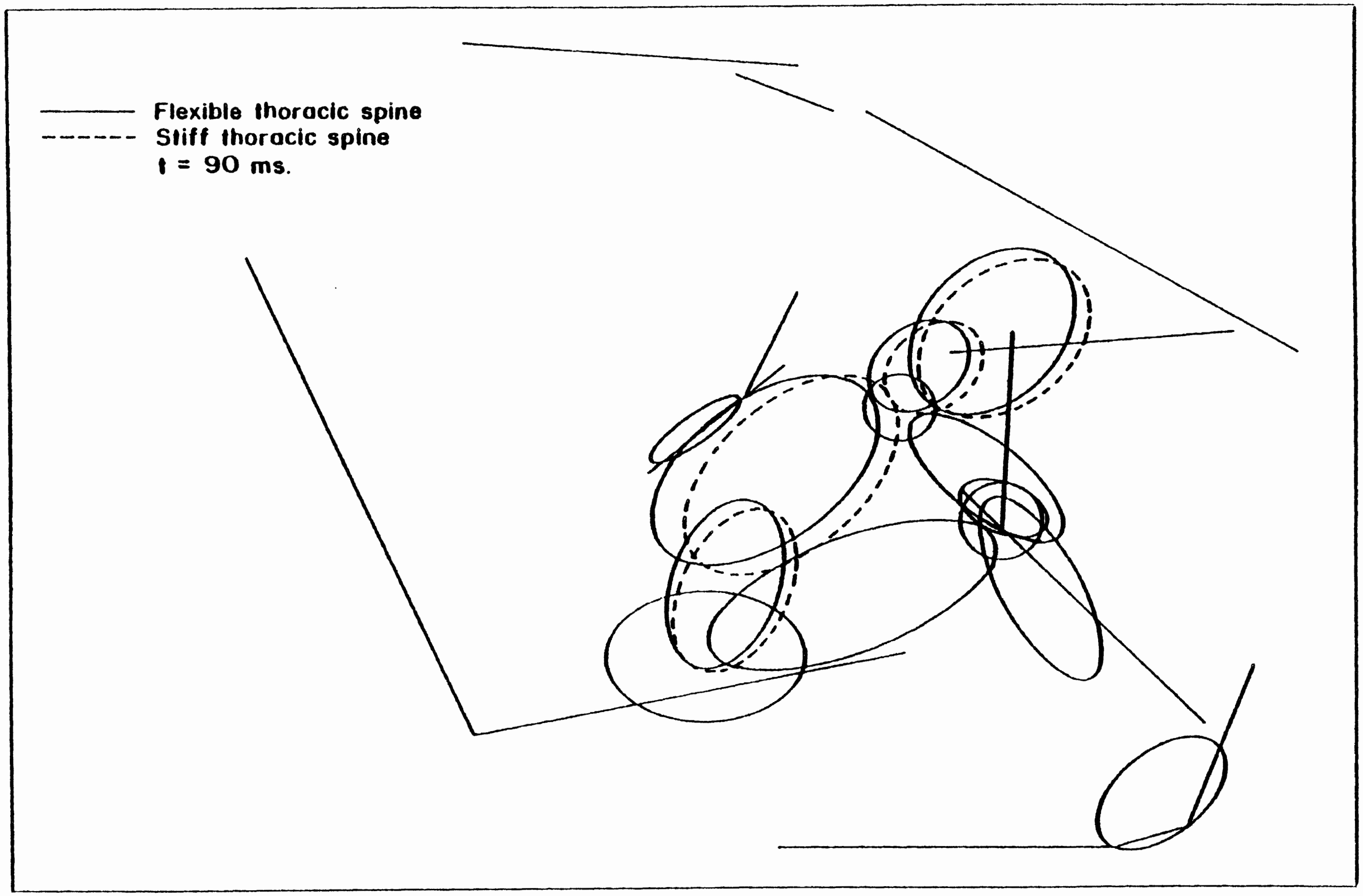

FIGURE 4-15. Effect of thoracic spine and shoulder girdle flexibility: unrestrained case, superposition of vehicle.

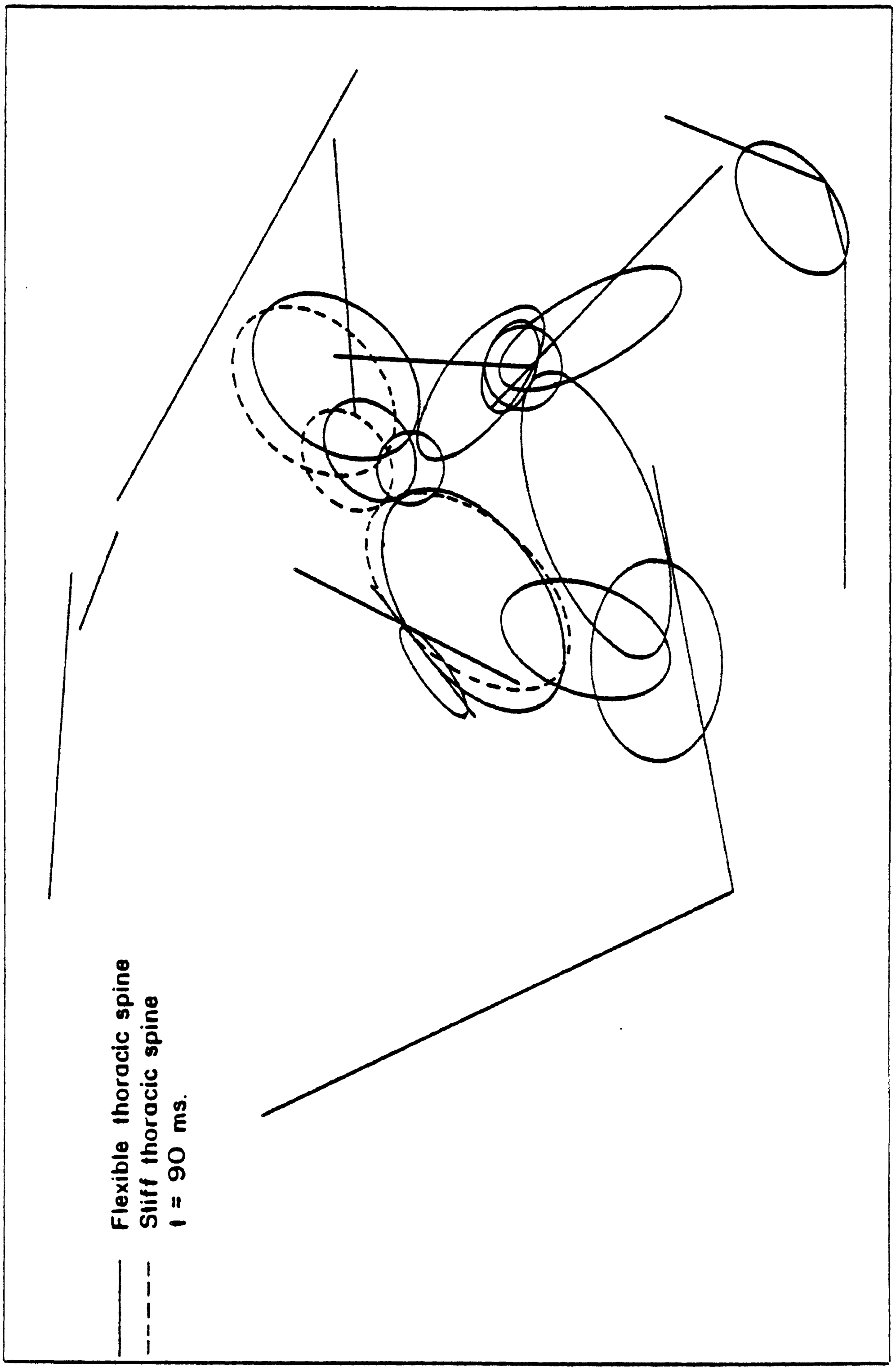

FIGURE 4-16. Effect of thoracic spine flexibility: unrestrained case, superposition at abdomen.

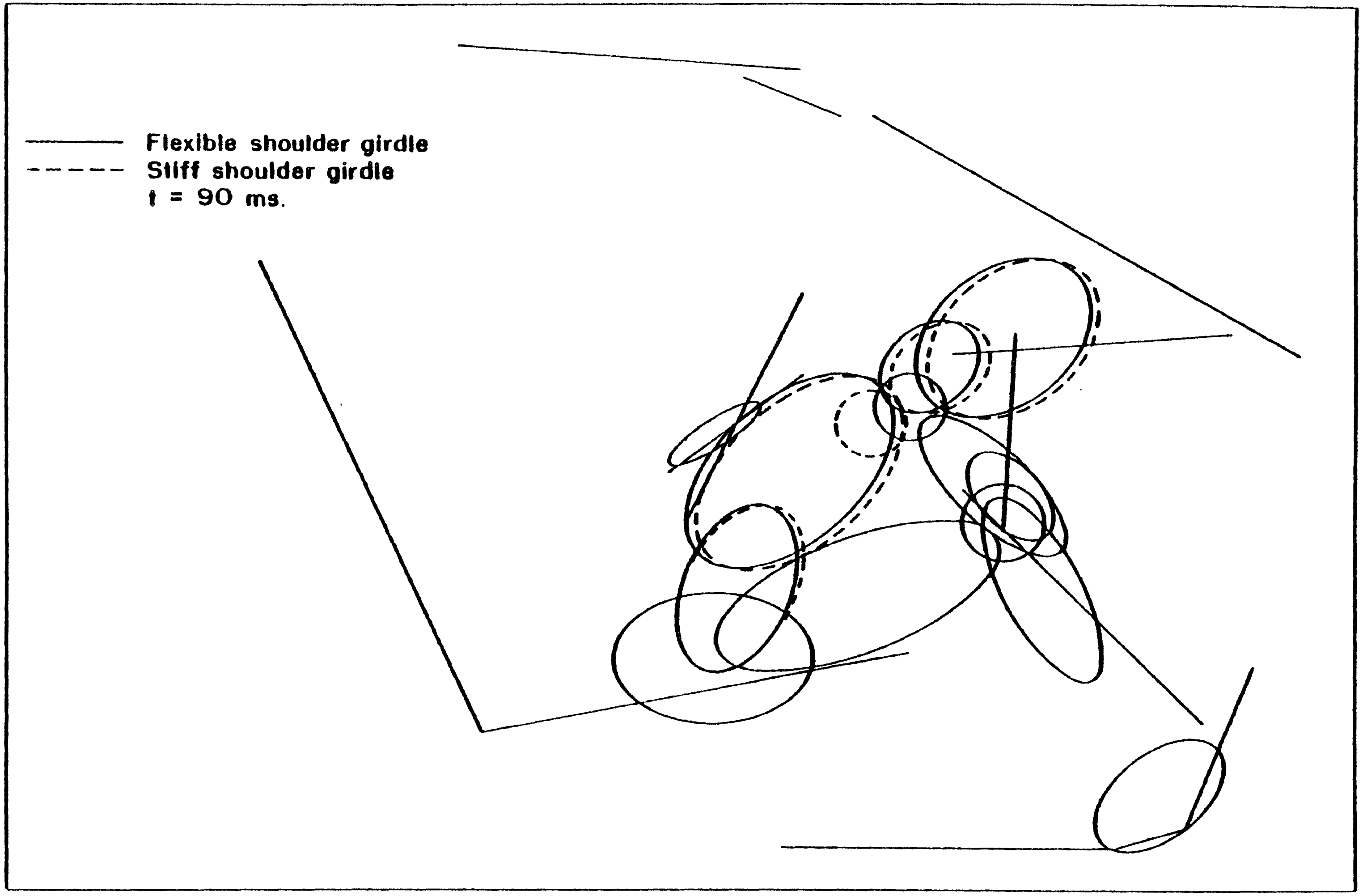

FIGURE 4-17. Effect of shoulder girdle flexibility: unrestrained case, superposition of vehicle.

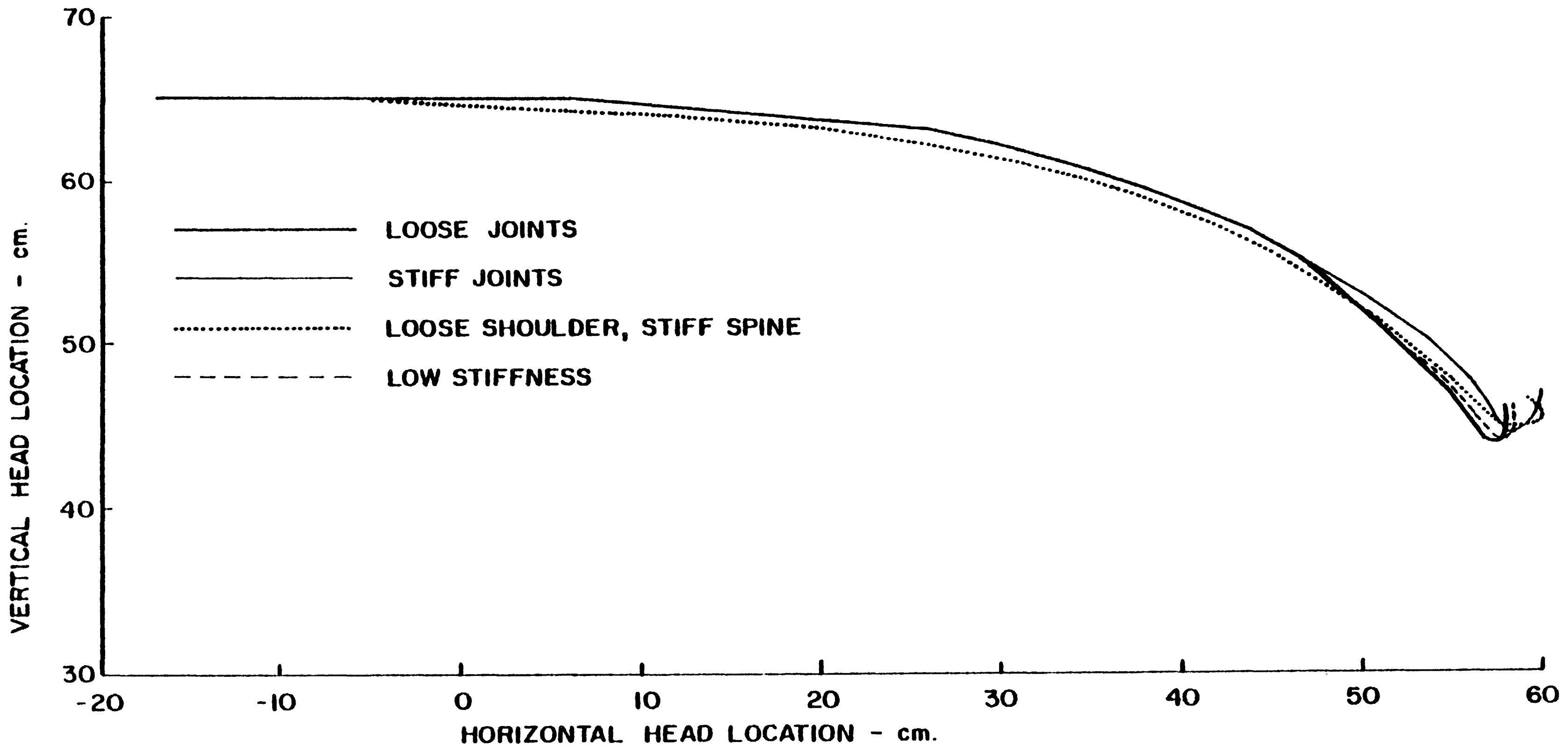

FIGURE 4-18. Head movement: unrestrained case.

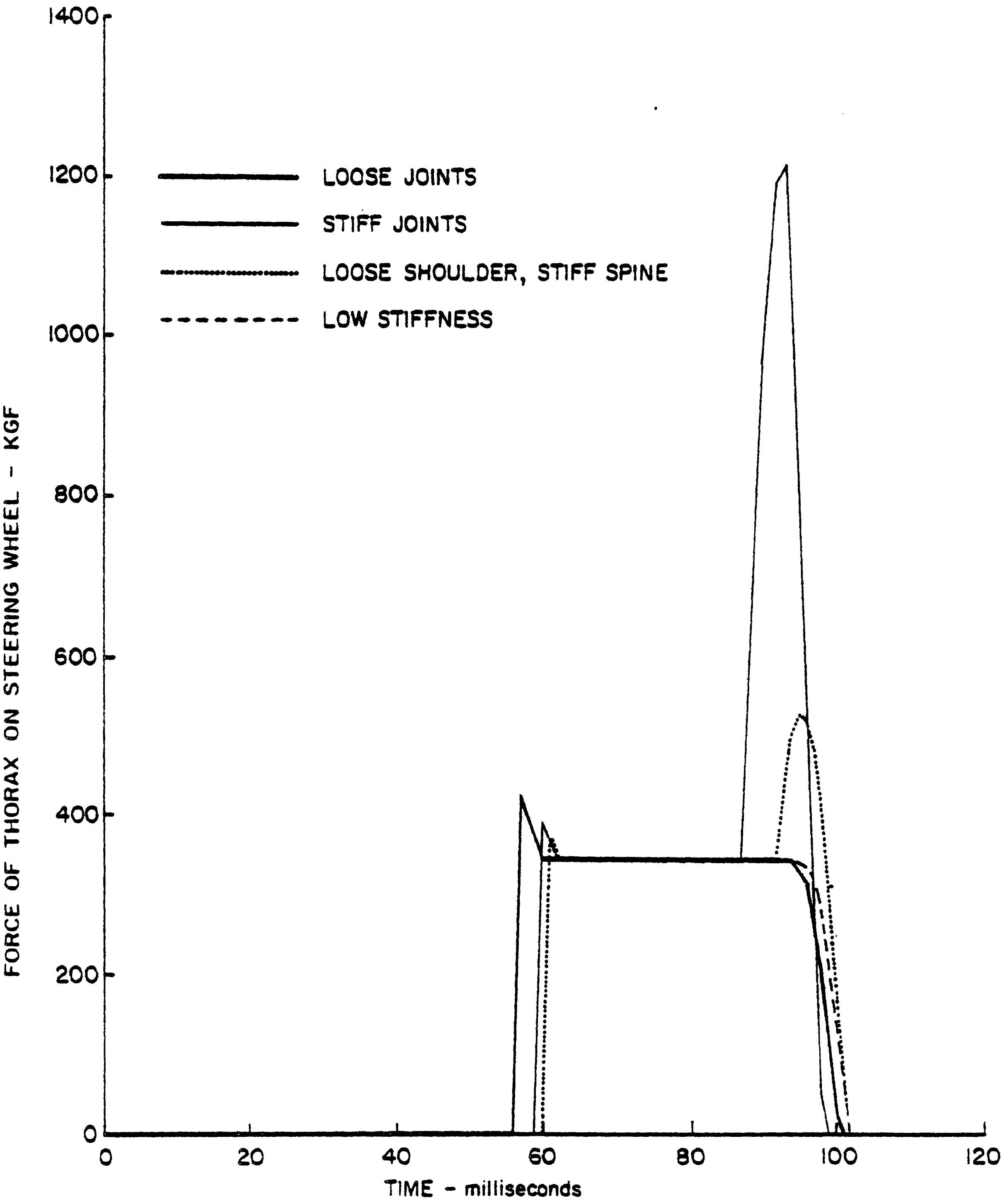

FIGURE 4–19. Force of thorax on steering wheel versus time.

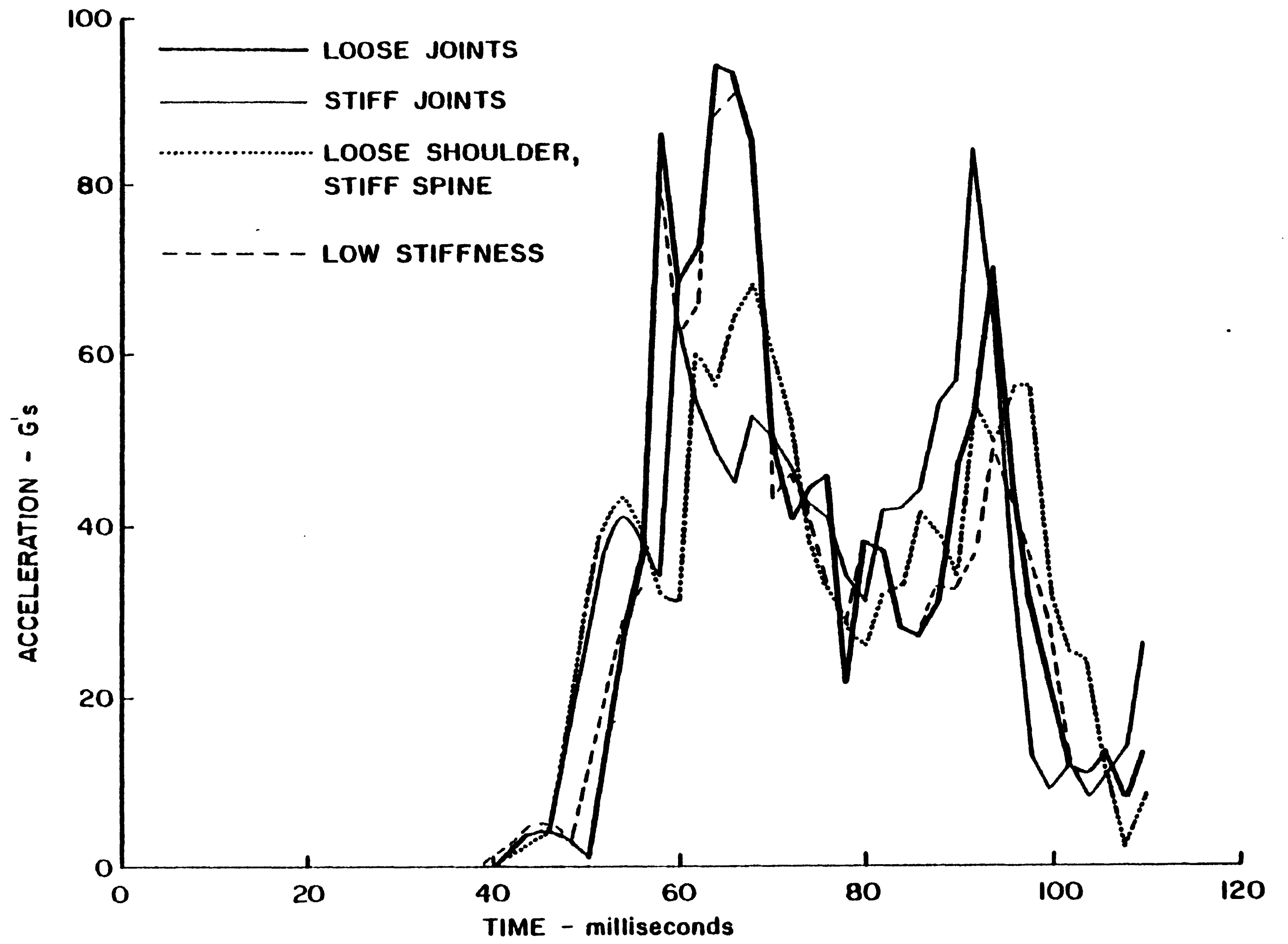

FIGURE 4-20. Thorax segment acceleration: unrestrained case.

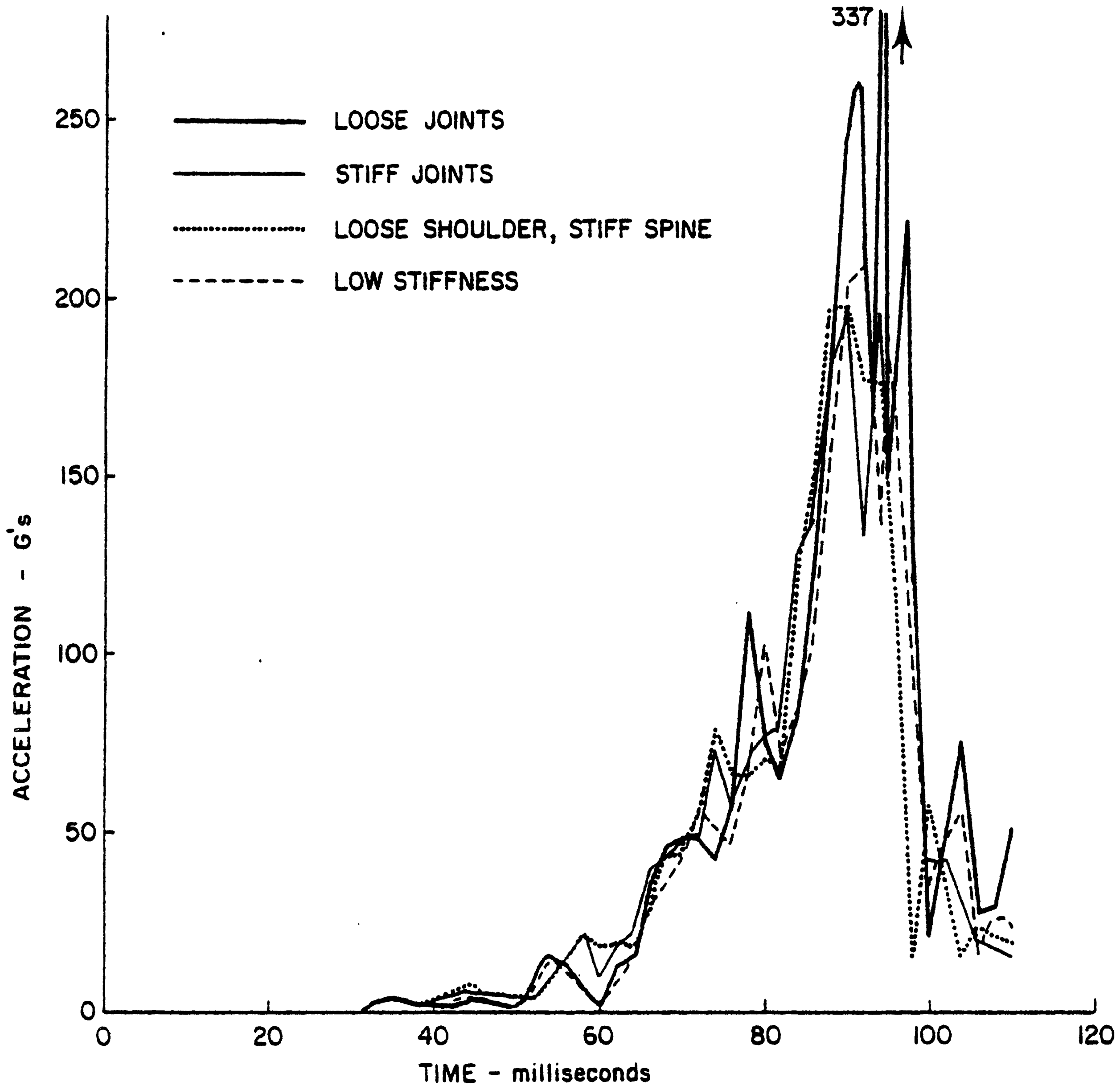

FIGURE 4-21. Head accelerations: unrestrained case.

CHAPTER 5

ATD CRITIQUE

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A review of existing anthropomorphic test device (ATD) designs was made from the standpoint of biofidelity, measurement capability, directionality, and impact testing performance. The ATDs included in this review are listed below, along with the organizations primarily responsible for their development and/or use.

APROD 82 (Peugeot S.A./Renault, France)
Hybrid III (General Motors, USA)
MIRA (Motor Industry Research Association, England)
ONSER 50 (Organisme National de Securite Routiere, France)
OPAT (David Ogle Ltd.; MIRA, England)
Part 572 (General Motors; NHTSA, USA)
Repeatable Pete (University of Michigan, USA)
SID (University of Michigan; Calspan; NHTSA, USA)
Sophisticated Sam (General Motors; Sierra Engineering, USA)

Other isolated components reviewed include the following:

APR honeycomb face (Peugeot S.A./Renault, France)
Biokinetics frangible faceform (Biokinetics, Canada)
Daniel/Yost leg (Ford Motor Company, USA)
GMR frangible head (General Motors, USA)
ONSER pelvis (Organisme National de Securite Routiere, France)
TNO abdomen (Research Institute for Road Vehicles, The Netherlands)

REVIEW OF ATDS BY BODY REGION

Mertz (1985) has recently presented an excellent summary of the biofidelity characteristics and injury predictive measurement capabilities of nine ATDs used in automotive restraint-system testing. The ATDs were categorized into frontal impact dummies and side impact dummies. No discussion of the directional limits of the ATDs within those categories was given. The specific designs were:

Frontal Impact	Side Impact
Hybrid III	APROD 82
OPAT	MIRA
Part 572	ONSER 50
Repeatable Pete	SID
Sophisticated Sam	

ATD CRITIQUE

This critique of ATD designs used the Mertz summary as a starting point and expanded upon it in areas of particular relevance to the AATD program. The following discussion of the design features of each of the ATDs is presented by major body region or structure.

Head. Most ATD head designs consist of a rigid aluminum shell structure covered by a vinyl or plastic skin. These include the Part 572, Hybrid III, OPAT, APROD 82, SID, and MIRA dummy heads. The combination of the aluminum shell mass and stiffness and the skin mass, shape, and compressive properties determine the response of the head structure to direct rigid impacts. None of the designs has a humanlike hard surface impact-response except the Hybrid III, which has appropriate response for forehead impact only. The Hybrid III skin is of a constant, but greater than human, thickness and may give humanlike response in other impact directions, but this has not been evaluated.

The ONSER 50 skull is unusual in that, although it is a metal shell (Zn-Al alloy), it is intended to be frangible. It is also unusual in that the upper skull (calvarium) and lower skull have a horizontal parting line around the periphery of the head.

The nonmetallic ATD head designs use ceramics (Sophisticated Sam), glass-fiber reinforced polyester (GMR frangible head), or cast polyurethane (Repeatable Pete). The first two designs were intended to be frangible, and, although it was possible to produce skull structures with fracture loads in the range of human values, the fracture patterns were not humanlike, and the degree of damage was found to be excessive at those loads. This is indicative of the need to match not only bone strength and stiffness but bone material fracture toughness as well.

The cast urethane skull of Repeatable Pete is a solid casting of stiff urethane, unlike the skull castings of the other two designs that had cavities intended for filling with a brain-simulating material, such as soft silicone rubber. The purpose of the solid casting was to produce an overall skull-like structural stiffness with a low stiffness material. All three nonmetallic designs used a humanlike scalp thickness to achieve humanlike impact response in conjunction with the underlying skull structure.

Many ATD designs have human-looking facial features cast into the skin. Some also have underlying features cast into the aluminum skull. There is no biomechanical fidelity associated with these features. In fact, the solid aluminum casting of the face and jaw results in an excessively stiff structure in comparison to the weak facial structure of the human. The Repeatable Pete and OPAT ATDs eliminate the facial features for the sake of improving repeatability, but the underlying structures are not adjusted to provide humanlike response. The Association Peugeot-Renault (APR) developed a facial modification for the Part 572 ATD head that replaces the rigid facial structure with a crushable metal honeycomb that is then covered with a skin simulation. The facial structure gives humanlike head acceleration response for facial impacts, and the skin has humanlike laceration properties. Prediction of facial bone fracture is possible from head acceleration measurements and honeycomb deformations.

Frangible facial structures have been developed (GMR frangible head and Biokinetics frangible faceform) that will fracture at humanlike load levels. Biokinetics has also investigated modifications to the jaw of the Hybrid III to produce more realistic head accelerations during facial impact. Load-sensing facial structures have also been studied (Warner and Niven 1979) for application to the Part 572 ATD, but no consideration to biofidelity was given.

Spine. At the present time, two basic approaches exist for ATD cervical and lumbar spine design. Either there is a monolithic rubber cylinder in bending or a segmented metal system with rubber discs compressed between the segments. The latter has only been used for necks. The Part 572, SID, OPAT, MIRA, and ONSER 50 ATDs all have solid rubber cylindrical necks, while the Hybrid III, Repeatable Pete, and APROD 82 ATDs have segmented necks. The lumbar spines of all ATDs have a monolithic rubber cylinder, and the thoracic spines of all ATDs, except Repeatable Pete, have a rigid spine construction. Repeatable Pete has a segmented thoracic spine with limited flexibility provided by rubber spacers between the metal segments.

The traditional cylindrical rubber neck is a simple approach to providing a continuously flexible linkage, but it suffers from a reliance upon the entire molded structure for the overall system response. Designing such a neck for directional stiffness and range-of-motion differences, as well as controlling for the distribution of flexibility along the spine, is a difficult problem. Degradation of one region requires that the entire unit be replaced. Because of these factors, the manufacture of such structures requires careful control of large volumes of molded rubber materials.

Segmented spines, on the other hand, are more complicated structurally than the monolithic rubber spines, but they offer much greater design latitude in controlling directional responses and motion distribution along the spine. By using smaller, specially shaped elastomeric response-control elements, segmented spines can minimize quality control problems and can aid in the identification and replacement of degraded elements. Such systems also have the potential for reconfiguring the spine incrementally through the use of reshaped elements or segments. The use of a curved lumbar spine, as in the Hybrid III, can also accomplish this reconfiguration, but this requires the availability of a totally new molded structure. An example of the redesignability of a segmented spine is given by the modification of a Hybrid III neck for the APROD-82 ATD. Here the upper nodding joint and the lower-neck response-control element have been redesigned to produce more humanlike lateral flexion response of the overall head/neck system.

The traditional use of a rigid thoracic spine puts a considerable burden upon the neck structure alone to provide all of the head/neck/thoracic-spine mobility of the human. This may be an excessive requirement that can lead to unrealistic conformability of the ATD upper torso and subsequent non-humanlike head trajectories in shoulder belt and steering system impact tests. (See Chapter 4 of this report.)

Thorax. Thoracic structural design in most ATDs centers around rib-like springs with damping provided by auxiliary materials. The Part 572, Hybrid III, OPAT, SID, and MIRA ATDs have this type of construction. The APROD 82 uses ribs to transmit loads, but the actual response-control structures for lateral impacts are pistons attached to the ribs that compress rubber elements. The ONSER 50 has a molded foam plastic chest, and Repeatable Pete has a molded urethane thick shell with very flexible ribs for attachment of the chest to the thoracic spine only.

The human thorax is a rate-sensitive structure with a low stiffness static behavior and a very stiff velocity-dependent behavior under automotive impact conditions. Current ATD designs can only simulate the nonlinear load-deflection behavior of the chest over a narrow range of impact velocities, due to the methods of employing stiff elastic elements with auxiliary damping. Such designs may be deficient at lower and higher impact velocities. Similarly, these attempts to obtain total structural stiffness through the bending of the ribs alone can result in an inability to respond properly to local loading, such as from a shoulder belt. This can also lead to incorrect interaction with vehicle interior structures, such as the steering assembly and instrument panel, particularly when combined with the rigid thoracic spine structures typical of current ATDs.

The OPAT ATD is the only design to date that sought to provide a humanlike static load-deflection response using a spring-like rib cage and also achieved a humanlike dynamic load-deflection response using a separate "lung pack" that simulated internal organ response (Warner 1974). The "lung pack" was originally polyethylene foam interleaved with lead sheets and was formed to fit in close proximity to the rib cage. A more durable plastic lung was developed, but the repeatability of the system was less than that of the Hybrid III ATD, on which the Part 572 was based. Recent OPAT literature no longer shows such a chest design.

Shoulder. A number of different shoulder designs have been developed for ATDs, particularly those intended for lateral impact. Frontal test ATDs, such as the Part 572 and Hybrid III, have shoulders that are rigid aluminum castings pin-jointed to the rigid thoracic spine. The joints allow for fore/aft motion, but the shoulder is essentially rigid in the lateral direction. The APROD 82 shoulder is a modification of the Part 572 shoulder and allows lateral translation through a sliding shaft in association with a polyurethane clavicle with steel inserts for a connection linkage. This assembly, in conjunction with the chest, produces a humanlike lateral force-deflection response. The MIRA ATD shoulder and the ONSER 50 shoulder are both designed to telescope and move laterally, but they do not produce a humanlike force-deflection response.

The OPAT shoulder design is the most humanlike in configuration with steel clavicles and scapulas having humanlike mass and the clavicles attached to the sternum. The design, however, does not allow for lateral deflection and does not have humanlike force-deflection response.

Abdomen. The abdominal structures of all ATDs have consisted of foam-like or air-filled bladders, the purpose of which was to fill the abdominal cavity in an innocuous manner. The Research Institute for Road Vehicles TNO has recently developed an abdominal insert for lateral impact that produces a humanlike lateral force-penetration response. In addition, it has "go/no-go" force-penetration switches to indicate potential for injury. The design, however, is not suitable for frontal impact testing, because the cast aluminum support structure for the switches appears to interfere with the forward flexion of the lumbar spine.

Pelvis. The pelvic skeletal structures of all ATDs are metallic (usually cast aluminum) and reproduce the complex geometry of the human pelvis but not its mass or stiffness. All ATD pelvic structures are too heavy and too stiff. Two interesting departures in pelvic design are the lateral load-sensing designs of the MIRA ATD and the ONSER pelvis for the European side impact dummy. The MIRA design features a four-piece pelvic structure with humanlike contours, a triaxial load cell to measure ilium loading and uniaxial load cells to measure pubic symphysis lateral forces and acetabulum forces along the femoral neck axis.

ONSER has recently developed a new lateral impact pelvis for the European side impact dummy (EUROSID). Lateral forces are measured by three uniaxial load cells, one at the pubic symphysis, one at the upper sacrum, and one at the lower sacrum. The external geometry of the pelvis is humanlike, but the hip-joint geometry has been changed to minimize the effect of leg position on pelvic loading, by placing the equivalent of the greater trochanter on the hip joint rather than on the femur. This region was covered with a polyurethane block to provide force attenuation and energy absorption in lateral impacts.

Test results show that this pelvis produces lower lateral impact forces than other ATDs but still gives higher forces than comparable cadaver test data (Cesari et al. 1984).

A number of modifications to existing pelvic designs have been made to allow for indication of submarining under lap belts in frontal crashes. Load transducers have been mounted singly or in groups on the anterior-superior iliac spines to indicate the presence of the lap belt as it moves up over the pelvis during submarining.

Extremities. The upper and lower leg structures of all the ATDs, except for Sophisticated Sam, consist of metal shafts and joints. Sophisticated Sam has ceramic structures for the femur and lower leg that were designed to fail at humanlike loads. The material, however, does not have the appropriate fracture toughness (lack of brittleness) of bone even though it matches bone failure strength. The result is excessive damage to these components during testing.

As with the pelvis, the metal leg skeletal structures do not possess humanlike mass and stiffness characteristics, which, in conjunction with the stiff knee-joint designs, cause the knee impact response of most ATDs to produce loads that are too high. The direct rigid knee impact-force response of the Hybrid III has been made humanlike through the use of butyl rubber inserts in front of the metallic knee joint. The mass distribution of the upper leg, however, is not humanlike.

A great deal of effort has been put forth recently to provide lower extremity load measurement capability that is greatly expanded over the traditional axial femur force measurement. The Hybrid III and the Daniel/Yost leg modification for the Part 572 ATD (Daniel and Yost 1981) have developed the capability to measure femoral and tibial axial, shear, sagittal and lateral bending, and torsional loads; ankle bending and shear loads; and knee shear load and displacement.

The upper extremities of ATDs are constructed in a manner similar to the lower extremities and therefore suffer from the same deficiencies of non-humanlike skeletal mass and stiffness. The Hybrid III has bending moment measurement capability in the lower arm.

The design of extremity joints in ATDs involves simple pin joints, combinations of pin joints, or ball-type joints. The resistance of the joint to rotational motion is produced by adjustable frictional torques, while the range of motion of a joint is controlled by providing stops internal to the joint. All ATDs feature different design details that incorporate the above features with differing degrees of success. The durability, adjustability, and repeatability of joint designs are the critical factors.

The joints of Repeatable Pete are noteworthy for their departure from conventional ATD joint design. Instead of using a pinch bolt or set screw approach for providing frictional force on the joint, these pin joints use bronze friction washers that are compressed by Belleville spring washers to produce a predesigned 1-G torque for the particular joint. This design produces a very rugged joint with very constant joint torque behavior, because friction washer wear is accommodated by the spring washers. The design is bulky and heavy, however. Repeatable Pete is also unusual in that two pin joints at right angles to each other are used at the hip joint instead of a single ball joint. This was done, again, to provide better joint frictional torque control.

At present, the joints of the Hybrid III represent the most practical compromise between the complex joint design of Repeatable Pete and the need for improved joint friction control over that of the Part 572. The Hybrid III joints use plastic frictional materials with adjustable screw-type frictional forces in combination with elastomeric spring washers in the pin joints.

ATD joint designs must include a joint-stop mechanism that provides a progressive resistance to motion instead of an abrupt limit. An abrupt stop can lead to unrealistically large forces being introduced into the ATD skeleton. The Hybrid III has used metal-to-rubber stops instead of the metal-to-metal stops of older ATD designs.

OVERALL EFFECTIVENESS OF HYBRID III AND SID COMPARED WITH AATD

At present, the most commonly used ATDs in automotive testing are the Part 572, Hybrid III, SID, and APROD 82. Of these, the Hybrid III and SID ATDs are being used in research and development testing in this country.

The Hybrid III was developed over ten years ago, and its design is based on biomechanical knowledge available at that time. It is a frontal-loading-only ATD whose design represents an evolutionary improvement over conventional ATD design. For example, the rib cage uses the same design as the previous Hybrid II, but with altered structural stiffness to produce a humanlike impact response to mid-sternal moving-mass impactors. The Hybrid III also possesses humanlike hard-impact forehead response and midsagittal neck bending response. As presently configured, the Hybrid III has the greatest measurement capability of any ATD, with 44 data channels.

The SID was developed more recently than the Hybrid III and represents a modification of the chest region only in an otherwise standard (non-biomechanical) ATD. The SID was developed to provide lateral chest response biofidelity under rigid and padded impacts. The shoulder response is included in the chest response, and as a result the design has no separate shoulder structure. The remainder of the SID structures are standard Part 572. Except for additional chest wall accelerations and lateral chest displacement, the SID has the same measurement capabilities as the Part 572 ATD.

Both the Hybrid III and the SID are examples of ATDs intended for use in restricted test conditions and/or directions, and as such they have only limited biofidelity in the principal directions and none in other directions. One of the most serious deficiencies of both ATDs centers around the designs of the upper torso, both the rib cages and the spines. The IPR analysis has indicated the great importance of the head and chest as primary sources of injury, disability, and death of unrestrained occupants. The development of effective countermeasures to minimize injury to these regions depends strongly upon having an ATD that produces realistic responses in terms of trajectories, contact points, and loadings. The combination of rigid thoracic spines with present neck designs (including that of Hybrid III) and inadequate thoracic rib-cage conformability are producing head contacts and chest/steering-system interactions that are quite unlike those in real-world crashes. All present ATD designs are quite inadequate in this respect in the crucial head/torso regions for frontal, lateral, and oblique impacts. The lack of realistic concentrated load response in the Hybrid III and SID chests is compounded for the case of shoulder-belt loading. Neither chest exhibits humanlike stiffnesses at the lower loading rates associated with belt restraint systems. This, again, will have an influence on both chest deformations and on head trajectories.

Even with the biomechanical shortcomings discussed above, the combination of Hybrid III for frontal crash testing and SID for lateral crash testing allows occupant protection assessments to be made on a comparative basis using the data generated by their measurement systems. Putting biofidelity questions aside and considering only *measurement capability*, an analysis was performed to investigate how an AATD with multidirectional response and expanded measurement capability would improve our ability to address the crash protection problem. This analysis utilizes the IPR measure of injury cost developed by Carsten and O'Day (1984). It should be kept in mind that the IPR values presented in the tables of their report are given as a percent of the total IPR for a given parameter, such as body region or occupant seat position. Therefore, while the numbers in a column can be summed to yield 100%, the numbers in a row (e.g., for the different body regions or seat positions) cannot be summed to yield the summary numbers found in the last columns of these tables. Figure 5-1 summarizes the steps involved in this ATD affectiveness comparative analysis.

The first step was to estimate the *IPR Measurement Capability* or *Measurement Effectiveness* for each ATD *by body region.* The numbers involved in this process along with results are shown in Table 5-1. As indicated in column 1, the body was divided into the four body regions: *head/face/neck*; *shoulder/chest/back/abdomen*; *pelvis/lower extremities*; and *upper extremities*, in order to correspond to the distribution of data by principal direction of force (Carsten and O'Day 1984, Table 17). Each body region is comprised of the different body parts for which IPR ratings have been determined by Carsten and O'Day (Table 12). In column 2 of Table 5-1, the percent of total body IPR is given for each body part and these percentages are summed to give the *Percent of Total Body IPR due to that Body Region.* Using these *Regional IPR Percentages*, the *Proportion of Body Region IPR Due to Each Body Part* within that region was determined. The results are presented in column 3. For example, in the head/face/neck region, the head has 42.6% of the total body IPR and the region has 60.5% of the total body IPR. Thus, the head accounts for 70.4% (42.6/60.5 × 100) of the IPR for the head/face/neck body region.

The next step in the process was to rate the measurement capability for the SID, Hybrid III, and advanced ATDs for left-front occupants for each of the body parts used in the IPR analysis (Carsten and O'Day 1984, Table 12). The measurement capabilities used were none (0%), partial (50%), major portion (75%), and complete (100%), and were based on existing measurement technology and injury criteria for the two existing dummies, and on projected capabilities for the AATD. These ratings are given for the different ATDs by body part in columns 4, 5, and 6 of Table 5-1.

Multiplying these *Measurement Capability Percentage* values for the respective ATDs by the *Percent Regional IPR* values of each body part (column 2), and summing for the body parts in each body region, gave the *IPR Measurement Effectiveness Percentages for each body region for each ATD.* These numbers are shown in columns 7, 8, and 9 for the body-region rows of Table 5-1.

The next step was to utilize these *ATD Body Region Effectiveness Estimates* to determine the *Overall Measurement Effectiveness of Each ATD by Principal Direction of Force (PDOF).* The numbers involved and results of this exercise for each of the ATDs are shown in Table 5-2. Column 2 of this table gives the *Percent of Total Body IPR* for each of the four body regions (from column 2 of Table 5-1), and column 3 gives *Body Region Effectiveness Percentages* taken from columns 7, 8, and 9 of Table 5-1 for the three ATDs, respectively. The next several columns (4) give the *Percent of Total Body IPR by Body Region for Each Clock Direction* that is relevant to each ATD. The final columns (5) give the *Percent of Body Region IPR Measured by the ATD* for the different clock directions. These values were obtained by multiplying the *Percent of Total Body IPR* (column 2) by the *Body Region Effectiveness Percentages* (column 3) and then times the *Percent of Total Body IPR by Body Region and Clock Direction* (column 4).

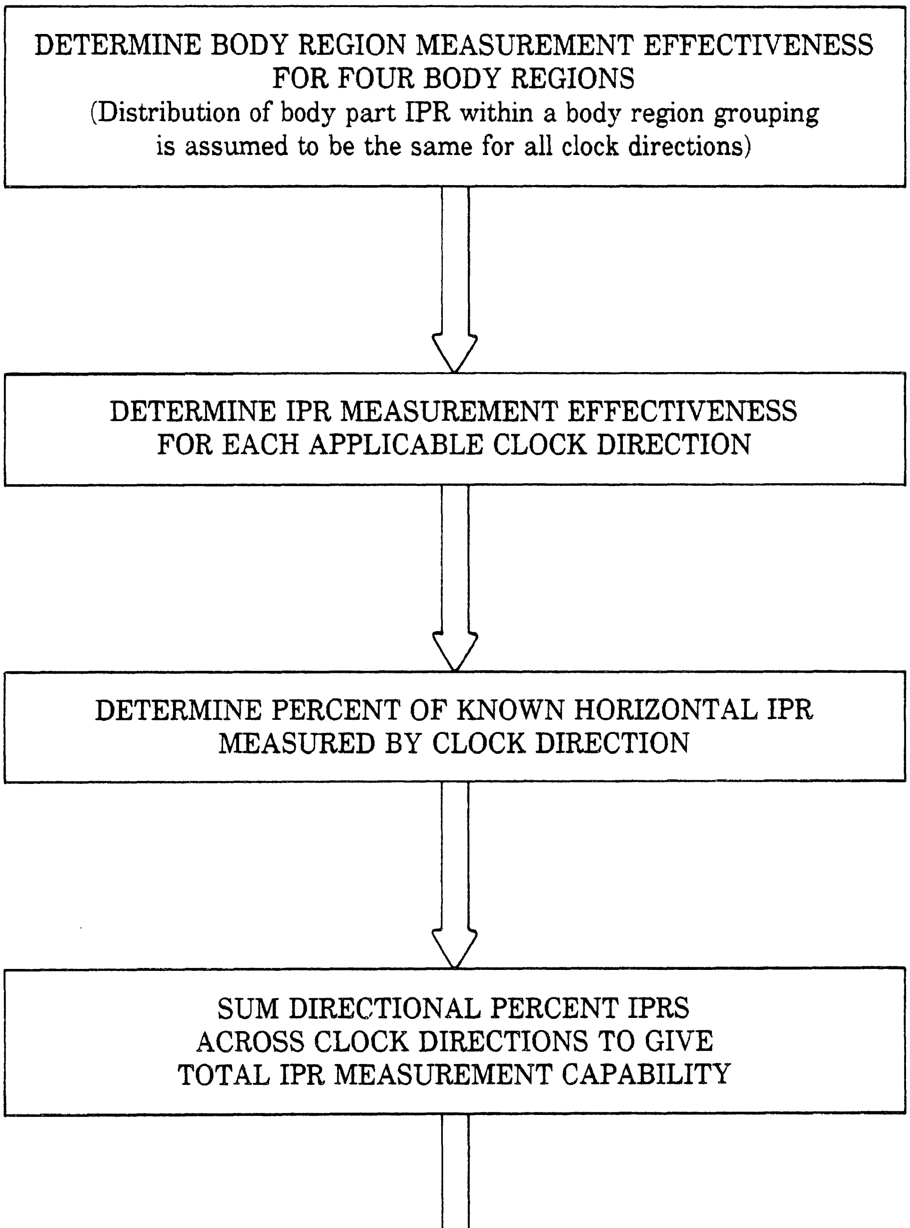

FIGURE 5-1. Flow chart of steps involved in comparative analysis of IPR measurement effectiveness for AATD versus SID plus Hybrid III.

TABLE 5-1

BODY PART/REGION EFFECTIVENESS ANALYSIS OF HYBRID III, SID, AND AATD
(Left-Front Occupant)

Body Part/ Region (1)	Body Part IPR* as % of Body Region IPR (2)	Body Part IPR as % of Body Region IPR (3)	Estimated Measurement Capability, %			Body Part/Region IPR Measurement Effectiveness, %		
			Hybrid III (4)	SID (5)	AATD (6)	Hybrid III (7)	SID (8)	AATD (9)
Head	42.6	70.4	75	50	100	52.8	35.2	70.4
Face	11.7	19.3	0	0	100	0	0	19.3
Neck	6.2	10.2	100	0	100	10.2	0	10.2
REGION TOTAL	60.5					63.0	35.2	99.9
Shoulder	0.4	1.5	0	0	0	0	0	0
Chest	20.5	77.9	50	75	100	39.0	58.4	77.9
Back	0.5	1.9	0	0	100	0	0	1.9
Abdomen	4.9	18.6	0	0	100	0	0	18.9
REGION TOTAL	26.3					39.0	58.4	98.4
Pelvis	1.4	18.4	0	100	100	0	18.4	18.4
Thigh	2.3	30.3	50	0	100	15.2	0	30.3
Knee	1.9	25.0	100	0	100	25.0	0	25.0
Lower Leg	1.3	17.1	75	0	75	12.8	0	12.8
Ankle/Foot	0.7	9.2	75	0	75	6.9	0	6.9
REGION TOTAL	7.6					59.9	18.4	93.4
Upper Arm	1.8	38.3	0	0	0	0	0	0
Elbow	0.7	14.9	0	0	0	0	0	0
Forearm	1.5	31.9	75	0	0	23.9	0	0
Wrist/Hand	0.4	8.5	0	0	0	0	0	0
Upper Limb	0.3	6.4	50	0	0	3.2	0	0
REGION TOTAL	4.7					27.1	0	0

*From Carsten and O'Day (1984), Table 12.

Summing these *Body Region IPR Percents Measured* for the four body regions for each of the clock directions, gives the *Percent of IPR Measured by Each ATD in Each Clock Direction.* These values were then divided by the *Percent of Total Body IPR* contributed by each clock direction (from Table 17, Carsten and O'Day 1984) to give the *Measurement Effectiveness Percent by Direction* (i.e., *Directional Effectiveness %*) for each ATD. These percentages are shown in the last row of these tables.

Finally, to illustrate the improvement in overall effectiveness that a theoretical advanced ATD with multidirectional response and measurement capability (omnidirectional in the frontal-to-lateral range) would have in comparison to the combination of the Hybrid III and SID ATDs, the computations illustrated in Table 5-3 were made. Column 2 of this table gives the percentages of total IPR associated with *known horizontal* PDOFs only. These numbers were obtained by taking the IPR values in the last column of Table 17 (Carsten and O'Day 1984) and eliminating the entries for non-horizontal and unknown categories before calculating the directional percentages. The *Overall Horizontal IPR Measurement Capability* of each ATD was then calculated by taking these *IPR Directional Percentages* and multiplying them by the *Directional Effectiveness Percentage* of each ATD in each direction (from last row in Table 5-2) shown in columns 3 and 4 of Table 5-3. The sums of the resulting *Directional Measurement Capabilities* for each ATD (columns 5 and 6) give the *Percent of Total-Horizontal-Force IPR Addressed by Each ATD* or a measure of the *Overall ATD IPR Measurement Effectiveness*. These are the numbers in the last row of Table 5-3.

In conducting this analysis for the left-front unrestrained driver position, it was judged that the combination of Hybrid III and SID ATDs could address directions 11, 12, and 1 o'clock (Hybrid III) as well as 9, 10, and 3 o'clock (SID). The potential gap in the oblique direction between 10 and 11 o'clock was ignored to give the Hybrid III/SID the benefit of the doubt. The 2 o'clock PDOF, however, was not included because SID is judged to be kinematically unreliable in farside oblique impacts. In comparison, the AATD will be able to continuously address the full range of Primary Direction of Force (PDOF) from 9 through 3 o'clock in a clockwise direction. In addition, the more extensive measurement capability to be available on the AATD will provide a higher level of injury assessment capability in those directions.

Based on the above considerations and analysis, the AATD will address 90.6% of the total IPR, while the combination of Hybrid III and SID addresses only 43.4% of the total IPR. The AATD would thus be twice as effective as the combination of the two present ATDs. The results of this analysis are summarized graphically in Figure 5-2.

TABLE 5-2

DIRECTIONAL EFFECTIVENESS ANALYSIS OF HYBRID III, SID, AND AATD
(Left Front Occupant)

AATD

Body Region (1)	% of Total Body IPR (2)	Regional IPR Measurement Effectiveness (3)	Percent Total Body IPR by Clock Direction (4)							Percent of Body Region IPR Measured for Each Clock Direction (5) = (2) x (3) x (4)						
			12	11	10	9	3	2	1	12	11	10	9	3	2	1
Head/Face/Neck	60.5	99.9	37.3	3.9	7.3	2.9	2.8	1.5	5.8	22.6	2.4	4.4	1.8	1.7	0.9	3.5
Shoulder/Chest/ Back/Abdomen	26.3	98.4	36.4	6.0	4.6	2.0	0.2	24.5	1.5	9.4	1.6	1.2	0.5	0.05	6.3	0.4
Lower Extremities/ Pelvis	7.6	93.4	50.3	6.0	5.4	22.4	0.3	3.4	3.2	3.6	0.4	0.4	1.6	0.02	0.2	0.2
Upper Extremities	4.7	0.0	22.5	30.9	0.3	0.1	0.1	13.2	11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% IPR Measured by Clock Direction										35.6	4.4	6.0	3.9	1.8	7.4	4.1
% Directional IPR for All Body Regions*										37.3	5.9	6.0	4.3	1.8	8.4	4.7
Directional Effectiveness, %										95.4	74.6	100.0	90.7	100.0	88.1	87.2

HYBRID III

Body Region (1)	% of Total Body IPR (2)	Regional IPR Measurement Effectiveness (3)	Percent Total Body IPR by Clock Direction (4)			Percent of Body Region IPR Measured for each Clock Direction (5) = (2) x (3) x (4)		
			12	11	1	12	11	1
Head/Face/Neck	60.5	63.0	37.3	3.9	5.8	14.2	1.5	2.2
Shoulder/Chest/ Back/Abdomen	26.3	39.0	36.4	6.0	1.5	3.7	0.6	0.2
Lower Extremities/ Pelvis	7.6	59.9	50.3	6.0	3.2	2.3	0.3	0.2
Upper Extremities	4.7	27.1	22.5	30.9	11.5	0.3	0.4	0.2
% IPR Measured by Clock Direction						20.5	2.8	2.8
% Directional IPR for All Body Regions*						37.3	5.9	4.7
Directional Effectiveness, %						55.0	47.5	59.6

TABLE 5-2 (Continued)

SID										
Body Region (1)	% of Total Body IPR (2)	Regional IPR Measurement Effectiveness (3)	Percent Total Body IPR by Clock Direction (4)				Percent of Body Region IPR Measured for each Clock Direction (5) = (2) x (3) x (4)			
			9	10	2†	3	9	10	2†	3
Head/Face/Neck	60.5	35.2	2.9	7.3		2.8	0.6	1.6		0.6
Shoulder/Chest/ Back/Abdomen	26.3	58.4	2.0	4.6		0.2	0.3	0.7		0.03
Lower Extremities/ Pelvis	7.6	18.4	22.4	5.4		0.2	0.3	0.08		0.0
Upper Extremities	4.7	0.0	0.1	0.1		11.5	0.0	0.0		0.0
% IPR Measured by Clock Direction							1.2	2.4		0.6
% Directional IPR for All Body Regions*							4.3	6.0	8.4	1.8
Directional Effectiveness, %							27.9	40.0	0.0	3.3

*From Carsten and O'Day (1984), Table 17.

†SID judged not applicable in this direction.

TABLE 5-3

COMPARISON OF DIRECTIONAL AND OVERALL EFFECTIVENESS FOR AATD VERSUS HYBRID III AND SID

Clock Direction of Force (1)	% Known Horizontal IPR* (2)	Directional Effectiveness Percentage		% Horizontal IPR Measurement Capability	
		AATD (3)	HIII and SID (4)	AATD (5)	HIII and SID (6)
12 O'Clock	53.5	95.4	55.0 (HIII)	51.0	29.4 (HIII)
11 O'Clock	8.5	74.6	47.5 (HIII)	6.3	4.0 (HIII)
10 O'Clock	8.6	100.0	40.0 (SID)	8.6	3.4 (SID)
9 O'Clock	6.2	90.7	27.9 (SID)	5.6	1.7 (SID)
3 O'Clock	2.6	100.0	33.3 (SID)	2.6	0.9 (SID)
2 O'Clock	12.1	88.1		10.7	0.0
1 O'Clock	6.7	87.2	59.6 (HIII)	5.8	4.0 (HIII)
Overall ATD IPR Measurement Effectiveness				90.6	43.4 (HIII & SID)

*Percent of known IPR for horizontal impacts in each direction.

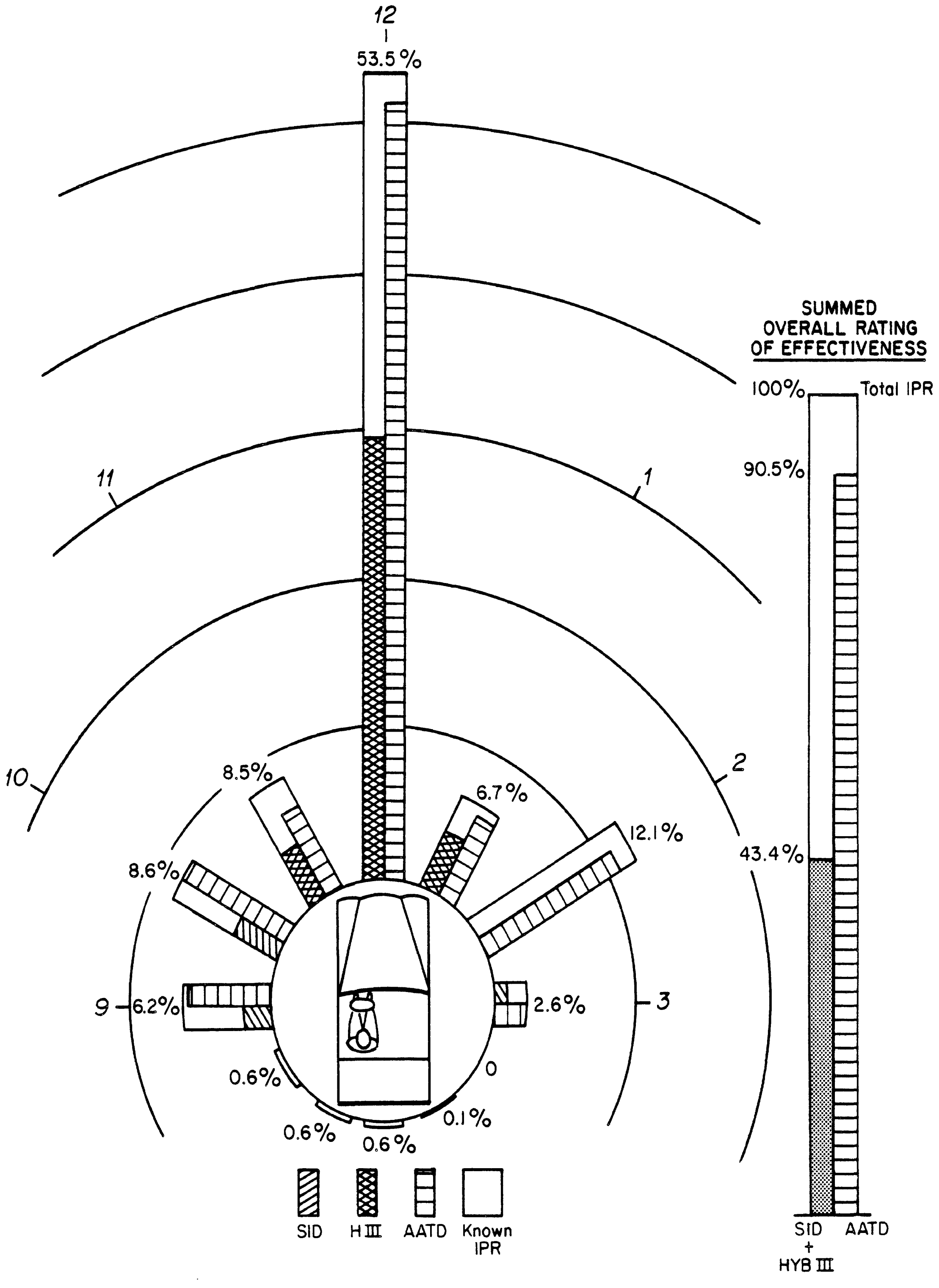

FIGURE 5-2. Estimated effectiveness of Hybrid III, SID, and AATD for unrestrained left-front occupants by principal direction of force. (Percentages denote proportion of horizontal force IPR in each direction.)

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