ASPECT

AUTOMOTIVE SEAT AND PACKAGE EVALUATION AND COMPARISON TOOLS

A Research and Development Program

PROGRAM DOCUMENTATION

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CONTENTS

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PREFACE

The ASPECT program was conducted to develop new Automotive Seat and Package Evaluation and Comparison Tools. The primary goal of ASPECT was to create a new generation of the SAE J826 H-point machine. The new ASPECT manikin has an articulated torso linkage, revised seat contact contours, a new weighting scheme, and a simpler, more user-friendly installation procedure. The ASPECT manikin simultaneously measures the H-point location, seat cushion angle, seatback angle, and lumbar support prominence of a seat, and can be used to make measures of seat stiffness. In addition to the physical manikin, the ASPECT program developed new tools for computer-aided design (CAD) of vehicle interiors. The postures and positions of hundreds of vehicle occupants with a wide range of body size were measured in many different vehicle conditions. Data from these studies were analyzed to develop posture-prediction models that will allow human CAD models to be used accurately for vehicle design. The ASPECT program also produced a CAD representation of the new physical manikin, and high-quality, three-dimensional surface representations of small-female, midsize-male, and large-male drivers. The new tools developed in the ASPECT program represent a major step forward for vehicle and seat design.

The objective in compiling this report is to provide a single resource document for information about the program. Some of the content was previously published at the 1999 SAE International Congress and Exposition as a series of technical papers, but other sections are new material based on work during the last year of the program. Some of the material derived from the SAE papers has been revised to reflect progress in manikin design and usage since the SAE papers were written. Where there are differences between the SAE papers and this report, this more recent material should be referenced.

Chapter 1 gives an overview of the entire ASPECT program, starting with the origins of the program in the SAE Design Devices Committee. The objectives of the program are described, together with the foundational activities conducted during the first year of the program to define the applications, features, and functions of the new tools. Chapter 1 concludes with an overview of the primary ASPECT outcomes, which include a new H-point manikin, an extensive posture database, detailed posture prediction models, a CAD version of the physical manikin, and three-dimensional human body reference forms in CAD.

Chapter 2 describes the design and development of the ASPECT manikin. The evolution of the hardware from the first modifications of the J826 manikin to the final APM-5 prototype are presented. The performance objectives developed from the foundational activities, and their subsequent modification in light of the findings from the human posture studies, are discussed in detail. Finally, the results of validation testing of the APM are presented.

Chapter 3 lays out the application procedures that were developed for use with the new ASPECT manikin and associated CAD tools. Considerable effort in the program went toward ensuring that the new tools would be fully integrated into current and future vehicle design and evaluation methods. The procedures for applying the manikin to design, audit, and benchmarking applications are discussed. This chapter has been updated recently to conform to the decisions of the ASPECT/SAE Pedal Reference Point Task Group.

Chapter 4 discusses the integration of the ASPECT outcomes into the other SAE interior design practices. The new Seating Accommodation Model and Eyellipse recently developed by UMTRI are discussed in the context of the new H-point machine and posture prediction models. This chapter includes a discussion of continued importance of task-oriented percentile models and other population-based tools, even with the development of accurate posture prediction for CAD manikins.

Chapter 5 introduces the vehicle occupant posture studies that comprised the majority of the experimental work in ASPECT. Eight studies were conducted, using hundreds of subjects in dozens of different test conditions. These studies produced a large, detailed database of vehicle occupant postures that was drawn on to develop the ASPECT vehicle occupant posture prediction models. Chapter 5 summarizes the subject pools, test conditions, and experimental methods, along with the primary findings from each study.

Chapter 6 describes the methods developed in ASPECT for measuring and representing vehicle occupant posture. A kinematic model of the human body was selected, and algorithms were developed to estimate internal skeletal joint locations from external body landmarks. This chapter includes calculation diagrams describing the estimation procedures for each joint.

Chapter 7 presents the ASPECT vehicle occupant posture prediction models. These equations, developed from extensive statistical analysis of ASPECT and other UMTRI posture data, allow the accurate prediction of driver or passenger posture in a wide range of vehicle and seat configurations. Developed initially using laboratory data, the models were tuned and validated using actual in-vehicle driver and passenger postures. Chapter 7 includes examples illustrating how the ASPECT posture prediction models can be used to perform accurate ergonomic evaluations of vehicle interiors.

The report concludes with an overall discussion of the program and its outcomes. The scope of applications is described, along with the limitations of the new tools. The need for additional validation and testing, particularly within the industry, is discussed.

This report includes two annexes containing drafts of updated SAE Recommended Practices affected by the ASPECT program. Annex 1 contains a draft of an entirely new SAE J826, specifying the new ASPECT manikin as the SAE H-point machine. Annex 2 presents a draft of a new addition to SAE J1100 containing seat dimensions and revisions to other dimensions necessitated by the ASPECT developments. The Annex content is introduced by Chapter 3, which describes application procedures for the new ASPECT tools.

Many of the references in the text are to the SAE papers published at the 1999 SAE Congress. As noted above, some of the material in those papers has been updated as it has been incorporated into this report. Table 1 lists the corresponding chapters where the updated material may be found.

Table 1
SAE Paper Material and Corresponding Chapters

SAE Paper Number	Title	Corresponding Chapter
1999-01-0962	ASPECT: The Next-Generation H-Point Machine and Related Vehicle and Seat Design and Measurement Tools	Chapter 1
1999-01-0963	Design and Development of the ASPECT Manikin	Chapter 2
1999-01-0965	ASPECT Manikin Applications and Measurements for Designing, Auditing, and Benchmarking	Chapter 3
1999-01-0967	New Concepts in Vehicle Design Using ASPECT	Chapter 4
1999-01-0960	Human Subject Testing in Support of ASPECT	Chapter 5
1999-01-0959	Methods for Measuring and Representing Automobile Occupant Posture	Chapter 6
1999-01-0966	Automobile Occupant Posture Prediction for Use with Human Models	Chapter 7

CHAPTER 1

ASPECT: THE NEXT-GENERATION H-POINT MACHINE AND RELATED VEHICLE AND SEAT DESIGN AND MEASUREMENT TOOLS†

1.0 INTRODUCTION

During the 1950s, vehicle designers were among the first to take advantage of the newly emerging science of engineering anthropometry: the application of the human body measurement and data analysis techniques of physical anthropologists to the problems of designing tools, workspaces, and products. In 1955, Professor Wilfred Dempster of the University of Michigan published a comprehensive study titled "Space Requirements of the Seated Operator," which revolutionized vehicle-interior design (1)*. In the auto industry, S. P. Geoffrey of Ford Motor Company developed a two-dimensional human body template specific to the needs of the vehicle interior designer (2). A 1961 Society of Automotive Engineers (SAE) technical paper documented his methods for using x-rays to identify the locations of the skeletal joints that provide torso and limb range of motions. The result was a two-dimensional, articulated template of the human body used to incorporate anthropometric data into the vehicle design process.

At about the same time, Michael Myal of General Motors constructed a three-dimensional "comfort dimensioning" tool, a weighted manikin with legs and a torso that could be placed in a vehicle seat (3, 4). Because one application of the manikin was to measure legroom, the manikin was based on men who were 90^{th} percentile by stature, and hence likely to have long legs. However, an average seat deflection was sought, so the eight men who were measured to determine the shape of the manikin back and buttock surfaces were selected to be 50^{th}-percentile U.S. male by weight but 90^{th}-percentile U.S. male by stature. A casting made of one of these men sitting on a typical car seat was used to develop the contoured shells for the manikin. Fitted with leg and thigh segment lengths set to 90^{th}-percentile male values, the new tool defined the H-point of a seat and provided measures of leg room based on knee and hip angles.

Beginning in 1962 with the adoption of SAE Recommended Practice J826, these two early tools were modified and standardized through the SAE Design Devices Committee, becoming the SAE 2-D template and the SAE H-point machine. Today, when an

† Portions of this chapter were previously published in SAE Technical Paper 1999-01-0962.
* Numbers in parentheses denote references at the end of the chapter.

automotive human factors engineer measures a vehicle interior, the primary tool used is still the SAE J826 H-point machine (5), which has remained essentially unchanged in design and performance since the late 1960s, when vehicle seats and vehicle interiors were substantially different from today's models. The H-point machine is a weighted manikin named for its most important reference point, which is intended to represent the hip-joint pivot between the thighs and torso of an adult vehicle occupant. It is now normally used with 95^{th}-percentile leg-segment lengths, although the weighting and shell contours remain based on 50^{th}-percentile-male body weight. When the manikin is installed in a vehicle seat within a particular vehicle interior, the location of the H-point and the relative angles between the manikin's thigh, leg, foot, and torso segments provide key measures of the vehicle interior geometry. Many industry design practices and government standards are based on measurements obtained with this tool.

In 1994, Manary et al. (6) compared the J826 H-point location and back angle measures of the H-point manikin to the postures and hip joint locations of male and female drivers in three vehicle seats with different levels of foam stiffness, lumbar support, and seat contouring. The results indicated that the J826 H-point machine produced reasonably consistent representation of human hip joint location across a range of seat styles, although the H-point tended to be rearward of, and lower than, the mean driver hip joint locations. However, the back angle measured by J826 did not vary in a consistent way with human torso posture across these seats. The rigid torso shell of the J826 manikin appeared to be inadequate to provide effective and meaningful measures of occupant seatback interactions, particularly for highly contoured and firm seatbacks.

Manikin users have noted that the J826 manikin may be outdated for current and future seats and vehicles, and that it is used in many applications for which it was not designed or intended (e.g., seat design, seat pressure measurements, measurements of head restraint locations). As a result of these concerns, a task group of the SAE Design Devices Subcommittee met to establish a plan for redesigning the H-point manikin to better meet current and future needs. In response to these task group meetings, researchers from UMTRI's Biosciences Division and the Michigan State University Biomechanical Design Research Laboratory outlined a four-year research and development program, known as ASPECT (Automotive Seat and Package Evaluation and Comparison Tools).

Funds to support the effort were provided by eleven international auto manufacturers and suppliers, including BMW, DaimlerChrysler, Ford, General Motors, Johnson Controls, Lear, Magna, PSA Peugeot-Citroen, Toyota, Volkswagen of America, and Volvo. Representatives of these companies form an Industry Advisory Panel (IAP) that has worked closely with the research team to ensure that the new tools address current and future industry needs and practices. The Society of Automotive Engineers has coordinated the collection and distribution of funds to the university researchers. Now nearing the end of its fourth and final year, the program is completing manikin development and production of an integrated set of new tools that will provide the industry with new, easier to use, and more accurate methods for designing and measuring their products.

This chapter presents an overview of the methods and outcomes of the ASPECT program. Details of human subject testing, manikin development, application procedures, computer tools, posture-prediction models, and other ASPECT outcomes are found in the following chapters (7-13).

2.0 METHODS

2.1 Program Goals

The ASPECT program had two primary goals. The first and foremost objective was to design, develop, and evaluate a new physical manikin and related usage procedures to revise SAE J826. The second objective was to create an extensive vehicle occupant posture database, and to use this database to formulate statistical posture-prediction models for use with CAD tools. Additional objectives and tasks were defined to ensure that the ASPECT outcomes met the needs of industry for an integrated set of tools.

Accomplishing these program goals required the coordination of numerous interrelated and interdependent design, research, and development tasks. A number of foundational tasks were conducted during the first year to establish the scope of the program and to address important issues that would affect the direction of the research. As shown in Figure 1, these activities included:

- conducting surveys of industry manikin users and vehicle package and seat designers to identify current and future manikin applications and manikin design needs and priorities,
- surveying human modeling groups to assess the capabilities of the currently available CAD manikins,
- developing procedures and methodology for describing and measuring occupant posture and position,
- identifying anthropometric, vehicle package, and automotive seat factors that potentially affect occupant posture and positioning,
- establishing an anthropometric basis for manikin size,
- developing criteria and strategies for subject selection and sampling in ASPECT posture research studies,
- establishing and modifying test facilities and associated instrumentation, and
- developing an initial statement of ASPECT manikin design and performance objectives.

Using the results of the foundational activities as a basis, the effort during years two and three of the program was directed primarily toward vehicle occupant posture measurement and manikin design and development. Experimental research to understand driver and passenger posture as a function of body size, vehicle factors, and seat factors, as well as testing to define manikin contours and examine seat interface pressure distributions, was conducted in laboratory vehicle mockups and in actual vehicles. Manikin design and development was carried out simultaneously with development of new manikin usage procedures and new concepts for vehicle design and audit.

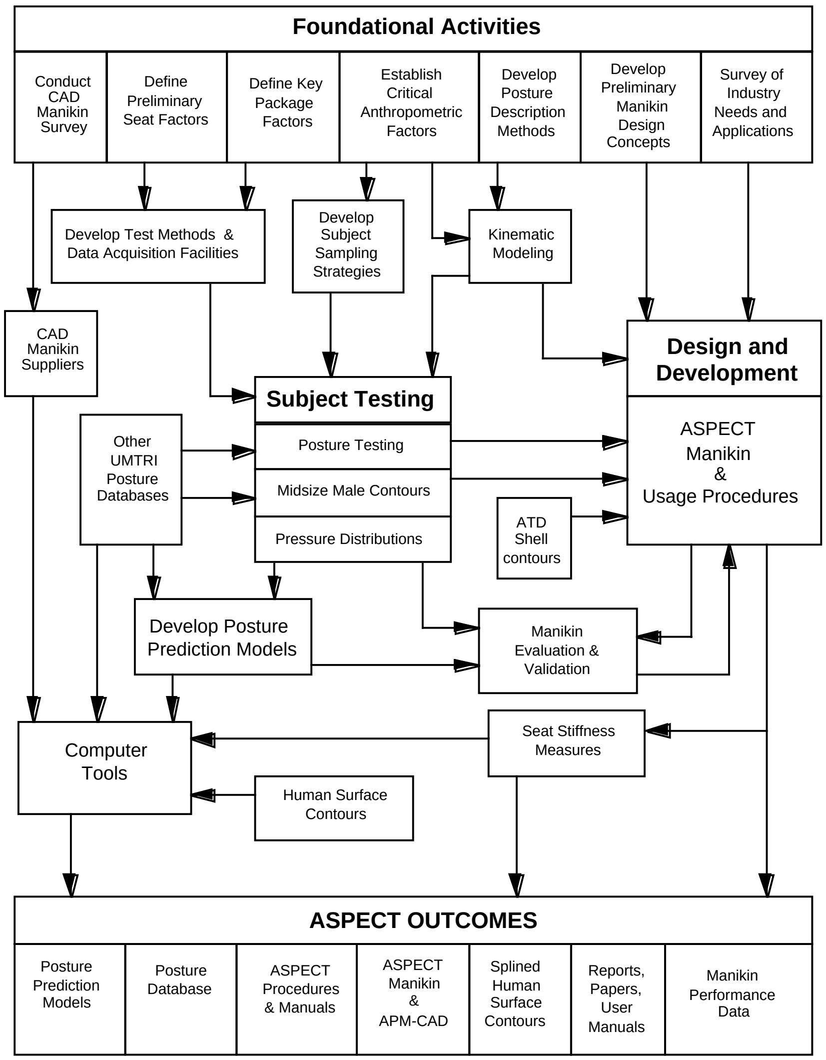

Figure 1. ASPECT program activities and outcomes.

2.2 Foundational Activities

2.2.1 User Surveys

In addition to obtaining industry input from IAP representatives during preprogram meetings, two surveys were taken of manikin users within the IAP companies to identify and prioritize current and future applications of the physical manikin, and to identify problems that the new manikin and procedures should be targeted to resolve. These surveys confirmed that the first and foremost application of the manikin is to *define and measure vehicle reference points* that are functions of both interior package geometry and vehicle seat features. These measurements are made for *auditing* of a manufacturer's own vehicles to verify seat and vehicle build accuracy relative to design specifications, as well as for *benchmarking* of competitor vehicles, for which package dimensions and seat characteristics are unknown.

The second and increasingly important use of the manikin is for *designing* vehicles and seats for user accommodation and comfort. In large part, this is accomplished through the use of manikin reference points and to assess and design vehicle geometry. Dimensions measured relative to the design H-point or SgRP are used in population accommodation models such as the seating accommodation model of SAE J1517 and the eyellipse model of SAE J941. However, the dimensions of the physical manikin are sometimes used to guide the design of seat features, such as spacing of cushion bolsters and seatback wings, and the pressure distributions produced by the manikin are sometimes used as a basis for seat comfort assessment. These and other potential uses of the manikin were considered, along with the primary applications, in the development of the new tools.

The user surveys revealed three principal areas for manikin improvement based on current problems and experience with the J826 manikin. These include improving manikin *ease of use*, *repeatability and stability*, and *accuracy*. When used in modern seats with contoured, firm seatbacks, the rigid torso of the J826 manikin is unstable, making it difficult to obtain consistent measurements. The current manikin is relatively heavy to lift and position into a vehicle seat, and the leg and shoe segments are cumbersome and hard to install. The accuracy of the manikin with respect to human posture and position was also of concern, primarily because of the way the rigid torso interacts with seatbacks.

The user surveys also documented the use of the J826 manikin for purposes that have not been standardized in SAE recommended practices. In particular, add-on devices have been developed for head restraint measurement (14) and seatbelt fit assessment (15). These applications of the current H-point manikin were considered during the development of the new tool.

2.2.2 CAD Manikin Survey

One of the initial goals of the program was to identify developers of human models who could implement the products of ASPECT in versions of their software adapted for automotive applications. A survey of state-of-the-art computer human models identified RAMSIS, SafeWork, MDHMS, Jack, and JOHN as the models with potential to incorporate the products of the ASPECT program in CAD tools for the automotive environment. Of these, only the RAMSIS model, published by TecMath, had been developed specifically for the auto industry, using posture, position, and anthropometric data collected in the automotive environment. For this reason, representatives from TecMath were invited by the IAP to participate in the ASPECT program during the second program year. In the third year of the program, representatives of Transom Jack and Safework were also invited to participate and to implement the ASPECT products into their models.

2.2.3 Identification of Anthropometric, Package, and Seat Factors

As illustrated in Figure 2, occupant posture and position in a motor vehicle are influenced by a number of important anthropometric, vehicle, and seat factors. In addition, for drivers, there are operator tasks, such as using the pedals, steering, and seeing inside and outside of the vehicle, that have important influences on posture and position in the context of the package geometry. As part of the initial ASPECT activities, these critical factors were identified and defined to aid in the design of experiments for posture studies. The results of ASPECT subject testing, combined with findings from previous posture studies, were then used to establish statistically based posture-prediction models for positioning CAD manikins in motor vehicle environments, and to guide the design and performance of the new manikin.

2.2.4 Posture Description and Measurement

New methods for measuring and describing occupant posture and position were developed. Body landmark locations were recorded using coordinate measurement equipment. These landmark locations were used to estimate body joint locations, using techniques developed for ASPECT (8). These methods provide a consistent method to quantify subject postures and to apply posture data to physical and computer versions of the ASPECT manikin, or to whole-body CAD manikins (10). Figure 3 shows the kinematic linkage and angles of body segments used to represent human body posture in the ASPECT program

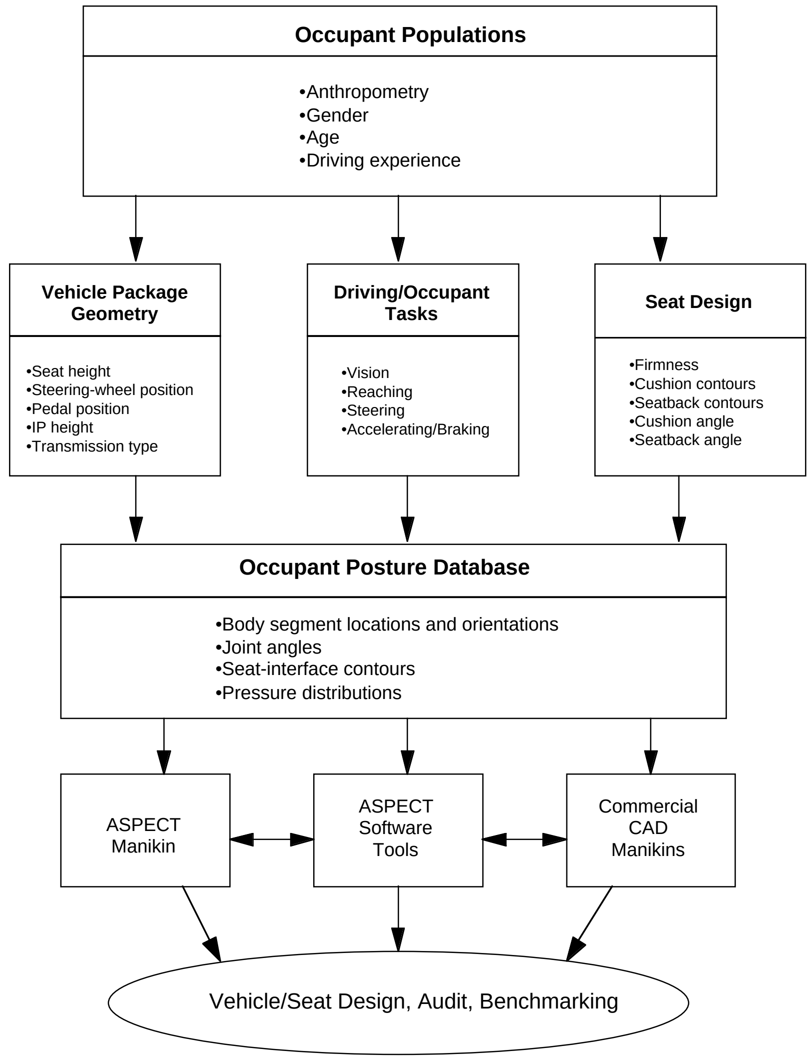

Figure 2. Hypothesized relationships between anthropometric, vehicle interior package, seat, and task factors on occupant posture for use in developing physical and computer design and measurement tools.

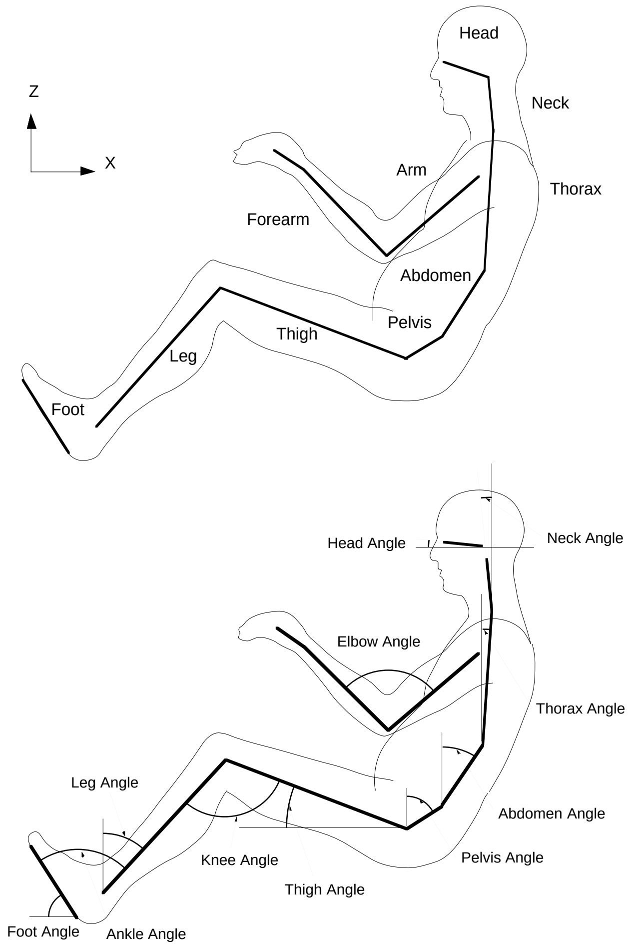

Figure 3. Kinematic model used to represent vehicle occupant posture showing body segment (left) and segment angles (right).

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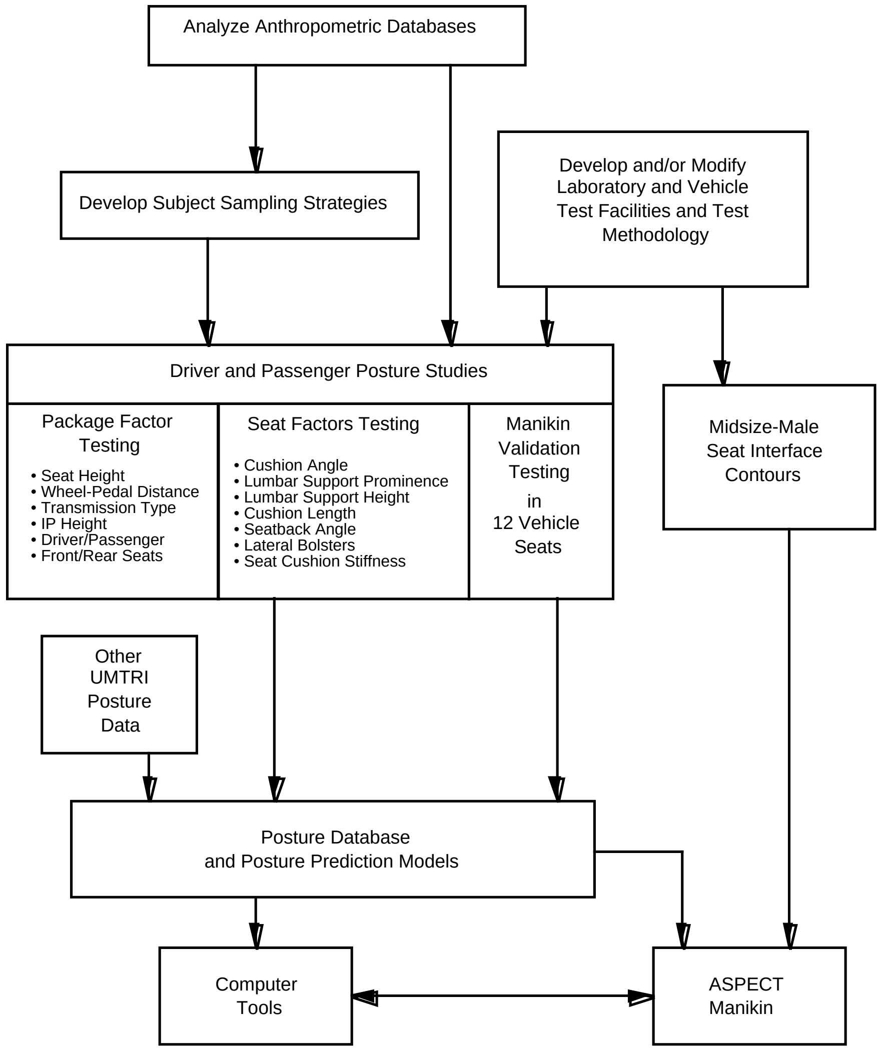

Figure 4. Scope and information flow in ASPECT subject testing.

2.2 Data Collection

During the ASPECT program, the postures of hundreds of men and women with a wide range of body size were measured in dozens of vehicle and seat conditions. Testing was conducted both in vehicles and in laboratory vehicle mockups. Figure 4 illustrates the scope of subject testing. The experiments were designed to determine the effects of anthropometric, vehicle, and seat factors on driver and passenger posture. Seven different posture studies were conducted over the course of the program. The subjects' postures were measured by recording the three-dimensional locations of body landmarks using a sonic digitizing system or FARO arm, as shown in Figures 5 and 6. Details of the posture studies are presented in Manary et al. (12). In addition to posture testing, the seat interface contours of midsize men were measured to develop new contours for the ASPECT manikin (13).

Figure 5. Digitizing a subject’s body landmarks using a FARO arm.

Figure 6. Digitizing a subject’s body landmarks using a sonic digitizer

2.3 ASPECT Manikin Development

Many of the ASPECT tasks were focused on the primary objective of developing a new physical manikin to replace the J826 H-point manikin. The program also provided the opportunity to take a fresh look at the procedures by which the manikin is used for seat and vehicle design and measurement. Early in the first year of the program, a set of questions were put forth with regard to manikin design features, including the following:

- How many manikins are needed?
- What size people should the manikin represent?
- Should the manikin have a fixed or articulating torso?
- Should there be articulations between the pelvis and the thighs?

- What should the manikin measure for different applications, and what are its performance specifications?
- If an articulating torso is used, how many articulations and where should they be located?
- Does the manikin need to have legs and feet?
- Should the manikin provide for leg and thigh splay?
- Should the manikin have arms and hands? Neck and head?
- Should the manikin shells be rigid or deformable?
- Should the manikin respond to both seat and package factors?

Answers to some of these questions were established during the first year of the program, but answers to other questions required considerably more exploration and evaluation of prototype manikins using an iterative process illustrated in Figure 7.

Starting with modifications to the J826 manikin, several versions of the ASPECT manikin were developed and tested. The term APM has been used to refer to the ASPECT physical manikin and subsequent prototypes have been numbered sequentially as APM-1, APM-2, etc. In successive versions of the manikin, design features and modifications were implemented, tested, and evaluated as performance results of a previous iteration suggested and as design concepts evolved. Modifications were made to manikin linkages, contours, and mass distribution to improve manikin stability in seats with highly contoured seatbacks and to improve sensitivity to lumbar support prominence across a range of seat types. Thigh splay was implemented in one version of the manikin prototype design, but was subsequently dropped because it added complexity that is not needed for primary manikin measurements. Details of the manikin design and development are provided in Reed et al. (7).

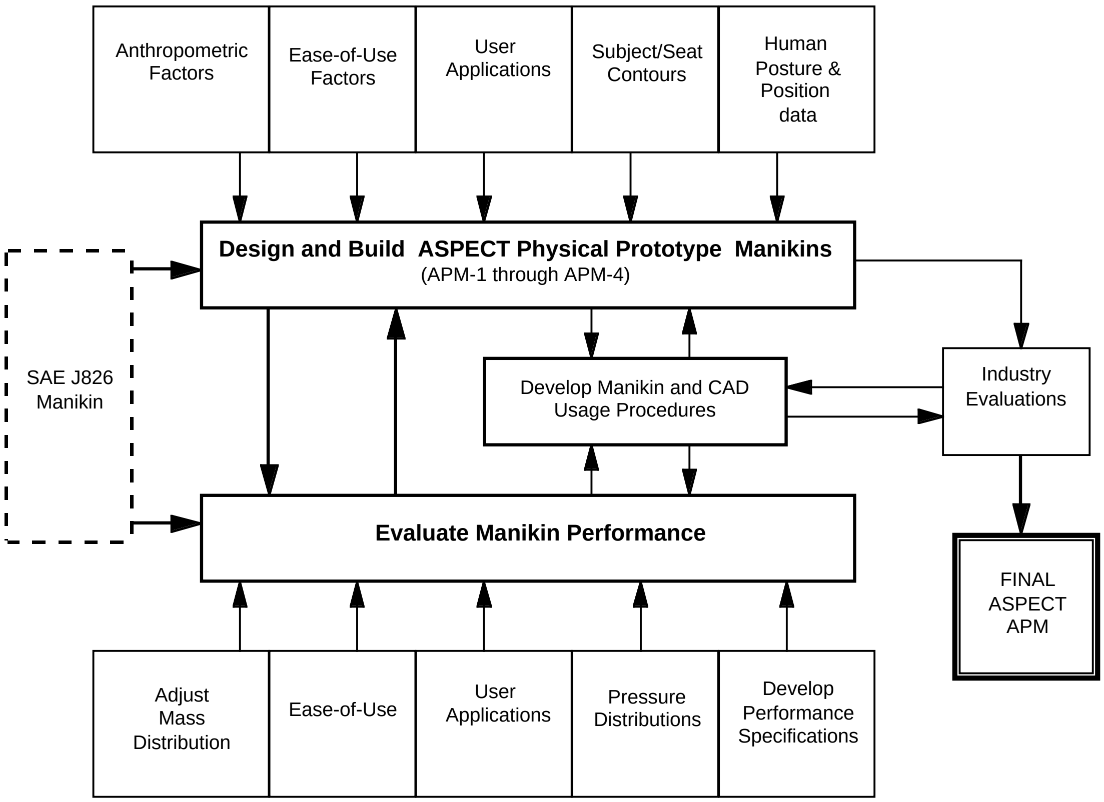

Figure 7. Iterative process of manikin design, development, and evaluation.

3.0 RESULTS

The ASPECT program produced an integrated set of new tools for vehicle and seat design and measurement. Table 1 lists the tools and some of their features and functions. The primary ASPECT development is a new physical manikin intended to replace the SAE J826 H-point machine. A CAD version of the manikin has been developed for use in design. New posture-prediction models have been developed to facilitate the accurate use of CAD manikins in vehicle and seat design. In addition, three human body reference forms, representing the three-dimensional body surfaces of small-female, midsize-male, and large-male occupants, were developed for use in CAD.

3.1 ASPECT Physical Manikin (APM) and Usage Procedures

3.1.1 Manikin Design Features

The new ASPECT manikin represents an evolution of the J826 manikin, preserving much of the functionality of the old manikin while adding additional features and measurement capability. Figure 8 shows the ASPECT manikin along with the current J826 manikin. The most important difference between the tools is the new articulating torso in the ASPECT manikin. Figure 9 shows the torso linkage, which includes two joints that simulate human lumbar spine motion. A torso rod stabilizes the manikin and provides continuity with the current manikin torso line.

Table 1
New Tools Developed in the ASPECT Program

Tool	Function	Key Features
ASPECT Physical Manikin (APM)	Define and Measure Seat and Package Characteristics	Articulated Torso New Contours New Procedures
APM-CAD	Represent APM in CAD for use in design	Essential Geometry of APM as a 3-D CAD File
ASPECT Posture Prediction Models	Predict Posture for Any Vehicle Occupant	Anthropometric, Seat, and Package Factor Inputs Emphasis on Accuracy in Eye and Hip Locations Applicable to any CAD Manikin Software
Human Body Reference Forms (Small Female, Midsize Male, Large Male)	Standardized, Three-Dimensional Body Surface Contours for Vehicle Occupants	Three Sizes Spanning a Large Range of the Population High-Quality Parametric Surfaces (NURBS) in CAD Files

Figure 8. Current SAE J826 manikin (left) and new ASPECT manikin prototype (right).

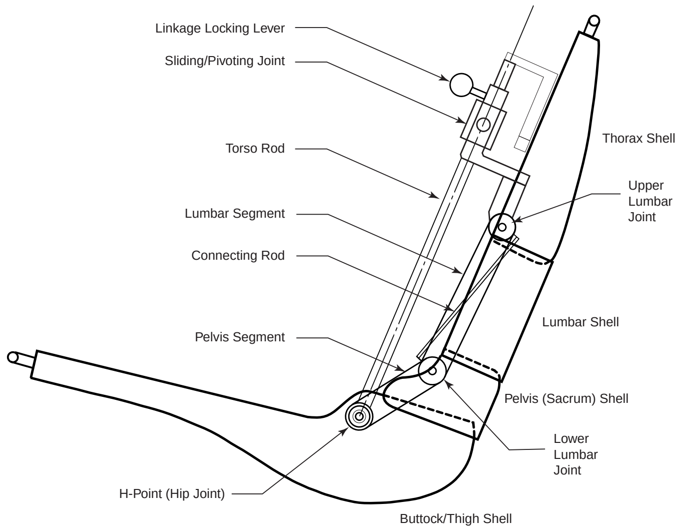

Figure 9. Schematic of ASPECT manikin showing articulated torso linkage.

A connecting rod in the lumbar linkage distributes flexion motion between the two lumbar joints. The torso shell is comprised of separate thorax, lumbar, and sacral sections, each connected to a corresponding segment in the torso linkage. Figure 10 demonstrates the variation in torso contour provided by the linkage. The dimensions of the ASPECT manikin were determined after specifying a set of reference anthropometric dimensions. Because the purposes of the manikin would be best served by a manikin that was approximately the same dimensions as the current J826 manikin and the midsize-male crash dummy, ASPECT manikin dimensions were chosen to be representative of midsize U.S. males (7).

The external shell sections of the ASPECT manikin are constructed of molded fiberglass, like the shells of the J826 manikin. Shells made of deformable materials were considered, but were ultimately rejected because of manufacturing, weight, and durability concerns. The shells are designed to represent the typical deflected flesh contour of a midsize male. The buttock and thigh contours were developed from data collected for ASPECT (13), while the torso contours were developed using data collected in earlier research to develop anthropometric standards for crash dummies (16, 17). The total weight of the manikin was determined by subtracting a typical resting heel weight from the target weight defined by the reference anthropometry (7).

3.1.2 Independent Seat and Package Measures

The current J826 H-point manikin, shown at the top of Figure 8, takes simultaneous measures of the vehicle seat and the vehicle interior geometry. When the manikin is installed with the legs and feet according to standard practice, the H-point location in the seat may be influenced by the seat height and fore-aft seat position via the orientation of the thigh and leg segments. In practice, this has meant that any change in the package geometry requires redefinition and remeasurement of the H-point location. Using the primary application procedures, the ASPECT manikin is installed in the seat without leg segments, so that it contacts only the seat. The H-point and other seat measures, such as lumbar-support prominence, are thus independent of the seat position in the vehicle, and do not need to be redefined or remeasured if the seat is moved during the design process.

The ASPECT manikin makes four primary measures of the seat: H-point location, seat cushion angle, seatback angle (i.e., manikin back angle), and lumbar support prominence, shown in Figure 11. Lumbar support prominence is measured by the displacement of the manikin lumbar segment relative to a neutral, flat-back condition. Typical lumbar-support prominences in auto seats range from –10 to +20 mm of lumbar support, measured in this manner. The ASPECT manikin is the first measurement tool to provide a quantitative measure of effective lumbar support that is closely related to the seatback contour experienced by occupants.

The ASPECT manikin can also be used with supplemental thigh, leg, and shoe segments to measure the vehicle package geometry. Figure 12 shows these segments and associated tools schematically and Figure 13 shows the leg and thigh segments installed on the ASPECT manikin. The thigh and leg segments are constructed of lightweight materials so that installing them does not change the H-point location or other measures of the seat. In conjunction with the ASPECT program, proposals have been developed for a new pedal reference point (PRP) that can be defined independent of the manikin (11).

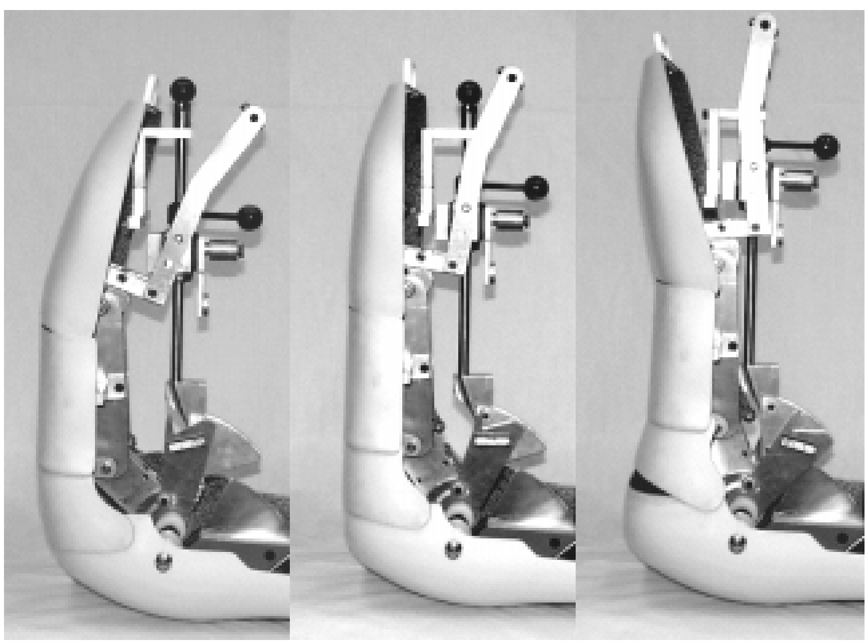

Figure 10. Side view of ASPECT manikin prototype showing torso articulation.

In addition, new techniques for orienting the manikin shoe relative to the accelerator pedal in more humanlike positions have been developed. Using these new procedures, the supplemental thigh, leg, and shoe tools can be added to the ASPECT manikin installation to measure package dimensions in driver or passenger seating positions. Detailed procedures for using the ASPECT manikin in design, audit, and benchmarking applications are presented in Roe et al. (9).

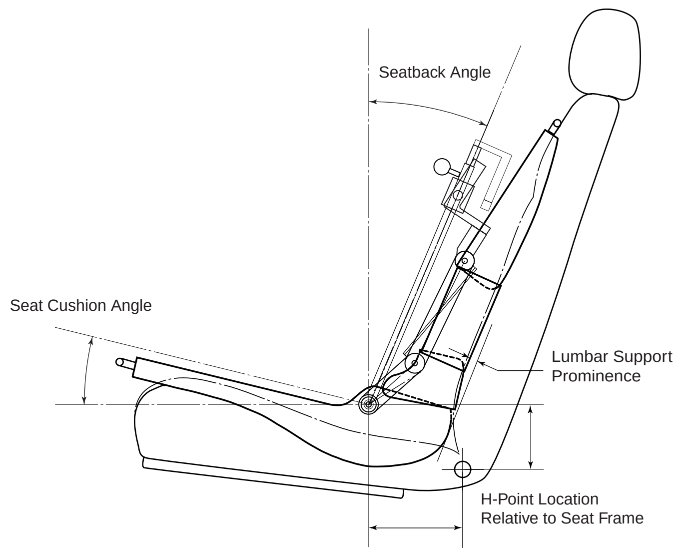

Figure 11. Primary ASPECT manikin measures of the seat.

3.2 APM-CAD

In current design practice, the SAE J826 manikin, or the two-dimensional template based in part on the J826 manikin geometry, are commonly represented in CAD to facilitate vehicle packaging. The orientations of the manikin segments are used to assess the package geometry, and clearances to vehicle components are measured relative to the template contours. To provide continuity with current practice, a CAD version of the ASPECT physical manikin (APM-CAD) was developed. APM-CAD includes the essential geometry of the manikin, including the external shell contours, the linkage geometry, and the thigh, leg, and shoe segments.

3.3 ASPECT Posture Prediction

Along with the manikin development, a primary goal of the ASPECT program was to develop data and models to facilitate the use of CAD manikins. Software tools that depict human occupants have become an increasingly important part of vehicle and seat design processes. Industry surveys conducted early in the ASPECT program demonstrated that although the currently available CAD manikins have sophisticated capabilities for anthropometric scaling, only RAMSIS has posture prediction capability specifically validated for vehicle occupants. There is a clear need for a comprehensive, systematically constructed database of occupant posture data that can be applied to any CAD manikin

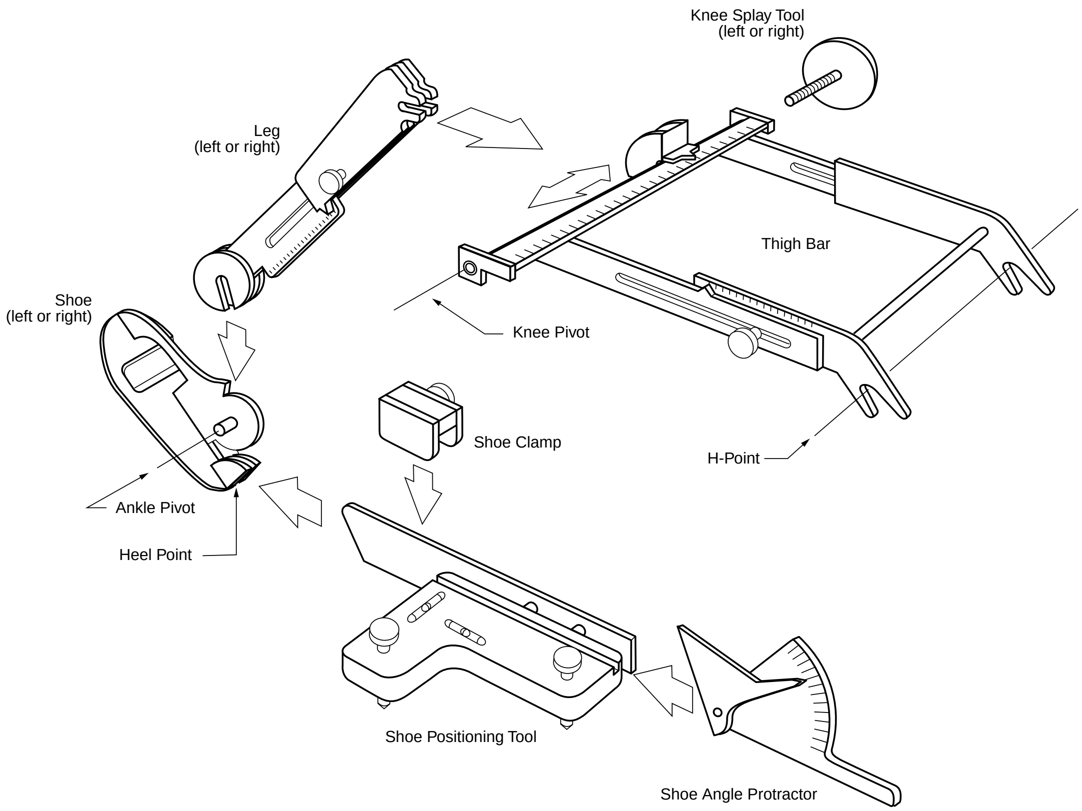

Figure 12. Illustration of supplemental thigh, leg, and shoe tools.

Figure 13. ASPECT manikin with thigh and leg segments installed between H-point and shoe tool.

The extensive posture database gathered in ASPECT studies was analyzed together with other UMTRI data to create a set of posture-prediction models. A new approach to posture prediction was developed, called the Cascade Prediction Model (CPM). The CPM emphasizes accurate prediction of hip and eye locations, since these body landmarks are usually the most important for conducting accurate assessments of vehicle interior geometry. A "cascade" of submodels, using inverse kinematics combined with heuristics based on the findings from the posture data analysis, creates a three-dimensional prediction of whole-body posture for drivers or passengers. Inputs to the models include anthropometric variables, such as gender and stature; vehicle package variables, such as seat height and steering wheel position; and seat characteristics, such as seat cushion angle and lumbar support prominence. Details of the development and validation of the ASPECT posture prediction models are presented in Reed et al. (10). The developers of the RAMSIS, Transom Jack, and SafeWork CAD manikins have joined the ASPECT program to implement ASPECT posture prediction models in their software. These new tools will allow accurate placement of CAD manikins within a design, providing more accurate fit, vision, and reach assessments.

3.4 Human Body Reference Forms

In current design practice, there are no standard three-dimensional representations of the human body other than the SAE J826 manikin and the crash dummies. The SAE J826 manikin does not include a full three-dimensional body surface, and crash dummies have been designed primarily for dynamic performance, not for the representational accuracy of their external geometry.

Although collecting new whole-body contour data was beyond the scope of the ASPECT program, whole-body contours were available that were based on detailed anthropometric measurements. In a previous study at UMTRI, three standard reference shells, shown in Figure 14, were developed to form the basis for future crash dummy anthropometry (16, 17). Digitized versions of these shells were manipulated using a commercial software package (Imageware Surfacer) to produce parametric splined surfaces (NURBS) that can be used in many CAD programs. The midsize-male body reference form is shown with the ASPECT manikin in Figure 15.

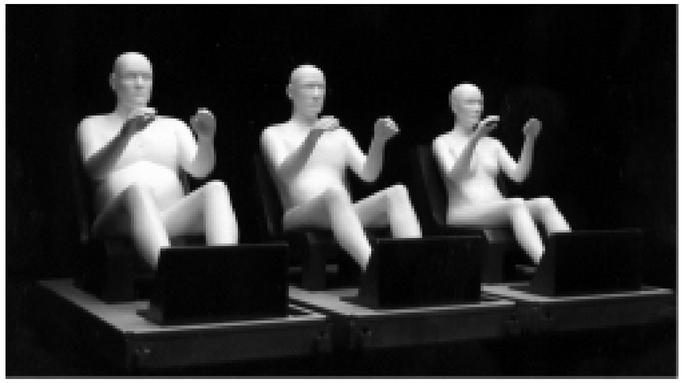

Figure 14. Large-male, midsize-male, and small-female standard reference shells developed for crash dummy anthropometry.

Figure 15. Midsize-male reference form and ASPECT manikin images overlaid.

There are a number of potential uses for these three-dimensional representations in vehicle design. The reference forms can be used to visualize vehicle occupants of different sizes in a vehicle package, and provide a way of ensuring consistency in body contour among CAD manikins. The standardized body surfaces could also function as three-dimensional tools for conducting some of the analyses that are currently performed using the two-dimensional SAE J826 template. Details of the development and use of the human body reference forms in vehicle design are presented in Reed et al. (11).

4.0 DISCUSSION AND CONCLUSIONS

At the conclusion of the ASPECT program in September 1999, the industry will have a new set of tools for vehicle and seat design and assessment. The program has produced a new, easier-to-use, physical manikin designed to function better in current vehicle seats and to measure important seat characteristics. The new manikin measures H-point and other important seat factors without interacting with package geometry, and has an articulated torso that provides for improved measures of seatback geometry. To measure a vehicle package, lightweight thigh, leg, and shoe segments can be installed without affecting the H-point location.

The ASPECT program has also established new procedures by which the manikin is used and has proposed new concepts for integrating the manikin with CAD tools in designing and evaluating vehicle and seat designs. A substantial amount of new data on driver and passenger posture and position were collected in the program. These data have been analyzed, along with data from other studies, to develop posture-prediction models that establish accurate driver and passenger postures for a wide range of occupant sizes and vehicle environments.

Considerable work remains to implement the products of ASPECT as accepted industry standards. The ASPECT researchers will work with the SAE Human Accommodation and Design Devices Committee to turn the detailed specifications of the new manikin and associated procedures into new SAE recommended practices. Because the H-point manikin defines reference points that are used in many other SAE practices, which are in turn referenced by national and international safety standards, implementation of ASPECT program results will also involve working with federal and international organizations such as NHTSA and ISO.

Although the ASPECT program is a large step forward in vehicle-interior design methods, there are many issues that remain to be addressed in future research. The manikin and the associated posture-prediction models were developed using primarily passenger car conditions, but the manikin must ultimately be applicable to the design of heavy-duty trucks and buses, as well as off-road equipment. Additional studies will be necessary to validate the manikin for those applications and to extend the posture prediction models to those environments.

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CHAPTER 2

DESIGN AND DEVELOPMENT OF THE ASPECT MANIKIN[†]

1.0 INTRODUCTION

The current standard tool for measuring vehicle seats is the SAE J826 H-point manikin (1).[*] The H-point manikin was developed in the early 1960s in response to the need for a three-dimensional tool to represent vehicle occupants in the design process (2). Although the H-point manikin has been used successfully for over 30 years, the limitations of the H-point manikin in modern seats and vehicles and in the contemporary computerized design environment pointed to a need for a new manikin. This chapter presents an overview of the ASPECT manikin, a new tool for vehicle and seat design and evaluation that builds evolutionarily on the success of the original H-point manikin. Figure 1 shows the SAE J826 manikin and the new ASPECT manikin. Among other features, the ASPECT manikin has a three-piece articulated torso, a single supplemental leg, a lightweight thigh segment separate from the weighted buttock/thigh pan, a revised mass distribution, new seat interface contours, and a new, less-complicated installation procedure.

1.1 History of the H-Point Manikin

In 1955, Professor Wilfred Dempster of the University of Michigan conducted an in-depth study of skeletal kinematics to develop a three-dimensional kinematic linkage representing the seated operator (3). Dempster was on the forefront of the emerging science of engineering anthropometry, seeking to apply the human body measurement and data analysis procedures of physical anthropologists to the problem of workspace and equipment design. The new methods originally developed for military applications were rapidly adopted by the auto industry. Geoffrey of Ford Motor Company conducted a series of radiographic experiments to create a two-dimensional template describing a seated automobile occupant (4). In the late 1950s, Myal of General Motors completed the first prototype of a “comfort dimensioning manikin,” a three-dimensional, weighted representation of an automobile driver (2, 5). The manikin was intended to provide three measures of the vehicle interior geometry that were previously unavailable. First, the manikin included a reference point at the hip, known as the H-point. When the manikin was installed in a seat and weighted, the location of the H-point provided a more useful predictor of occupant position than seat reference points on the undeflected contour.

[†] Portions of this chapter were previously published in SAE Technical Paper 1999-01-0963.

[*] Numbers in parentheses denote references at the end of the chapter.

Second, the manikin torso was also weighted so that it deflected the seatback in a manner similar to the deflection produced by human occupants, providing an improved measure of seatback angle. Finally, the angles at the manikin's hip and knee joints provided a measure of legroom.

Figure 1a. SAE J826 H-point manikin.

Figure 1b. ASPECT manikin prototype.

To obtain a typical seat deflection, a median male weight of 170 lbs (77.3 kg) was selected, based on available civilian and military data (2). However, because a measure of legroom was also desired, the reference stature for the manikin was established at 5’11” (1803 mm), approximately the 90th percentile for male drivers at the time. The external contours in the seat contact areas were developed from the seat interface contours of eight men who were approximately 5’11” tall and 170 lb (1803 mm, 77.3 kg). One subject’s contour that was deemed to be most representative of the group was selected as the basis for the manikin contour. A contemporary examination of the contours suggests that some additional modifications were made, perhaps to improve manikin performance or because of manufacturing considerations. No record of these modifications is available, however.

In 1962, the SAE Design Devices Committee adopted SAE Recommended Practice J826, describing a weighted three-dimensional manikin with contoured shells. The new H-point manikin used the GM external surface shells, but modified the linkage geometry using input from Geoffrey and others. By 1968, J826 had been amended to specify use of longer leg and thigh segments identified as 95th percentile. A review of the calculations used to develop the longer leg and thigh segments suggests that the 90th-percentile segments developed by Geoffrey were adjusted by scaling the external buttock-to-knee and knee-to-heel dimensions to match 95th-percentile male values from the 1963 U.S. HES data (4, 6). The result is a total functional leg length (thigh plus leg plus foot) that is longer than the 95th percentile for male drivers of that time.

Since the original development of the H-point manikin, there have been a number of efforts to modify the manikin. Kohara and Sugi (7) created an articulated manikin torso intended to replicate human lumbar spine motion. Muscle tension was replicated using springs in the manikin torso. Thier (8) placed sensors in the manikin shells to record seat interface pressures. Unpublished modifications have included modified torso shells with lordotic spine curvature. Another adaptation of the manikin was recently included in SAE J826. The manikin is installed in a seat without legs, using a modified weight distribution, to measure the seat cushion angle (1).

The H-point manikin has been adapted for other uses beyond its original intent, largely because of its status as the most widely used physical representation of a vehicle occupant. SAE J1100 contains dozens of dimensions measured relative to the manikin, including measures of hip room, leg room, and headroom. International groups, including ISO, have incorporated the H-point manikin into standards. The H-point manikin has been used as a platform for other measurement devices, including a belt-fit test device (9) and a tool for measuring head restraint location (10). The U.S. Federal Motor Vehicle Safety Standards use the H-point manikin with modified leg lengths to establish reference points for positioning crash test dummies (11). Recently, a version of the H-point manikin with contours, segment lengths, and mass equivalent to the small female Hybrid-III crash dummy was created to facilitate crash testing (12).

While the widespread use of the H-point manikin testifies to the many potential applications for a physical representation of a vehicle occupant, the limitations of the current tool led human factors practitioners in the automotive industry to call for improvements. In the early 1990s, UMTRI researchers conducted a study comparing the H-point manikin measures of posture and position to data from human subjects in three vehicle seats (13). The SAE J826 H-point was found to be consistently located in the test seats relative to the human hip joint locations, but the manikin measure of seatback angle did not accurately represent human torso posture.

1.2 The ASPECT Program

In 1993, the SAE Design Devices Committee, which has jurisdiction over the H-point manikin, convened a task group to consider improvements to the manikin. Representatives from auto manufacturers, seat suppliers, and universities determined that a research and development plan focused on the development of a new manikin was needed. Researchers from the Biosciences Division of the University of Michigan Transportation Research Institute and the Biomechanical Design Laboratory of the Michigan State University College of Engineering drafted a program description, laying out a four-year effort that would culminate in a new set of vehicle and seat design tools, including a revised H-point manikin. Eleven automotive industry companies participated via yearly contributions coordinated through SAE's Cooperative Research Program. The research and development activities were conducted by the two university research labs, with industry consultation and coordination through an Industry Advisory Panel comprised of representatives from the funding companies. Work on the program began in July 1994 was completed by the end of September 1999.

The research program was called ASPECT, an acronym for Automotive Seat and Package Evaluation and Comparison Tools. The program objectives included the development of a new manikin and new statistical tools for predicting occupant posture and position (14-20). This chapter focuses on a description of the new ASPECT manikin, a tool for seat and vehicle measurement intended to replace the current H-point manikin. Figure 2 shows the latest ASPECT manikin prototype, designated APM-4 for the fourth major prototype of the ASPECT physical manikin. The final version of the manikin adopted by the SAE Design Devices Committee is expected to be slightly different, including changes in response to industry feedback regarding performance and ease of use. The final manikin specifications will be documented in SAE technical papers and recommended practices.

Figure 2. ASPECT manikin prototype (APM-4), shown with supplemental thigh and leg components.

2.0 METHODS AND MANIKIN SPECIFICATIONS

2.1 Industry Input

Early in the ASPECT program, the research team led a systematic effort to obtain input from the industry regarding the uses of the current H-point manikin and the needs for the future. Two written surveys were conducted, each completed by representatives of all eleven IAP companies. The survey findings were supplemented by information from on-site visits with participating companies, during which current uses of the H-point manikin were demonstrated and the limitations discussed.

In discussions with industry representatives, three limitations of the current H-point manikin were most frequently mentioned as opportunities for improvement.

2.1.1 Ease of Use

The current manikin was often described as difficult to use, particularly in rear seats. The manikin itself, without the legs or additional weights, weighs over 40 lbs (18 kg) and is difficult to maneuver inside a vehicle. The attachment between the legs and the thigh section (T-bar) is cumbersome, and the installation procedure requires various rocking and pushing steps that are difficult to perform consistently.

2.1.2 Stability in Seats with Prominent Lumbar Supports

The current manikin has a one-piece, rigid torso shell that does not conform to the seatback. When installed in a seat with a prominent lumbar support, the torso tends to pivot around the apex of the lumbar support, resulting in unstable readings. Some of the seat suppliers participating in the program indicated that their seatback designs were restricted by a need to obtain stable H-point readings with the rigid-torso H-point manikin.

2.1.3 Biofidelity

Industry participants were concerned that the H-point manikin, because of the anthropometry used in its definition and the lack of articulation in the lumbar spine, does not suitably represent a modern vehicle occupant, particularly with regard to torso posture and hip location. A study at UMTRI (13) had indicated that the H-point location was fairly consistent with human hip joint locations across three seats, but that the manikin torso did not accurately or consistently represent human torso interactions with seats.

Another issue that had been raised repeatedly in meetings of the SAE Design Devices Committee and other automotive human factors groups was the undesirable linkage between seat and package measures in the current J826 manikin. Because the standard procedures for measuring H-point location and seatback angle with the J826 manikin require use of the legs and shoes, the resulting measures represent some combination of the effects of the seat and the package geometry. Further, the accelerator heel point (AHP) and ball of foot (BOF) reference points are defined by the position and orientation of the manikin shoe when the manikin is installed in such a way that the manikin H-point is at the driver seating reference point (SgRP). Any change in the SgRP location, therefore, changes the pedal reference point locations, which in turn affects driver accommodation models.

One of the goals for the new manikin design was to separate the influences of the seat and package on occupant posture. The ASPECT manikin was designed to be primarily a seat measurement tool, able to be applied without interaction with the rest of the vehicle interior. ASPECT manikin H-point locations, for example, are independent of seat height or any other package-related influence. To provide continuity with current practice, supplemental leg, thigh, and shoe components are provided to facilitate package-related measures, such as hip angle and knee angle.

2.2 Manikin Applications

Input from industry representatives led to the identification of three broad application categories for the new manikin. These applications guided the development of the manikin functions and features.

2.2.1 Defining and Measuring Reference Points

The foremost function of the new ASPECT manikin, like the current H-point manikin, is the definition and measurement of a reference point (H-point) that provides a human-centered reference relative to the vehicle seat from which accommodation-related measurements can be made. The new manikin preserves the H-point as a representation of the hip joint location of the vehicle occupant. The original objective in locating the reference point on the new manikin and in prescribing the manikin performance was to obtain the best possible match between the manikin H-point and the average hip joint center location of males who are the same stature and weight as the manikin. However, as noted below, the findings from extensive posture data analysis resulted in a change in the manikin performance objectives to provide more continuity with current practice and to improve the manikin's usefulness as a seat measurement tool.

The J826 manikin is also used to define the accelerator heel point (AHP) and ball of foot (BOF), two reference points used to define the pedal and floor locations. The new manikin includes a supplementary shoe segment that can be used to define and measure a pedal reference point (PRP), a ball of shoe point (BOS), and an accelerator heel point (AHP). Details of the use of these supplemental segments to measure package related reference points and dimensions are published elsewhere (17).

2.2.2 Design of Vehicle Interiors for Accommodation and Comfort (Occupant Packaging)

Vehicle interior design applications of the manikin differ from the primary application (definition and measurement of reference points) in several important ways. The definition and measurement of the H-point are not directly useful in designing a vehicle interior. Rather, the H-point provides a human-centered reference from which measurements can be made and to which other prediction tools can be anchored. The ASPECT program encompasses both a new definition of the reference point and new use of the reference point to define interior vehicle measurements and to anchor posture-prediction tools.

For purposes of the ASPECT program, vehicle design for accommodation includes two general task categories: defining and using vehicle measurements, and predicting occupant posture and position. A clear and consistent set of definitions for vehicle interior dimensions is critical, since these measures are inputs to the models and practices used to design vehicle interiors for accommodation (e.g., SAE J1517 and J941). The manikin is used to define and measure a reference point (H-point). The H-point, in combination with other vehicle interior landmarks, is used to define measures such as seat height. Seat height is then used, for example, as input to statistical models that predict the distribution of driver-selected seat positions (SAE J1517). Importantly, the predicted “seat position” is actually the location of the seat H-point in package space. Thus, the manikin provides the essential reference used both to make interior measurements and to predict posture and position.

2.2.3 Seat Design for Accommodation and Comfort

The SAE J826 manikin was developed primarily as a seated position reference tool that accounts for seat deflection. It provides a reference point for positioning accommodation tools and describing consistent comparative spatial measures of vehicle interiors. Although it lacks some of the functionality that would be useful in a seat design tool, it has nonetheless been used to obtain measures relating seat design to comfort. The surveys and site visits undertaken at the start of the ASPECT program demonstrated that there is a strong desire in the industry to continue to use the manikin for seat design and comfort evaluations. One potential use of the manikin is to make pressure distribution measurements on seats, using the manikin as a standardized sitter for seat evaluation purposes. Seat surface pressure distributions produced by the manikin were monitored during manikin development, and some changes in contour were made in part to reduce unrealistic pressure patterns. However, further research beyond the ASPECT program will be necessary to determine if the ASPECT manikin pressure distribution is a reliable predictor of human pressure distributions.

A number of additional applications of the manikin beyond those listed above were noted, including those relating to vehicle safety. The H-point manikin is used for crash dummy positioning and as a platform for tools to measure seatbelt fit and head restraint location. Most of these applications involve modifications to the standard H-point manikin design and installation procedure. The manikin functionality required for these applications was considered, but not always accommodated, in the ASPECT manikin development process. Because the ASPECT manikin differs in important ways from its predecessor, both in features and performance, add-on tools such as the belt-fit test device cannot be used with the new manikin without modification. Further research will be necessary to determine how such things as seatbelt fit and head restraint location should be measured with the new manikin, or how the ASPECT manikin can be used for crash dummy positioning. In general, the ASPECT manikin is expected to provide more stable and easier-to-use measures of vehicle occupant posture and position than the current manikin, and is likely to be a better platform for other measurement devices.

2.3 Anthropometric Definition

The current SAE J826 manikin represents an amalgam of anthropometry resulting from the range of applications for which the manikin was developed. The manikin was intended to produce a reference point relative to a seat (H-point) that represents where people would be located in the seat. The reference point previously in use was the intersection between the undeflected seatback and seatpan contours, commonly known as the bite line. A reference point obtained from a weighted manikin predicts human positions in the seat more consistently. Noting that deflections of typical seat cushions of the time were approximately proportional to body weight, the developers of the original manikin chose median male weight as the reference value (2, 5).

The J826 manikin was also intended to be used as a legroom measurement tool, so relatively long legs were desired. The original manikin design was based on men who were 90th percentile by stature, according to data from about 1960 (2). In subsequent revisions, the leg and thigh segment lengths were adjusted so that each was 95th percentile for that dimension in the male population, using reference to data from the Health Examination Survey (6). The anthropometric definition for the current SAE J826 manikin is thus a combination of 50th-, 90th-, and 95th-percentile male values, taken from different civilian anthropometric surveys from the early 1960s.

An examination of the applications for which the ASPECT manikin was intended demonstrated that any reasonable manikin size would be adequate — no specific percentile of any particular population is required. Percentile targets for the manikin are inappropriate, because (1) percentiles imply a population, raising the question of what population should constitute the basis for a manikin to be used internationally, and (2) populations are dynamic, so that even if a chosen percentile for a particular population could be identified, the values would soon be in error with shifts in demographics.

The manikin must provide a reference point and other measurements of a seat that are related to the postures and positions of human occupants in consistent and predictable ways. For example, in some seats, the vertical position of a person's hips when sitting is related to the person's body weight. If the relationship between weight and hip position is known from studies of vehicle occupant posture, then the hip location of any individual can be predicted from the hip location of any other person and the relationship between weight and hip location. For vehicle and seat design applications, the objective is to use a measure from a surrogate sitter (weighted manikin) to predict hip locations of occupants of a wide range of sizes. In the ASPECT program, the posture and position of hundreds of occupants with widely varying anthropometry have been measured to quantify relationships between anthropometry and posture across a wide range of seats (15, 18, 20). The resulting data and analyses make it unnecessary to represent any particular occupant size in the ASPECT manikin.

Several considerations indicate that an extreme manikin size is less desirable. A manikin that is excessively large might not fit in vehicles or seats that are legitimately designed for smaller populations. A manikin that is excessively small might not deflect seats into a range typical of automobile occupants. In general, a manikin that produces measurement values near the middle of the range typical of automobile occupants would be best for predicting occupant posture and position.

Having established that a midsize occupant anthropometry would be best, the dominant consideration became continuity with current practice. Anthropometric specifications of midsize U.S. males were used to develop the two tools most commonly used to represent humans in the vehicle design and development process: the current H-point manikin (with the limitations noted above), and the Hybrid III crash dummy used in compliance testing for U.S. Federal Motor Vehicle Safety Standards (11). A midsize U.S. male body size was therefore selected as the target for the ASPECT manikin, with the stated objective of continuity with crash dummies.

The anthropometric specifications for the ASPECT manikin were determined using data from the 1974 National Health Examination and Nutrition Survey (NHANES) (21). At the time, these were the best data available to describe the U.S. population.* The 1974 NHANES data also formed the basis for the development of anthropometric standards for the next generation of crash dummies. In the early 1980s, Schneider et al. (22) conducted a study supported by the U.S. National Highway Traffic Safety Administration to develop anthropometric specifications for a new frontal impact dummy. The sampling categories for that study used the median male values of stature and weight from the 1974 NHANES for the midsize-male target values. Extensive measurements from 25 men within a narrow range of the target stature and weight were used to create anthropometric specifications (23) that were subsequently used to develop components for a new crash dummy (24). Selecting median male values from the 1974 NHANES study for the ASPECT manikin therefore provides a good match to the current standard Hybrid III crash dummy, ensures considerable continuity with future crash dummies, and makes the detailed data from the Schneider et al. study applicable to manikin development.

Table 1 shows the ASPECT reference anthropometry. The ASPECT manikin geometry should not be referred to as "50th-percentile male," even though some dimensions were obtained from median male values from one survey. The values are almost certainly different from the true median U.S. values today, and would be different from median values in almost any population of interest. The ASPECT manikin is specified on three variables: stature, weight (mass), and erect sitting height. Analyses have shown that these three variables account for a majority of the variance in anthropometric variables that are relevant to vehicle interior design (20). Note, however, than none of these values is represented directly in the manikin. The manikin does not have the body segments necessary to measure stature or erect sitting height, and the manikin weight is reduced by the force required to support the heels of a sitter matching the reference anthropometry (see below). Instead, the reference anthropometry was used to select people whose anthropometry and behavior form the basis for the manikin specification.

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* Since this time, more recent U.S. civilian data have become available from the 1990 NHANES study. In keeping with the rationale described above, the ASPECT reference anthropometry was not altered in response to this new information. Similarly, data from the CAESAR study, now underway, will not affect the ASPECT reference anthropometry or the design of the manikin.

Table 1
ASPECT Reference Anthropometry Compared to Crash Dummies

Variable	ASPECT*	Midsize Male Advanced Crash Dummy (23)*	Midsize Male Hybrid III Crash Dummy (25)
Stature (mm)	1753	1753	1754
Mass (kg)	77.3	77.3	78.3
Erect Sitting Height (mm)	913	913	906.8

* Median male values from 1974 NHANES (21).

2.4 Kinematic Linkage

One of the primary goals in the development of the ASPECT manikin was to provide a lumbar articulation that would allow the manikin to function better in seats with contoured seatbacks, particularly those with prominent lumbar supports. From the beginning of the ASPECT manikin prototype development, methods of simulating lumbar spine articulation in the manikin were explored. Kinematic computer simulations, based on previous work of Haas (26) and Reed et al. (27, 28), indicated that a relatively simple kinematic linkage with one or two lumbar joints would adequately represent human spine kinematics for ASPECT applications. The most promising approach used two lumbar joints, located at the anatomical positions of the T12/L1 and L5/S1 joints. This provided a single mechanical segment representing the lumbar spine, and facilitated connecting the external contours (shells) to the linkage. Figure 3 shows these lumbar spine joints relative to the manikin and a midsize-male human figure.

Work with early manikin prototypes demonstrated that the three degrees of freedom provided by the hip, lower lumbar, and upper lumbar joints resulted in poor manikin performance, particularly at more vertical seatback angles. The manikin was unstable, and tended to flop forward in the seat. Two additions to the linkage were made that provided the necessary performance and stability. Figure 4 illustrates the torso linkage schematically.

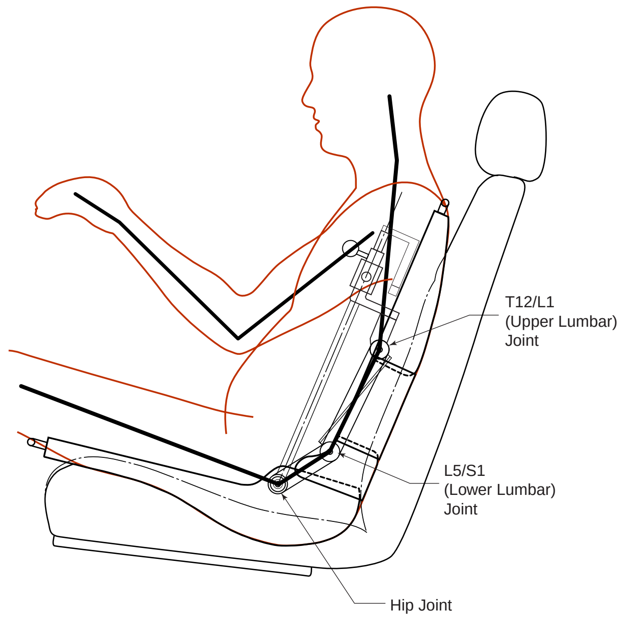

Figure 3. Side-view schematic of a kinematic model of a driver, showing hip, L5/S1, and T12/L1 joints. ASPECT manikin geometry is overlaid.

First, a connecting rod was added to link the thorax and pelvis together across the lumbar joints. The effect of this connection is to distribute lumbar flexion or extension approximately evenly across the two lumbar joints, reducing the lumbar spine to a single degree of freedom (flexion/extension). This concept was adapted from the mechanism used by Bush (29) for a two-dimensional seat design template. He demonstrated that the resulting kinematics were similar to those obtained using a six-joint lumbar spine. During the ASPECT program, prototype manikins were evaluated using a range of mechanical ratios to distribute the lumbar motion between the two joints. Ultimately, however, none of the alternatives was found to be superior to an approximately even distribution of motion.

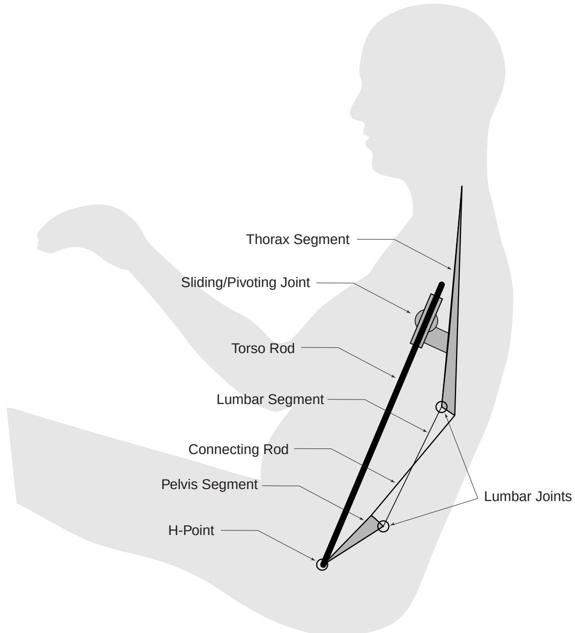

Figure 4. Schematic of ASPECT manikin torso linkage.

Second, a torso rod was added that provided a means of stabilizing the thorax at more vertical seatback angles. The torso rod, shown schematically in Figure 4, pivots at the hip joint and connects to the thorax at a sliding, pivoting joint (two degrees of freedom). The weights in the thorax area of the manikin are attached to the torso rod, rather than to the thorax segment itself. Hence, these weights create a rearward moment on the thorax whenever the torso rod is oriented rearward of vertical, which is the case for all intended manikin applications. Consequently, the manikin can successfully load the upper seatback without jeopardizing stability at upright seatback angles.

The torso rod also provides some compatibility with the current SAE H-point manikin. The torso line on the current manikin is parallel to the profile of the manikin torso shell in the lumbar area.   The torso rod on the ASPECT manikin is also designed to be parallel to the lumbar shell when the manikin is in its nominal condition with a flat lumbar surface, providing geometry equivalent to the current manikin. Note that the ASPECT torso rod does not have an anatomical referent; it does not connect the hip with some other specified anatomical landmark. Figure 5 shows the manikin linkage relative to the shells.

Defining the ASPECT manikin linkage required determining the appropriate locations for the hip and lumbar joints relative to each other and to the external manikin surfaces. Extensive analyses were conducted using data collected for the ASPECT program and other previous studies. The central issues were (1) the length of the lumbar segment, (2) the length of the pelvis segment, and (3) the location of the hip joint and lumbar joints relative to the external shell. Early in the ASPECT program, techniques for estimating anatomical joint locations from external body landmark locations were developed from a synthesis of the literature and additional analysis (15). These methods were used with data from several studies to obtain the required dimensions.

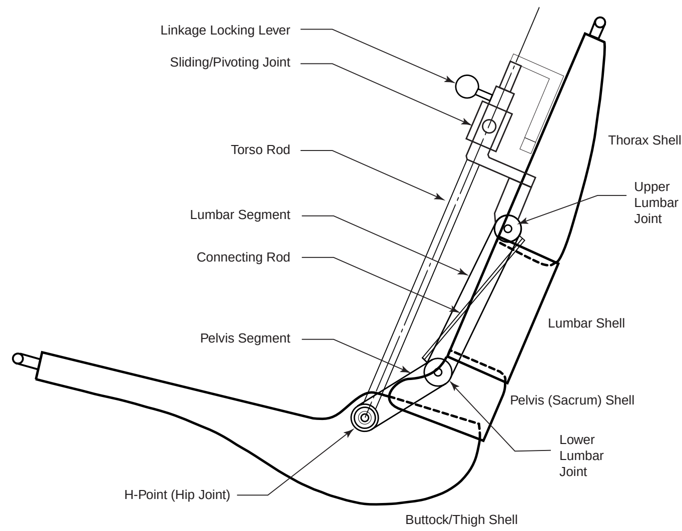

Figure 5. ASPECT manikin linkage with shell geometry.

An ideal approach to determining joint locations that would best represent the skeletal geometry of people matching the ASPECT reference anthropometry would be to use internal imaging techniques, such as radiography, with a large subject sample. However, such invasive techniques are not ethical (in the case of radiography) or are too expensive (e.g., MRI) for application to this problem. Moreover, the ASPECT manikin performance in its intended applications will not be substantially hampered if the linkage differs somewhat from the true average skeletal geometry. Consequently, the objective in linkage development was first to obtain reasonable estimates of the joint locations and segment lengths and then to revise these values as necessary to obtain appropriate manikin function.

Data on joint locations were obtained from a variety of sources. Body landmark locations from the Schneider et al. survey of 25 midsize males (22) were re-analyzed using ASPECT methods and compared to the original analysis (23). Body landmark locations were recorded from 25 men selected to be close to the ASPECT reference anthropometry as they sat in a laboratory hardseat. The resulting joint location estimates were consulted in the manikin design process.

Figure 6 shows the manikin linkage geometry. The distance from the hip joint to the posterior and inferior aspects of the contour were maintained equivalent to the current H-point manikin to improve continuity in H-point location. The pelvis segment length of 100 mm is similar to that reported by Robbins (23) for midsize males, but the lumbar segment length of 182 mm is greater than the 154-mm length estimated by Robbins. However, the large flesh margin below the pelvis in Robbin's analysis suggests that his estimate of pelvis location relative to the thorax and seat contour was too high, resulting in a shortened lumbar spine. Re-analysis of the data used by Robbins with ASPECT methods suggests a lumbar segment length more similar to the value obtained by analysis of ASPECT data, so the value from the ASPECT analysis was chosen.

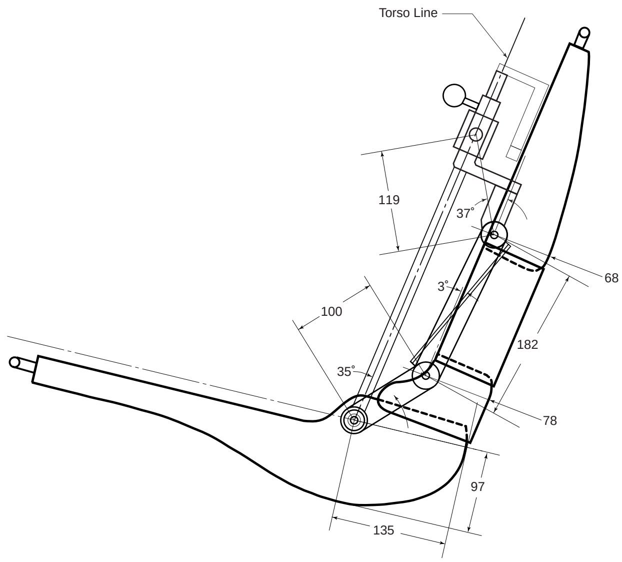

Figure 6. ASPECT manikin linkage geometry (mm).

2.5 Contour

New seat contact surface contours were desired for the ASPECT manikin, both to obtain greater anthropometric consistency and to improve the manikin performance. The current SAE H-point manikin has two rigid external shells that define the shape of the seat contact surface. These shells were developed from contour measurements of a man who was approximately 5’11” tall and 170 lbs (2, 5). At the time, these values corresponded approximately to the 90th-percentile U.S. male stature and 50th-percentile weight. The resulting torso was slightly taller and thinner than would be expected for men matching the ASPECT reference anthropometry. The current manikin shells also have an unrealistic contour in the buttock area that does not include the ischial prominences that are commonly observed in pressure distribution measurements of human sitters.

Consideration was given early in the program to the development of deformable manikin surfaces that would produce varying contours depending on the loading pattern. A more flesh-like manikin might be expected to produce more realistic pressure distributions and to better reflect the effects of changes in seat geometry on posture. However, repeatability, manufacturing, and durability considerations led to the selection of rigid shells of the same sort of construction used on the current manikin.

Contour measurements for the ASPECT program were conducted at Michigan State University. Details of the measurement procedures are presented elsewhere (16). After analyzing buttock and thigh contour data from seven approximately midsize-male subjects, the Michigan State researchers chose the contour of a single individual as most representative of the group. Critical dimensions, such as the distance from the hip joint to the bottom and back of the contour, were close to the mean values for the group.

Back contours taken from seven midsize males were averaged to obtain a representative contour. These data were merged with the buttock and thigh data to obtain a preliminary contour, and a full-size model of the contours was developed using computerized machining. Minor modifications to the contours were made by shaping and sanding the model. Fiberglass shells were then molded from the model and attached to a manikin prototype.

The buttock and thigh contours performed well, requiring only a few additional modifications. The back contours, however, were flatter than expected, and did not perform well in the test seats. The data were collected with the subject's upper arms positioned close to their bodies, rather than extended forward as in a typical driving posture. The difference in shoulder posture resulted in back contours that were flatter across the thorax area than the SAE J826 contour. When installed in seats designed with the current manikin, the new contour tended to bridge laterally across the seat in the thorax area, leading to unstable thorax positions as the shell contacted small areas on the side of the seat.

The undesirable performance of the flatter, more passenger-like back contour in contemporary seats suggested that a contour more similar to the current manikin was needed. A new prototype back contour was developed using contour data from the Schneider et al. study of anthropometry used for crash dummy design (22). In that study, back, buttock, and thigh contours of 8 midsize men were measured in four vehicle seats using a casting technique. The resulting data, along with body landmark location measurements and standard anthropometry from 25 midsize men, were used to create a physical three-dimensional, full-body shell representing a midsize male. The back surfaces of the physical shell were based on the measured contour data. For the ASPECT program, the shell was scanned at high-resolution and parametric surfaces fit to the resulting data. The data from the left side of the shell back were reflected to make a symmetrical contour. The resulting shape was merged with the new buttock and thigh contour data to create a new set of manikin shells.

The resulting surface shape produces more stable manikin readings than were obtained with the first prototype back contours, and provides a reasonable representation of the shape of a midsize-male driver's back. Combined with the buttock and thigh contours, the ASPECT manikin presents a surface interface contour that represents the typical deflected shape of a person matching the ASPECT reference anthropometry.

Figure 7 shows several cross sections comparing the ASPECT manikin contours with the current SAE J826 H-point manikin. In a lateral section through the H-point, the ASPECT manikin has the same overall breadth and depth, but has more pronounced ischial prominences. In profile, there is a more pronounced indentation in front of the buttocks, under the proximal thighs, than on the current manikin. The profile of the torso when the linkage is set to the nominal position is very similar to the current manikin profile, but the ASPECT manikin is wider in the lumbar area than the current H-point manikin.

The torso contour of the manikin was divided into three sections and attached to the respective linkage segments (pelvis, lumbar, and thorax segments). The sectioning planes were chosen based on linkage kinematics, so that the gaps in the external contour would remain as small as possible through a wide range of manikin spine movement. Figure 8 shows the manikin torso at a range of lumbar spine flexion levels.

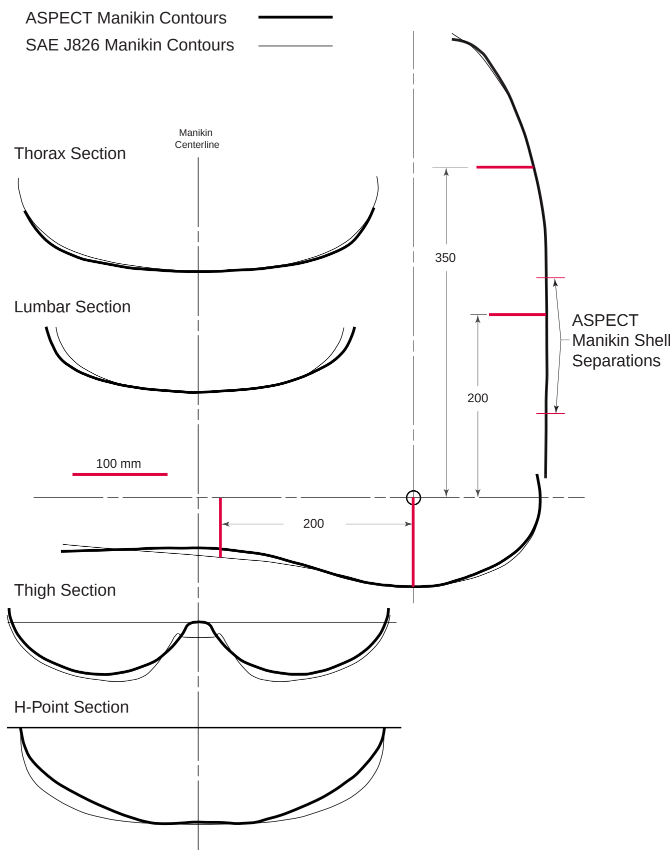

Figure 7. Comparisons of the external contours of the ASPECT and current SAE J826 manikins.

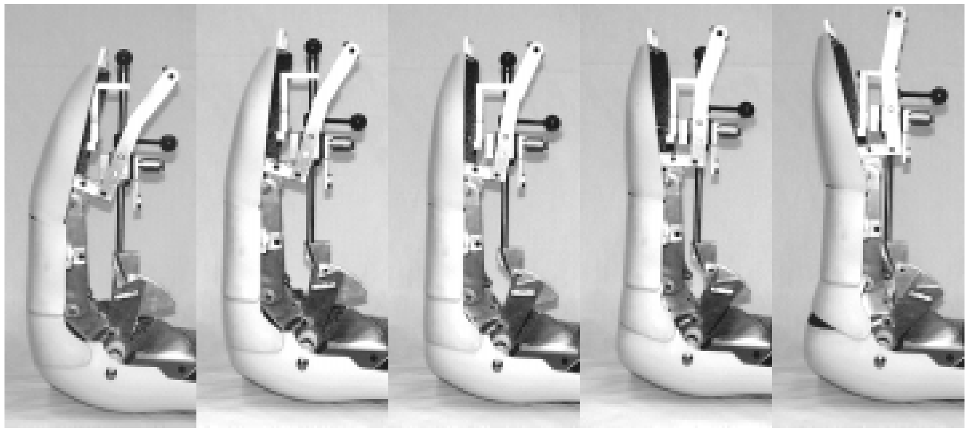

Figure 8. ASPECT manikin torso at a range of lumbar spine flexion levels (-20, -10, 0, 10, 20 mm lumbar support prominence, from left to right).

2.6 Mass and Mass Distribution

As noted above, the ASPECT reference anthropometry specifies a stature of 1753 mm and a mass of 77.3 kg. However, the ASPECT manikin does not represent the entire body of a person, and hence cannot reasonably have the specified weight. Instead, the manikin weight was chosen to represent the reference weight minus the weight supported under the heels of people matching the reference anthropometry in an automotive posture. Studies have shown that arm support force from the steering wheel varies with arm posture and muscle activity (28), so the manikin is weighted assuming that the full arm weight is carried by the seat. Thirty men ranging in stature (1582 to 1923 mm, average 1778 mm) and weight (57 to 141 kg, average 85 kg) sat in a typical vehicle seat with a seat height (H30) of 270 mm. After selecting a comfortable seatback angle, the subjects placed their feet with their heels resting comfortably on a force platform. The subjects' foot positions were adjusted so that there was no appreciable horizontal force applied to the platform. The vertical support force was recorded for three trials with each subject. Linear regression analysis on body weight was used to estimate the average heel support force for a person matching the reference anthropometry. The resulting value of 5.8 kg was subtracted from the reference weight to obtain the target manikin weight of 71.5 kg.

The manikin mass distribution cannot be directly representative of human mass distribution, because the manikin does not include the head, arms, and legs that comprise a substantial percentage of the body mass. Rather than attempting to relocate the head and arm masses in the thorax, as was done with the current H-point manikin, the ASPECT manikin mass distribution was determined based on performance considerations. The manikin components, without the removable weights, weigh 16.3 kg, 23 percent of the total manikin mass. Figure 9 shows the distribution of weights. Note that the thorax weights are actually attached to the torso rod and act primarily at the hip joint. This mass distribution produces stable manikin readings that meet the performance criteria established for the manikin (see below).

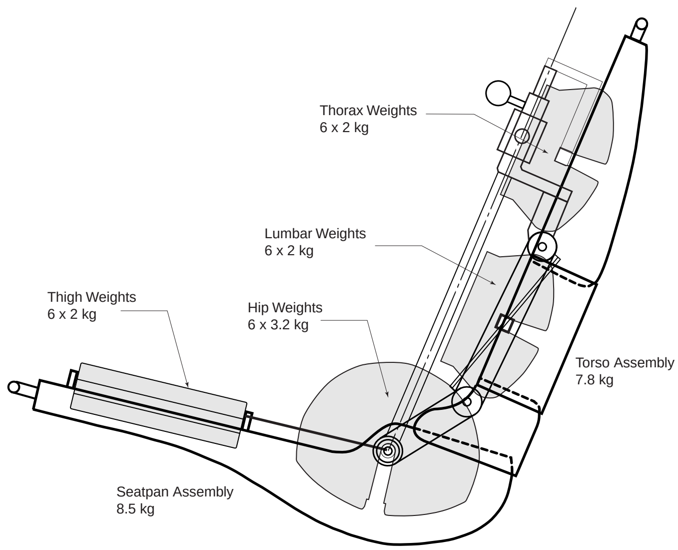

Figure 9. Schematic of ASPECT manikin mass distribution.

2.7 Supplemental Thigh, Leg, and Shoe

The ASPECT manikin is designed to be primarily a seat measurement tool that can be applied independent of the vehicle package geometry. For typical seat measurements, no leg or shoe is required. However, because the leg and shoe are integral parts of the current H-point manikin, supplemental leg and shoe components are provided with the ASPECT manikin to provide continuity with current practice.

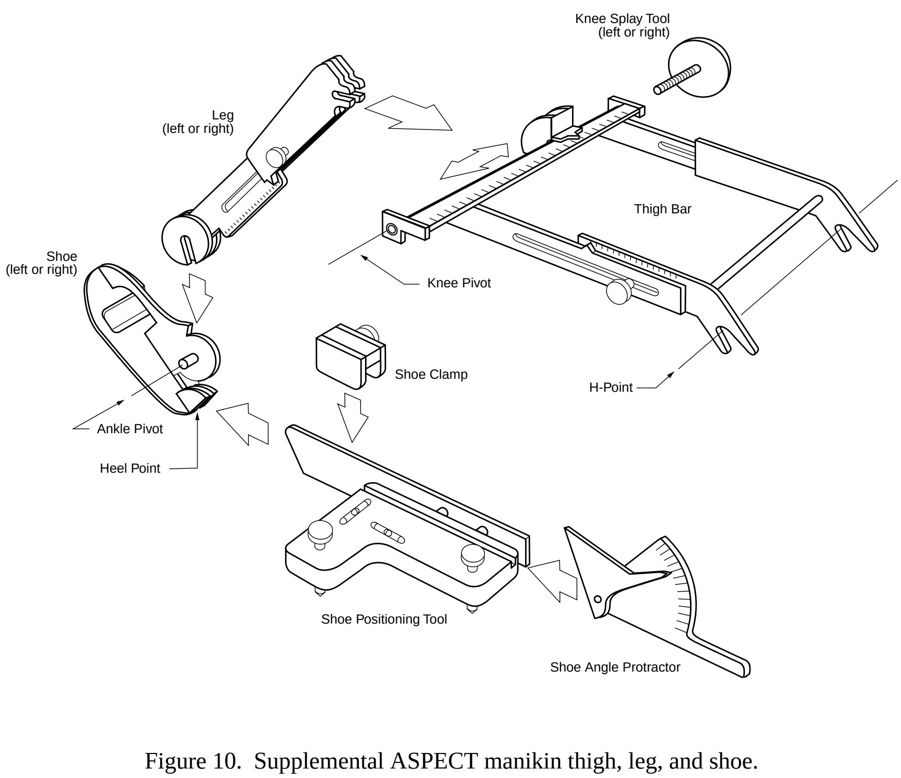

Figure 10. Supplemental ASPECT manikin thigh, leg, and shoe.

Figure 10 shows the thigh, leg, and shoe components schematically. The leg and thigh segments are adjustable in length and constructed of lightweight components. Adding the leg and thigh segments to the manikin after the manikin installation in a seat does not change any of the manikin measures, including H-point location. The shoe has the same length as the SAE H-point manikin shoe, but has a symmetrical plan-view contour and has a flat sole. Only one shoe and leg segment are used for measurements. The shoe is held in place by a clasping device, and can be used independent of the manikin to establish pedal reference points. A detailed discussion of the use of the leg and shoe in design and benchmarking applications is presented elsewhere (17).

Note that because the lightweight thigh segment is separate from the ASPECT manikin thigh section, the manikin creates two separate measures using segments analogous to the human thigh. The orientation of the weighted manikin thigh section after installation in a seat is the seat cushion angle, which is affected only by seat geometry. The angle of the lightweight thigh section after installation in a vehicle package with the seat and shoe in prescribed positions is the manikin thigh angle, which is affected only by package geometry. These values will usually be different, with cushion angle generally flatter (nearer to horizontal) than thigh angle.

2.8 Ease of Use

An important concern of the ASPECT industry participants was that the new manikin be easier to use, particularly for in-vehicle installations. The new manikin was developed with these concerns in mind, and has a number of features that simplify installation.

- *Separate buttock/thigh and torso pieces*. The manikin separates at the hip joint, so that the buttock/thigh section can be installed separately from the torso section. Each section weighs less than 10 kg and has handles for easy manipulation.

- *Smaller weights*. The ASPECT manikin has more but lighter weights, which are designed to install easily in their specified positions.

- *Clearer readouts.* The prototype ASPECT manikin has clearer, easier-to-read scales than the current J826 manikin. Additionally, provisions have been made for using electronic inclinometers to record segment orientations.

- *Package-independent measurement.* In its primary application, the manikin measures the seat independent of the package, meaning that the measurement can be made with the seat in any seat track position. The lightweight supplementary leg and shoe tools can be added to make package-related measures without changing the H-point location relative to the seat. This means that H-point measurements can be made without having the seat mounted in an accurately configured mockup; only the seat attitude with respect to vertical is required.

- *Integrated seat cushion angle measurement*. With the current J826 manikin, cushion angle measurement requires a separate manikin installation. The ASPECT manikin measures cushion angle, H-point, and other seat measures simultaneously.

- *Easier leg installation.* The lightweight supplemental leg and shoe tools are much easier to install than the legs of the J826 manikin. Only one leg and shoe are used with the ASPECT manikin, further simplifying installation. As noted above, the leg and foot are not required for the standard H-point measurement.

- *Simpler installation procedures.* The current installation procedures are simpler and clearer than the J826 manikin procedures, and the manikin installation can be completed more quickly.

Input from industry manikin evaluations will be used to improve the manikin's useability further. Particular emphasis is being placed on the procedures, to ensure that they are defined clearly to minimize interoperator variability.

2.9 Performance Specifications

The original objective for the ASPECT manikin performance was that the manikin should sit in seats in a manner quantitatively representative of people who match the manikin reference anthropometry. Specifically, the manikin H-point location should correspond to the average midsize male hip joint location, and the thigh, pelvis, abdomen, and thorax segment orientations of the manikin should match the average values obtained with humans.

During the ASPECT program, several large-scale studies of vehicle occupant posture and position were conducted, in part to develop manikin performance specifications (20). There were a number of important findings from these studies that led to fundamental changes in the manikin performance goals. The most important of these findings with implications for manikin performance are discussed here.

1. Package factors affect driver posture in ways that cannot be readily replicated in a manikin.

Specifically, the fore-aft position of the steering wheel relative to the pedals affects driver torso posture. More-forward steering wheel positions result in slightly more upright postures with slightly less lumbar spine flexion than more rearward steering wheel positions. Two potential ways to include this effect in the manikin were considered. The manikin could be physically tied to the steering wheel, for example, by use of a spring-loaded rod that would replicate the effect of the arms on the thorax. Alternatively, the manikin behavior could be altered by adjustments to the linkage made based on measures of the particular vehicle's steering wheel position. These and other potential approaches were rejected because they moved away from the basic objective of separating seat and package measures.

2. **Seat cushion angle does not affect driver or passenger thigh postures in a mechanistic manner.**

Prior to the ASPECT posture studies, the seat cushion angle with respect to the horizontal, measured using the legless J826 manikin procedure (1), was expected to have a direct effect on the thigh angles of both drivers and passengers. The effect was expected to be particularly noticeable with front-seat passengers, for whom the cushion angle would be the primary external constraint on leg posture. However, in two separate studies (48 and 68 subjects) in a wide variety of driver and passenger conditions, seat cushion angle did not have a signification relationship with driver or passenger thigh angle (20, 28). Higher seat cushion angles do produce some significant postural effects, including more-forward seat positions and more reclined torso postures, but do not directly affect thigh angle. This finding meant that manikin thigh angle performance could not be reasonably specified by the average thigh angles measured on subjects.

3. **Human torso posture responses to changes in seatback geometry are too small to be useful for seat measurement.**

The ASPECT manikin included, from the earliest prototypes, an articulated lumbar spine. The articulated linkage was expected to make the manikin more stable than the current H-point manikin in seats with prominent lumbar supports, and was expected to allow the manikin to replicate the effects of lumbar supports on human torso posture. However, the human subject studies in ASPECT demonstrated that differences in seatback geometry that are reasonable for production automobile seats (meaning lumbar support prominence and location) have only small effects on torso posture. For example, an increase of 40 mm in lumbar support prominence reduced lumbar spine flexion by only 1.8 degrees. Similar findings had previously been reported from other studies at UMTRI (27, 30). ASPECT studies showed that the effects of lumbar support prominence change on both driver and passenger posture are small relative to the postural variance between people.

4. **Human hip joint locations are affected by seat cushion angle in ways that are difficult to replicate with a manikin.**

Data from several ASPECT studies show that human hip locations relative to the seat are affected by changes in seat cushion angle. Higher seat cushion angles relative to horizontal cause people to sit with their hips more rearward on the seat than at lower cushion angles. Drivers also respond to higher seat cushion angles by moving their seats forward an offsetting amount, so that the average hip location aft of the pedals remains approximately constant. Efforts to duplicate this behavior with the manikin were unsuccessful. Seat cushion angles are highly constrained in production vehicles. In ASPECT research, a change in seat cushion angle from 11 to 18 degrees caused a significant rearward shift in hip location on the seat, but that seven-degree change in seat cushion angle is insufficient to cause any significant change in the position of a weighted manikin.

These findings necessitated a re-examination of the manikin performance objectives. The finding that the steering wheel position affected torso posture led to a redefinition of the manikin performance to replicating passenger posture. However, the findings with regard to seat cushion angle, both in its effect on hip joint location and the lack of effect on thigh angle, indicated that at least the thigh section of the manikin could not be designed to behave in a humanlike manner. Prototype development proceeded with a focus on obtaining humanlike responses to changes in lumbar support prominence and seatback angle. As the prototype was refined, the limitations of this approach became clear.

Because the torso posture of vehicle occupants is relatively insensitive to changes in seatback contour, a manikin that behaved in a humanlike manner would be a poor measurement tool. For example, data from ASPECT and previous studies indicate that a 45-mm change in lumbar support prominence, wider than the range expected in production seats, produces an average change in lumbar spine flexion of between two and six degrees. Thus, a humanlike manikin would be required to differentiate across the full range of vehicle seats using only six degrees of lumbar spine movement. The acceptable range of test-retest variability would have to be much smaller than one degree to reliably differentiate among seats.

In light of these findings, the manikin performance specifications were redefined. The goal of the manikin remains to characterize the seat. However, the manikin posture that results when the manikin is installed in a seat is not intended to represent human posture. Rather, the manikin uses a humanlike kinematic linkage and humanlike contour to obtain measures of deflected seat surface positions and orientations that have quantitative relationships with human posture and position. The measures obtained from the manikin refer to the seat, not to human posture. The ASPECT manikin measures H-point location, seat cushion angle, seatback angle, and lumbar support prominence, rather than the analogous human posture measures of hip joint location, thigh angle, torso angle, and lumbar spine flexion.

The result of this redefinition of performance objectives is that the manikin provides more useful measures of the seat geometry than would be obtained even using a large sample of human subjects. For example, the ASPECT manikin measures cushion angle, which is poorly measured using human postural response. Yet, cushion angle has important effects on some measures of human posture and position (28, 31). Similarly, changes in lumbar support prominence are readily measured using the ASPECT manikin. Although these changes have only small effects on posture, they have large effects on comfort ratings, and hence are important for seat design (32).

The manikin performance objectives are defined as follows:

1. Obtain an H-point location that is as close as practical to the SAE J826 H-point location in seats that produce a lumbar support prominence measure of zero (i.e., result in an ASPECT manikin back profile matching the SAE manikin back profile);

2. Record a cushion angle that approximately matches the SAE J826 seat cushion angle measure across seats;

3. Record a seatback angle that is parallel to the external lumbar shell, and approximately matches the seatback angle measured by the J826 manikin, when the lumbar support prominence is zero; and

4. Fully engage with the seatback to produce a deflected measure of longitudinal seatback contour, expressed as lumbar support prominence.

When a seat produces a lumbar support prominence reading of zero on the ASPECT manikin, the manikin should produce an H-point location and seatback angle that are similar to the values obtained with the current H-point manikin. However, in all other seats, deviations between the two manikins in H-point location and seatback angle are expected, since the ASPECT manikin torso interacts with the seatback in a way that is different from the rigid torso of the current manikin.

2.10 ASPECT Manikin Prototype Evolution

The ASPECT manikin was developed in an evolutionary process from the current J826 manikin. The J826 manikin shells were sectioned and adapted as a new linkage was designed. When new contours became available, they were installed on the manikin as the testing and development proceeded. Hundreds of manikin drops were conducted over the several years of prototype development to gauge the effects of various design changes. This section documents the design trajectory and highlights some of the major decision points and design concepts.

2.10.1 Initial Manikin Prototype

ASPECT manikin development began by sectioning a set of J826 manikin shells and installing a linkage. The basic structure of the linkage was already established, although considerable effort would follow in validating the linkage movement patterns and joint locations. Figure 11 shows one of the first manikin prototypes. Note the chain and sprockets connecting the thorax and pelvis to achieve a 1:1 movement ratio.

Figure 11. Initial manikin prototype (February 1997).

2.10.2 APM-2

A coding procedure was developed to describe the various modifications to the ASPECT manikin during development and testing. APM stands for Aspect Physical Manikin.

The numeral following APM indicates the prototype model. The letter following the model numeral designates the linkage modification. The last numeral designates the loading arrangement. The version shown February 1997 was designated APM-1A1. After the initial prototype, subsequent major prototype revisions were coded APM2, APM3, etc., with APM an abbreviation for ASPECT Physical Manikin. With APM2, the following revisions were made:

- Changed lumbar spine linkage from chain and sprockets to four-bar linkage for improved durability
- Changed torso weight mounting locations for improved stability
- Sectioned pelvis and thighs to permit thigh splay and changed thigh weight mounting.
- Attached pelvis shell to pelvis link so that sacrum buttock area forces can affect torso kinematics.

Experiments were conducted with separate pelvis and thigh segments, and the possibility of leg splay was introduced. Figure 12 shows an APM2 prototype. These revisions added a torso link that provides a correlation to the SAE J826 manikin. This link is parallel to the abdomen (lumbar) seat contact surface of the mid-back section of the manikin and is a given distance from the abdomen link when the posture profile matches SAE J826 (neutral posture). Weights on the torso link load the upper-back (thorax) through an adjustable roller with a major portion of the weight transferred downward directly to the H-Point. Shifting weights between the torso link and thorax link varied the abdomen loads against the seat back. Lower torso modifications allowed the thighs and buttocks to be locked together (APM-2B) or be independent (APM-2A). The APM-2B version included a manikin thigh and buttocks pan similar to the present SAE J826 manikin. When the thighs and buttocks are independent (APM-2A) the pelvis link is locked to the buttocks causing the buttocks to rock with the pelvis link. Two different loads were developed resulting in designations APM-2A1 and APM-2B2, as shown in Figures 13 and 14.

Additional modifications were made to facilitate different loading techniques. Leg splay was set and locked to agree with the present J826 manikin. The manikin seat contact surfaces were shimmed to better fit the present manikin at the neutral posture position. Reference points on body links and at linkage pivots were added. Tabs were attached to the thorax, abdomen and pelvis link to facilitate angle measurement with an electronic inclinometer.

The control link between the thorax and pelvis was retained from APM-1. This link has an approximate 1-to-1 ratio such that angular interaction at the thorax/abdomen joint and the abdomen/pelvis joint is approximately equal and opposite. This control link stabilizes the behavior of torso articulation and was demonstrated by subsequent human subject testing to be reasonably biofidelic.

Figure 12. APM2 prototype (October 1997) showing leg splay features.

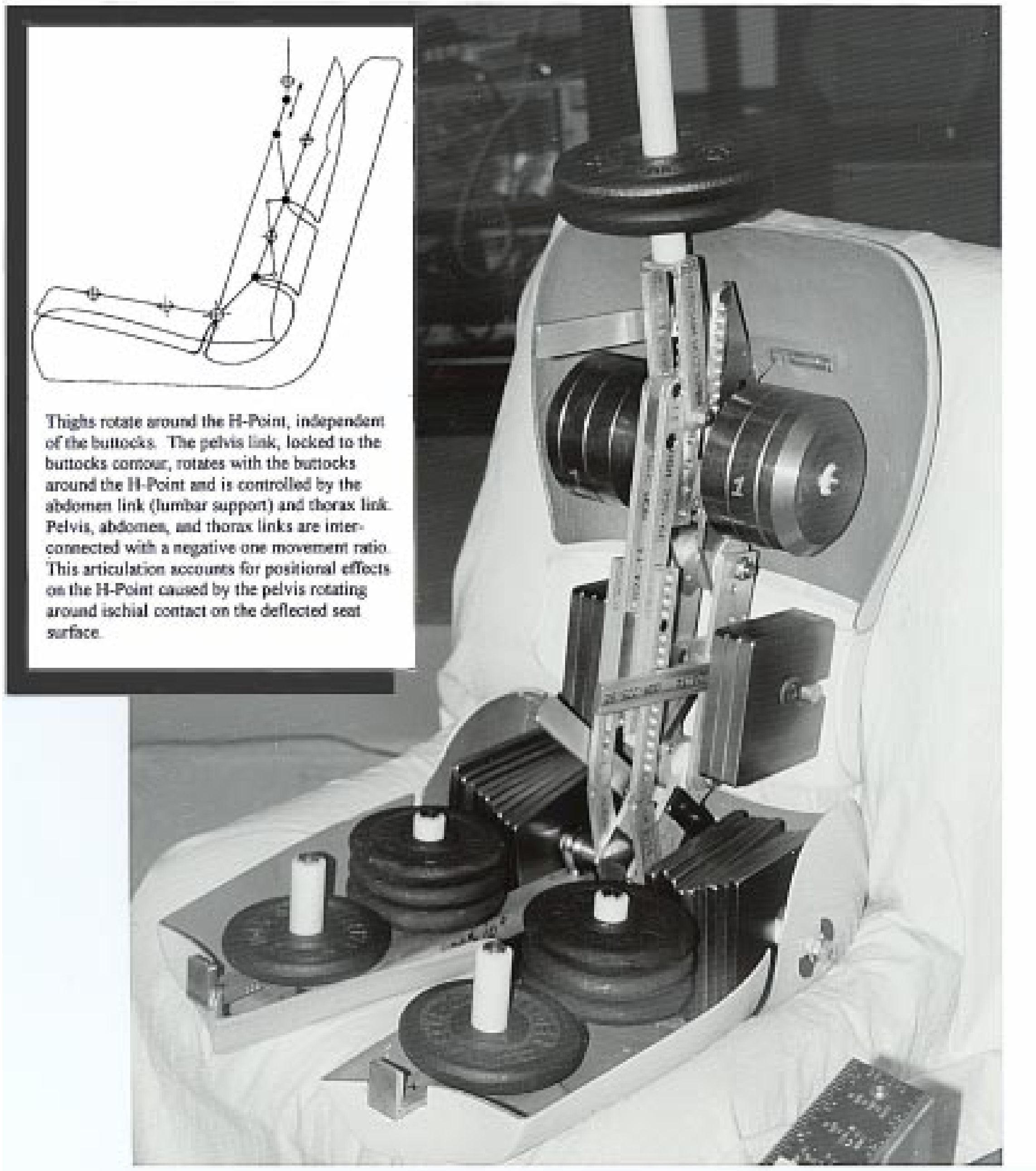

Figure 13. APM-2A

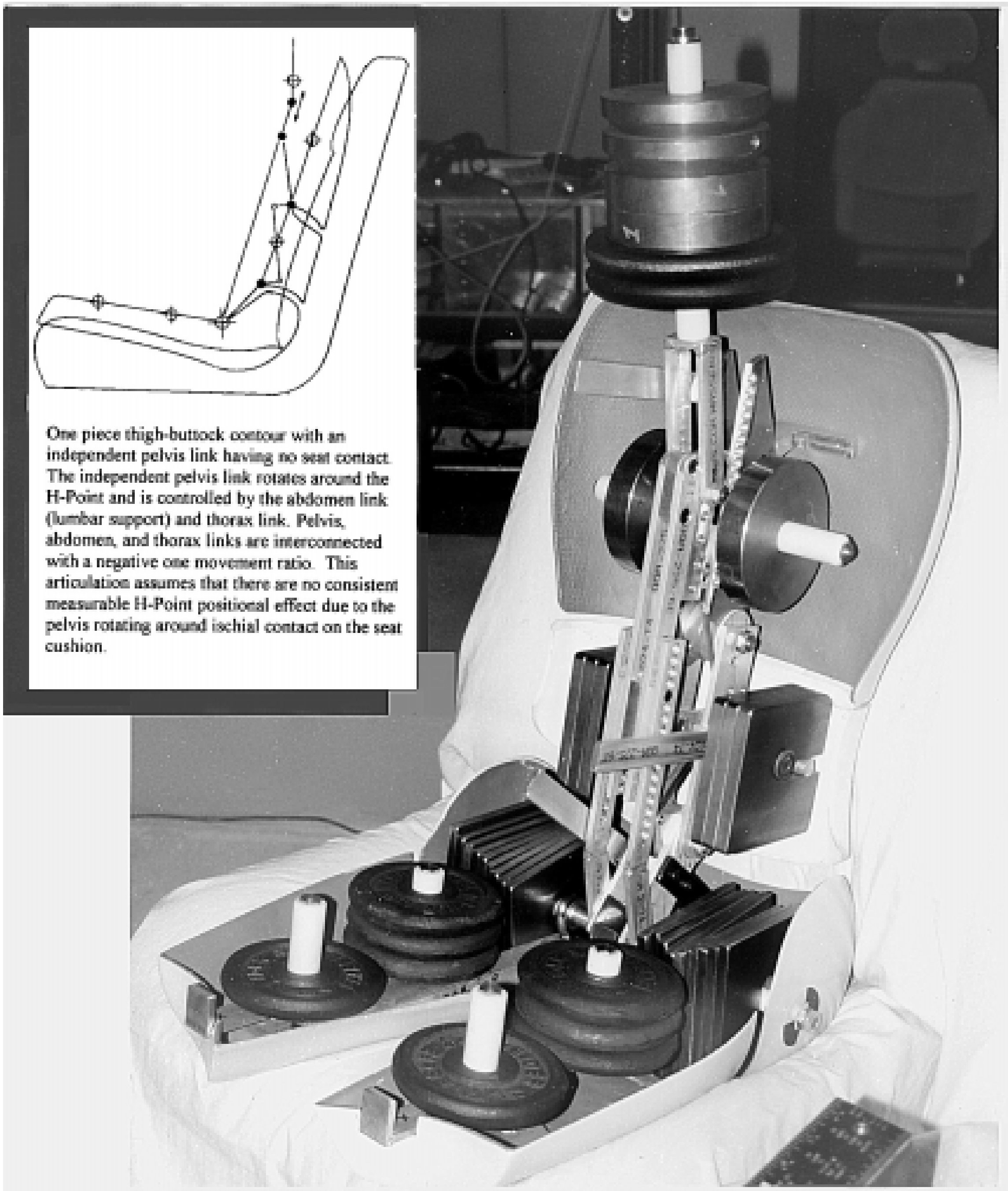

Figure 14. APM-2B

Additional revisions to APM-2 (APM-2C3) provided further refinement to the torso link simplifying the reaction load mechanism on the thorax and provision of adjustable stops for the articulated back. The connection of the torso link at the upper-back (thorax) link was modified with a roller encased in a slot to provide smoother action and a fixed but adjustable range for torso articulation. Upper-back (thorax) load points were eliminated and moved to the torso link to stabilize the upper back. This was an extremely effective change to linkage operation in that vertical loads are now directed to the H-Point and normal loads to the upper seat back. Previous loading on the upper back tended to overload the lumbar portion into the seat back driving the H-Point forward resulting in a slumped manikin posture.

The thigh pan and buttock pan remained independent as in APM-2A. The foremost location points for the thigh pan weights were shifted forward. The bottom front corners of the seat (buttock) pan and lower rear edges of the thigh pans were rounded to prevent catching on the seat trim, as shown in Figure 15.

Figure 15. APM-2C

The first complete supplemental thigh/leg/shoe assembly was fabricated for APM-2C. A shoe clasping fixture was developed to aid in support of the shoe when measuring pedal and floor reference points, as shown in Figure 16. Note the Knee Splay measurement tool fitted to the Thigh Bar. A dual shoe was developed for passenger seat installations.

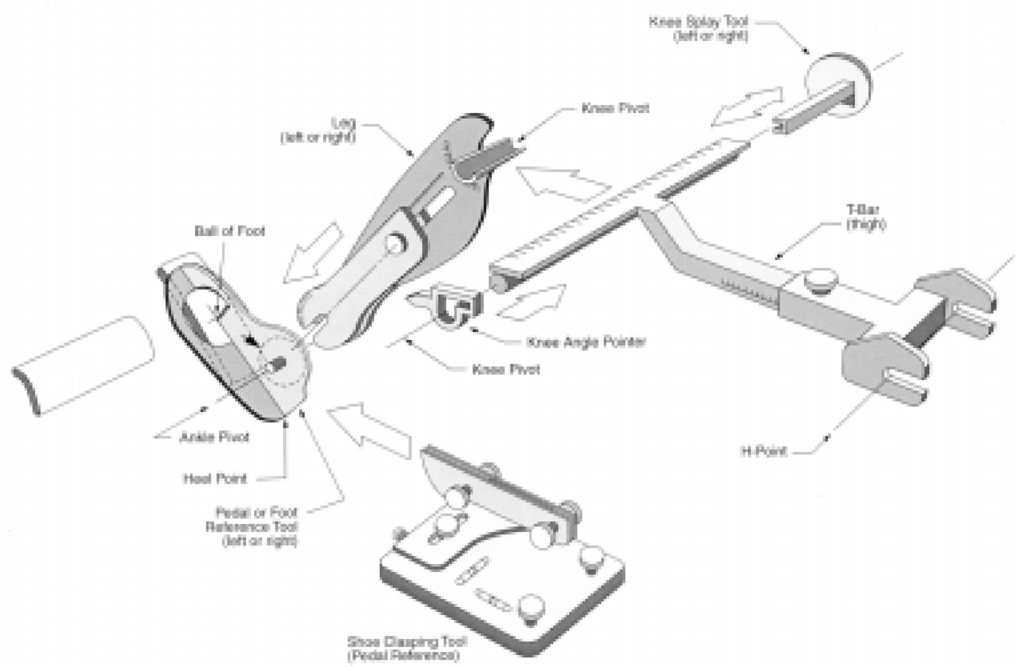

Figure 16. First thigh, leg, and shoe prototypes designs.

2.10.3 APM-3

By February 1998, further improvements were made on the APM-2 torso linkage system. The sliding back angle link became a circular rod with a locking collar to stabilize the torso linkage for installation and transport. This also facilitated certain installation requirements and procedures. The thigh and buttocks were combined in a single shell, since experiments with earlier prototypes had shown that the separate pelvis and thighs did not perform well in some seats. The torso section had three articulating panels with minimal gaps to provide smooth contact throughout the lumbar area. The lower portion of the thorax panel and upper portion of the sacral overlapped under the lumbar panel. The sacral portion of the three piece back pan extended downward such that the gap with the buttocks pan would be in the non seat contact surface at the bite-line between the seat back and seat cushion. The sacral pan was connected to the pelvis link. This prototype, designated APM-3, is shown in Figure 17.

APM-3 had a quick connect/disconnect at the H-Point between the back (torso) pan and the cushion (buttocks/thigh) pan. This facilitates ease of transport, handling and installation and allows for possible future use of buttock/thigh assembly with different torso assemblies. A direct readout of lumbar support prominence is provided with a linear scale

A pattern of holes were added at key sections on the thigh, buttock, sacral, lumbar and thorax seat contact surfaces to allow viewing and measuring seat surface contact geometry. These holes facilitate assessment of manikin seat trim “breakaway” points for measuring bolster widths, lengths and heights. New laminated steel weights were shaped to facilitate installation and removal with minimal interference. Modular loading procedures were developed to facilitate measurements of deflection and stiffness.

The supplemental thigh, leg and shoe have been revised. The shoe profile is symmetrical in plan view. The single leg and shoe assembly may be used on the left or right side. A fixture has been designed to hold the shoe in position and measure shoe angle. Features shown in Figure 18 include:

- Adjustable length thigh tray assembly for both right or left leg attachment
- Single adjustable length leg assembly for both right or left leg applications
- Symmetrical shoe profile with BOF indicator and ankle pivot connection to leg
- Clasping tool for foot (shoe) to hold shoe in place
- Protractor to measure Pedal and Floor Plane Angles

Figure 17. APM-3 showing the revised torso with three articulating panels.

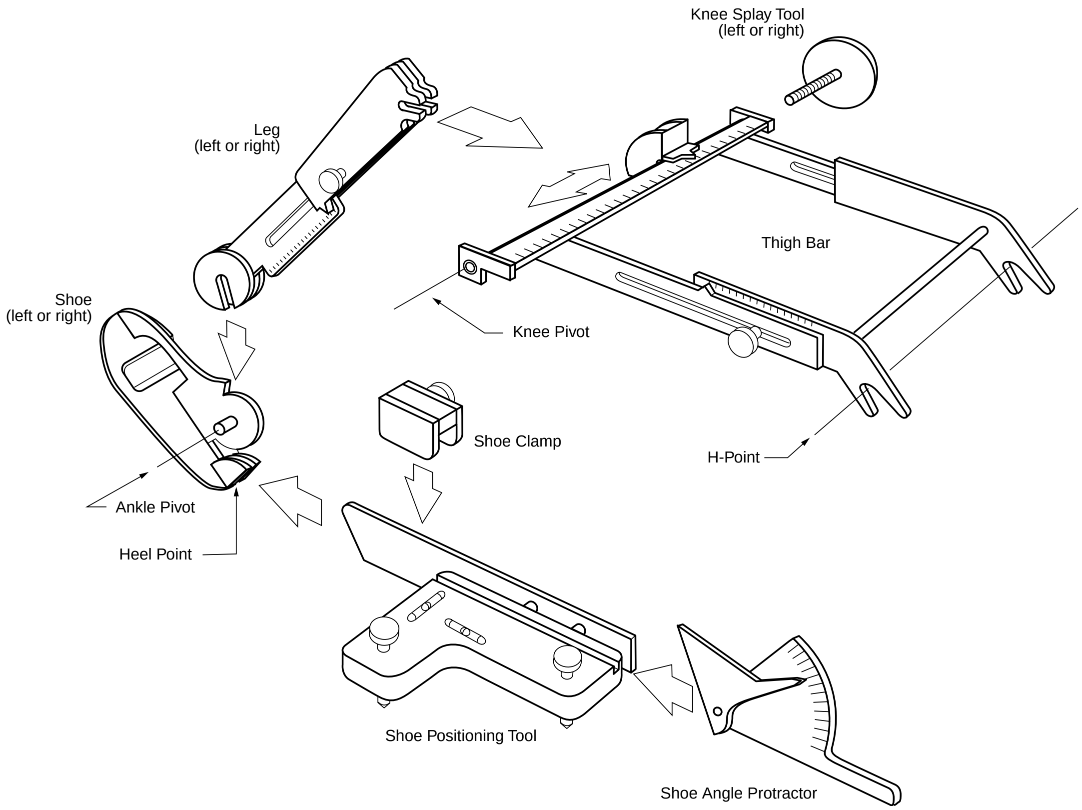

Figure 18. Updated thigh/leg/shoe.

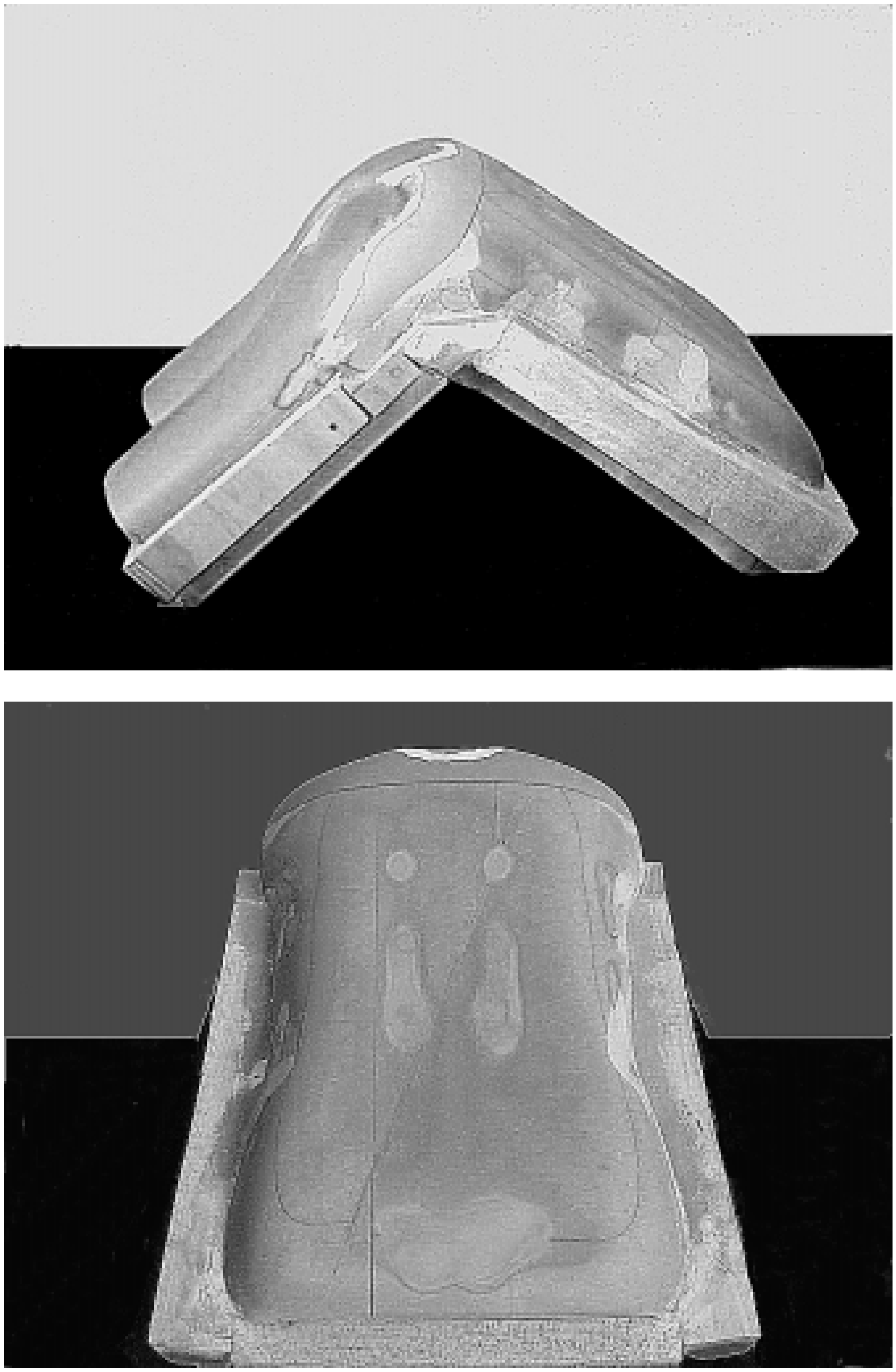

Figure 9. Model of the initial back and buttock surfaces developed by MSU.

APM-3 shown at the June 1998 IAP meeting retained the SAE J826 shells, because the new contour data from MSU were not yet available. A model of the proposed new contours from MSU was reviewed at that time, as shown in Figure 19. MSU data sets for the buttocks/thigh area provided seat contact surfaces but required extrapolation to define the surfaces at the sides above seat contact. Based on input from the IAP, the width of the contours at the H-Point was scaled to be dimensionally equivalent to J826 manikin

(385 mm). The H-Point was located 135 mm forward and 98 mm above the surface profile at centerline, to places the H-Point at the same position relative to skin surface as the present SAE J826 profile.

The MSU back data described a surface that was flatter and wider across the shoulders compared to SAE J826. After installing these contours on the APM, the contours were evaluated in several different vehicle seats previously used for manikin validation testing. The flat broad back contours did not work well laterally across seat back contours, creating unrealistic pressure distributions in the upper seatback area. The manikin thorax tended to bridge across the upper seat back bolsters resulting in varied lumbar support and back angle readings. A more rounded shoulder contour was needed to obtain the desired manikin performance. The back contour of the recently scanned midsize-male advanced crash dummy (AATD) shell was studied and the decision was made to use this surface. A slight adjustment to the side view profile of this surface was made to match the SAE J826 midline profile. Additional modifications were made to blend the surfaces at the sacral area where the AATD surface joins the MSU buttock/thigh surface.

2.10.4 APM-3 Revisions

After further evaluations, the buttocks contour termination was modified to be higher in the sacral area to provide buttocks contact against the seat back to stabilize fore-aft Cushion Pan location. The installation procedures, which had been under continuous development, were modified to further improve manikin consistency and accuracy. The linear lumbar support prominence scale was replaced with an angular pointer calibrated to the same linear scale as APM-3.

2.10.5 APM-4

APM4 was completed for the workshops with IAP companies, which began October 1998. APM4 is shown in Figure 10. The APM4 included new weight shapes, new components in the torso linkage, and the new leg/thigh/shoe designs.

Figure 10. APM-4 used in European IAP Workshops, January, 1999.

Following the workshops and feedback from the IAP representatives, modifications were made to APM4. A head room probe was added. The back angle protractor was moved from the H-Point to a higher more convenient location on the head room probe support structure. The angle indicator doubles as means to set the head room probe at the required 8 degrees.

A new method for applying installation loads to the cushion and back was developed. Several standard tools called automatic center punches were purchased. These tools use a spring release device to drive a punch when the tool is pressed against a surface. The spring used to drive the punch can be varied to provide desired and consistent impact loads against the driven surface. This provided an excellent means to load the manikin seat and back pans prior and during weight installation to insure consistency of seat and back pan position.

Other changes to APM-4 included:

- Add headroom probe (included in European Workshop version)
- Improved shoe lock, integrate with shoe (included in European Workshop version)
- More cushion angle indicator travel to beyond 22 degrees

- More positive lumbar support prominence indication
- Add hip, knee and foot (ankle) angle indicators (included in European Workshop version)
- Back Angle and Cushion Angle indications adjustable for calibration
- Numerals on indicators made larger and more readable (additional enlargement will be made on APM-5)
- Sacral panel interference with butt panel when joining back pan to butt pan eliminated with increased height to butt sides (sides of sacral panel are lowered on APM-5)
- Indentations added for better grip on thigh and pelvis weights)
- Improved consistency for load applications to back and cushion pans accomplished with application of "automatic center punch tool" load application tool.
- H-Point extension tube, to shift H-Point location outward from manikin, provided with hollow tube and removable H-Point buttons
- Specified reference points provided on linkage with standard divot holes
- Stops on ends of torso load bars to retain weights
- Single handle on seat pan, angled handle on torso to clear seat back

2.10.6 APM-5

As the ASPECT program concludes, a final prototype version is being produced by Technosports for the IAP companies. The APM-5 includes all of the functional changes to the APM-4, as well as many design changes for ease of manufacturing. A new, symmetrical master CAD model of the shells was developed, and new molds were created. Many of the linkage hardware components are now cast or machined using fewer parts than the earlier prototypes. Figure 20 shows an APM-5 prototype during assembly. A complete CAD drawing package for the APM-5 has been created.

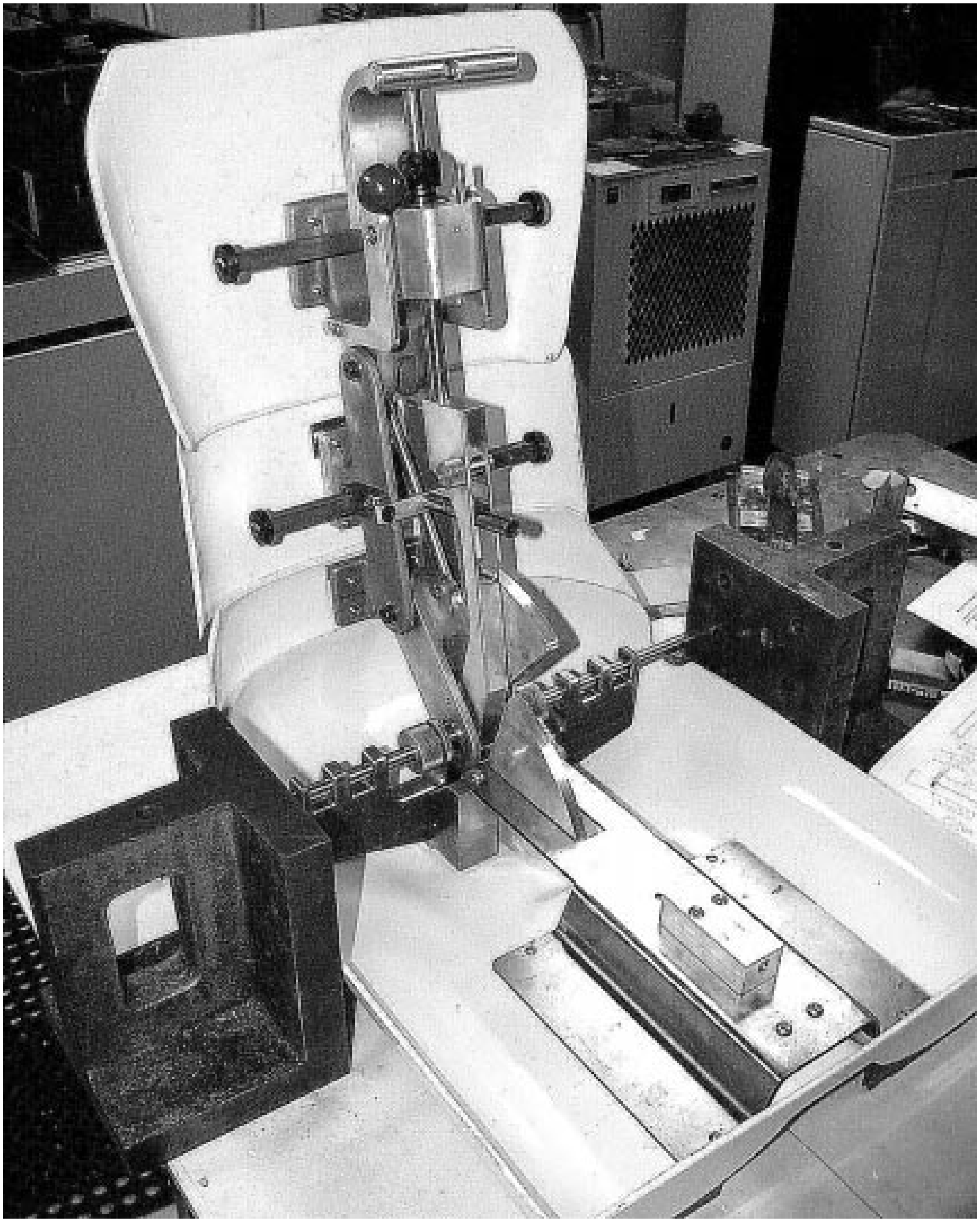

Figure 20. APM-5 during assembly.

3.0 COMPARATIVE RESULTS

The ASPECT manikin has undergone extensive evaluation and validation trials, conducted both at UMTRI and at the participating companies. The evaluations focused on the repeatability of the manikin and the success in attaining the performance objectives. As part of these evaluations, the ASPECT manikin measures of eleven driver seats were compared to the SAE J826 manikin measures.

The eleven seats were among twelve seats used in a study of male driver and passenger posture (20). One seat (seat six), a heavy-truck seat, was excluded from the present analysis because the seatback angle adjustment range was sufficiently limited that many subjects could not find a comfortable seatback angle. The seats were each mounted in a generic sedan-like vehicle package for testing (seat height 270 mm, steering-wheel-to-ball-of-foot horizontal distance 550 mm). In each of the seats, thirty male subjects with a wide range of anthropometry selected their preferred driver and front-seat passenger postures. Each subject adjusted the fore-aft seat position and seatback angle to obtain a comfortable posture, which was measured using a FARO arm digitizing device. Testing was conducted with and without the steering wheel and pedals to obtain both driver and front-seat passenger postures. Details of the posture measurement and analysis procedures are found elsewhere (15, 20).

One important finding from the study is that there were no important differences in torso posture across the eleven seats. For example, the angle with respect to the vertical of a side-view line from each subject's hip joint to the eye did not differ significantly across the eleven seats in driver or passenger postures and averaged about 8.5 degrees. This finding is consistent with other studies that have shown changes in seat geometry to have only small effects on torso posture (27, 28, 30).

For subsequent manikin testing, the seatbacks were fixed at the mean preferred seatback angle for the thirty subjects. Since the subject's torso postures were the same across the seats, on average, the mean selected seatback angles can be considered to represent equivalent seatback angles to the subjects. That is, the seatback angles were the same with respect to the postures that they supported. This provided a useful comparison for the two manikins.

Three SAE J826 manikin drops were conducted in each seat in accordance with standard procedures. Three ASPECT manikin drops were also conducted, using preliminary procedures documented by Roe et al. (17). A FARO arm digitizer was used to record the location of targets on each manikin's segments, including the H-point, relative to reference points on the seat frame.

Figure 11 shows the location of the ASPECT manikin H-point for each of the measurements, relative to the average J826 manikin H-point in each seat. Data from each seat are plotted using a different symbol. In the plot, a symbol at the origin would indicate that the ASPECT manikin H-point is directly coincident with the J826 manikin H-point. On average, the ASPECT manikin H-points are lower and rearward, relative to the J826 manikin H-points. The ASPECT manikin measurements for each seat are also tightly grouped, indicating good repeatability.

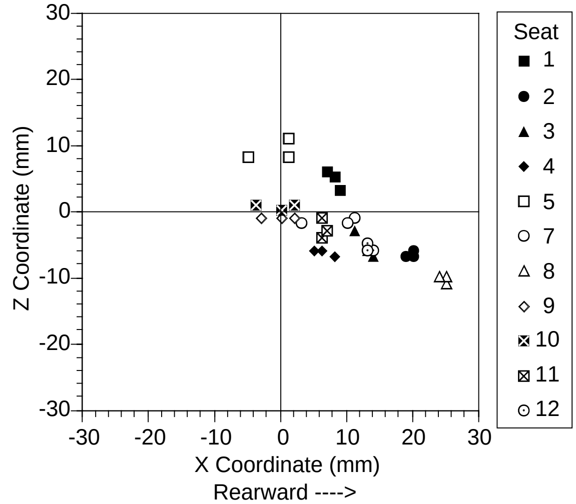

Figure 11. ASPECT manikin H-point relative to SAE J826 manikin H-point for three trials in each of eleven seats.

Further analyses of these data indicate an important relationship between the offset between the ASPECT and J826 manikin H-points. Figure 12 shows the horizontal offset between the two H-points plotted against the ASPECT manikin measure of lumbar support prominence. In the three trials in each of these eleven seats, lumbar support prominence ranged between 0 and 22 mm.

The lumbar support prominence measure is strongly associated with the horizontal offset between the two manikin H-points. This observation can be explained by considering the effect of the ASPECT manikin's spine articulation on manikin performance. In a seat with a prominent lumbar support, the rigid torso shell of the J826 manikin pivots around the lumbar support, pushing the H-point forward. In contrast, the articulated torso of the ASPECT manikin allows the buttock/thigh shell to slide fully rearward on the seat, while the torso wraps around the lumbar support during the installation procedure. As a result, the ASPECT manikin H-point is more rearward on the seat, relative to the J826 manikin H-point, as the lumbar support prominence increases.

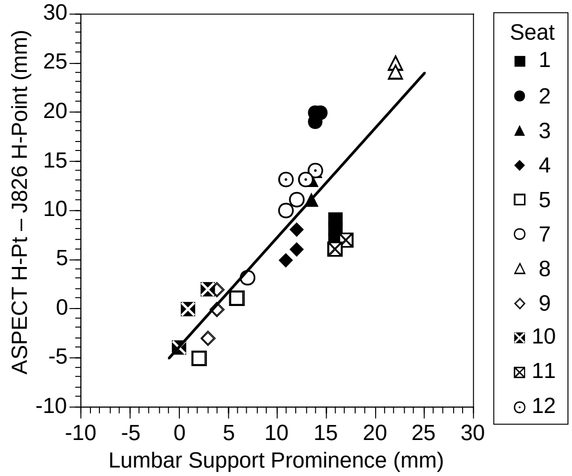

Figure 12. Horizontal offset between the ASPECT and SAE J826 manikin H-points as a function of ASPECT manikin lumbar support prominence measure.

This relationship suggests that J826 manikin H-point location can be predicted from the combination of the ASPECT manikin H-point location and the measured lumbar support prominence of the seat. Using a linear regression, the location of the J826 H-point forward of the ASPECT manikin H-point (mm) can be predicted from the equation

$$\text{ASPECT H-Pt (X)} - \text{J826 H-Pt (X)} = 1.14\ \text{LSP} - 4.3 \qquad [1]$$

where LSP is the lumbar support prominence as measured by the ASPECT manikin. The equation indicates that when the lumbar support prominence is zero, the two manikin H-points are approximately coincident. This confirms that the ASPECT manikin has met one of its performance goals, which is to replicate the J826 H-point in seats that produce a flat ASPECT-manikin back profile.

Using equation 1 and a similar equation developed for the vertical offset, the effectiveness of estimating SAE J826 H-point from ASPECT manikin measures was assessed. Figure 13 shows J826 H-point locations estimated from ASPECT manikin measures relative to the actual SAE J826 locations. Note that the discrepancies are less than 10 mm, indicating that it is feasible to predict J826 H-point locations from ASPECT manikin measures.

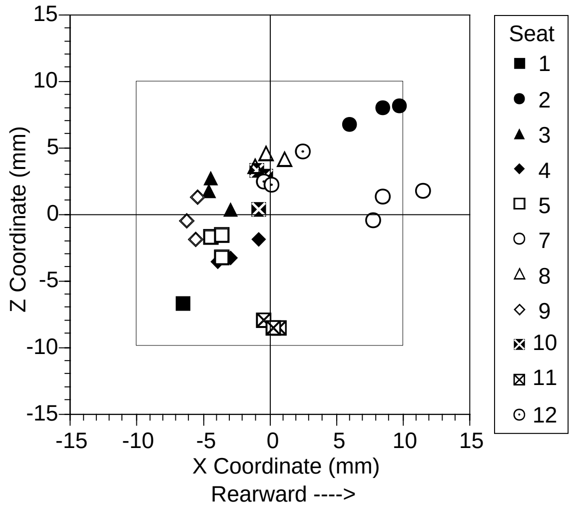

Figure 13. J826 H-point location estimated from ASPECT manikin measures relative to actual J826 H-point locations (averages of three trials with each manikin in eleven seats).

Table 2 summarizes some of the ASPECT and J826 manikin measures across the eleven test seats with each seat set to the mean preferred seatback angle. Each value represents the average obtained in three trials. In each case, the J826 H-point is defined as the origin for H-point measurements.

Figure 14 compares SAE J826 and ASPECT manikin seatback angles. The ASPECT manikin produced more upright seatback angle measures, on average. Ideally, a human-like manikin would record the same seatback angle in each of the seats, since they were each set to the subjects' mean selected angle, and each seat produced the same average preferred torso posture. However, the J826 manikin measured seatback angles between 21.5 and 27.3 degrees, a range of more than six degrees.

Table 2
Summary of Manikin Measures in Eleven Test Seats (Average of Three Trials per Manikin)

Seat	J826 H-Point (X, Z)	ASPECT H-point (X, Z)† (mm)	J826 Seatback Angle (degrees)	ASPECT Seatback Angle (degrees)	ASPECT Lumbar Support Prominence (mm)	ASPECT Seatback Angle (adjusted) (degrees)
1	(0, 0)	(8.2, 4.9)	21.5	19.6	16.0	22.9
2	(0, 0)	(19.6, -6.8)	27.3	22.3	14.2	25.3
3	(0, 0)	(12.9, -5.2)	23.3	21.1	13.7	24.0
4	(0, 0)	(6.2, -6.2)	23.8	21.6	11.7	24.1
5	(0, 0)	(-1.1, 8.7)	23.5	23.2	4.7	24.2
7*	(0, 0)	(8.0, -1.9)	25.0	20.9	10.0	23.0
8	(0, 0)	(24.9, -10.5)	24.7	18.5	22.0	23.1
9	(0, 0)	(-0.3, -1.0)	23.8	23.1	3.7	23.8
10	(0, 0)	(-0.6, 0.5)	24.8	22.6	1.3	22.8
11	(0, 0)	(6.1, -2.6)	23.7	20.9	16.3	24.3
12	(0, 0)	(13.3, -5.6)	21.5	17.9	12.7	20.6

* Seat number six, a heavy-truck seat, is omitted from this analysis because it had insufficient seatback angle adjustment range.
† Relative to the J816 manikin H-point; positive X and Z indicate that the ASPECT manikin H-point is above and behind the J826 manikin H-point.

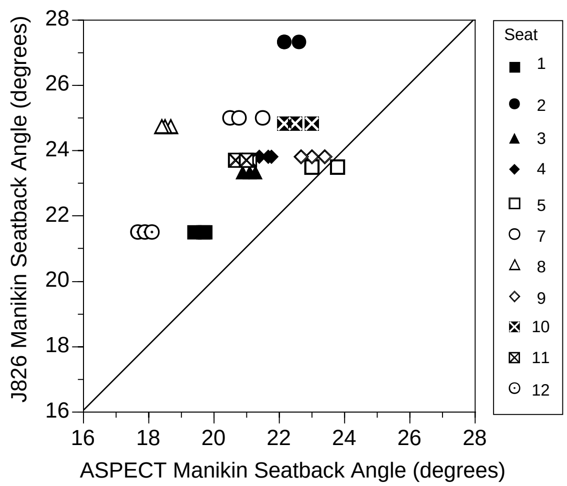

Figure 14. ASPECT manikin seatback angles for three trials in eleven seats compared to SAE J826 manikin (some points are coincident).

The ASPECT manikin seatback angles varied between 17.9 and 23.2 degrees, a similar range, but the ASPECT manikin lumbar support prominence measure provides a way of adjusting the manikin-measured seatback angle to obtain a more ideal seatback angle measure. Figure 15 shows the relationship between ASPECT manikin seatback angle and lumbar support prominence for the eleven test seats. The figure shows that increasing lumbar support prominence is associated with decreasing seatback angle measurements. This effect is produced by the buttock section of the manikin sliding rearward under the lumbar support, tipping the torso of the manikin more upright.

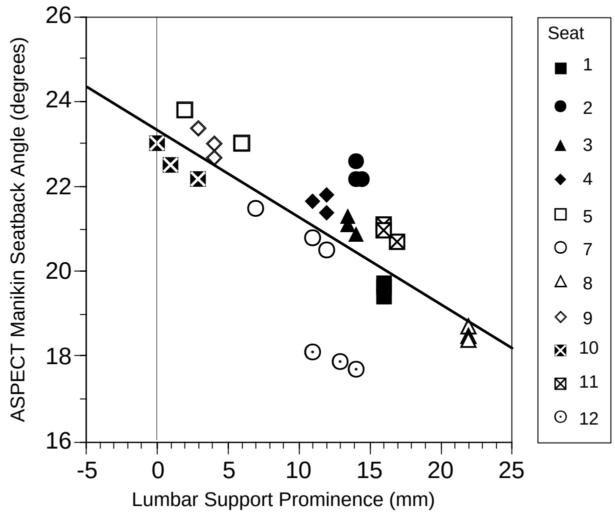

Figure 15. ASPECT manikin lumbar support prominence and seatback angle for three trials in each of eleven seats.

If the zero-lumbar-support condition is defined as the "true" seatback angle, each seatback angle measurement with the ASPECT manikin can be adjusted based on the lumbar support prominence. Using a linear relationship between seatback angle and lumbar support prominence, the adjusted seatback angle is given by

$$\text{SBA(adjusted)} = \text{SBA} + 0.209\ \text{LSP} \qquad [2]$$

where SBA is the seatback angle in degrees, and LSP is the ASPECT manikin lumbar support prominence. Adjusted seatback angle values in Table 2 vary between 20.6 and 25.3 degrees, a slightly smaller range than the unadjusted values. For all but two of the eleven seats, the adjusted seatback angle measure is within one degree of 23.5 degrees, the zero-lumbar-support intercept from Figure 15. Although this approach seems to be a promising method of relating seatback angle to human posture, more testing and analysis will be necessary to determine an optimal approach.

4.0 DISCUSSION

Human factors practitioners in the automotive industry initiated the ASPECT program to address the limitations of the current SAE J826 H-point manikin. The four-year program has culminated in the development of a new manikin, along with associated posture prediction models and other design and evaluation tools (15-20).

The new manikin is based on midsize-male anthropometry, providing compatibility with the current H-point manikin and midsize-male crash dummies. However, the manikin is not intended to represent a specific percentile on any dimension for any population. In fact, the manikin applications do not require a tool that matches any particular population percentile. The ASPECT manikin is intended to produce consistent measures of seat geometry that can then be related, via posture prediction models developed in the ASPECT program, to the posture of any occupant within any vehicle package (18).

Like the current J826 H-point manikin, the ASPECT manikin does not indicate whether a particular seat or vehicle is comfortable. Instead, the manikin provides measures of the position and orientation of the support surfaces on a seat that may be related to comfort. For example, the ASPECT manikin provides a new technique for measuring the contour of the seatback under occupant loading. This measure of lumbar support prominence may be more usefully related to occupant comfort than measures of the undeflected seat contour.

The ASPECT manikin described in this chapter is a prototype, subject to further revision after further testing. At this writing, the manikin is undergoing extensive evaluation at UMTRI and the participating companies. Minor changes in manikin features, including H-point location and mass distribution, may be required to meet the performance goals. The installation procedure, which is an important determinant of the manikin measures, is also subject to revision.

At the conclusion of the ASPECT program in September 1999, the SAE Design Devices Committee will begin the process of considering revisions to SAE J826 based on the ASPECT manikin and related research findings. A revised version of SAE J826 incorporating the new manikin is expected in June 2000. Implementation of the manikin into the vehicle design and development process is expected to take several years. Each company and organization will likely proceed at its own pace. The ASPECT research team will provide the supporting documentation necessary to assist companies with implementing the new tools. Although it is difficult to anticipate how any individual organization will proceed, the feedback from ASPECT participants suggests some potential paths to ASPECT manikin implementation.

The SAE Design Devices Committee will determine the other SAE practices that will be affected by changes in SAE J826. The H-point defined by the manikin is referenced in many other practices (e.g., J941, J1052, J1100, J1517). The Design Devices Committee will interact with the committees responsible for the affected practices to inform them about the new manikin and to suggest ways to make the necessary changes. Many practices will be able to incorporate the ASPECT manikin without change. In others, minor modifications may be required to account for the change in H-point location relative to the seat. Because the ASPECT manikin measures the seat independent of the vehicle package, it provides a platform for making many standardized seat-related measures that are not currently defined. A committee comprised of ASPECT participants has recently developed a preliminary list of seat dimensions based on the ASPECT manikin for potential inclusion in SAE J1100 (17).

Some of the issues that need to be considered as hardware and installation procedures are written into SAE Practices are:

- measurement accuracy definition,
- seat soak time and conditions prior to manikin installation,

- procedures for manikin calibration,
- define time after loading to take measurements,
- seat contact procedure using viewing holes,
- temperature and humidity requirements for installation, and
- definition of incremental loading and seat stiffness measurement procedures.

The SAE Design Devices Committee will also interact with the U.S. National Highway Traffic Safety Administration concerning the safety applications of the H-point manikin. Minor modifications to crash dummy positioning procedures would result from using the ASPECT manikin. However, as demonstrated above, there are straightforward ways of estimating J826 H-point from ASPECT H-point. UMTRI researchers have already begun the process of developing new crash dummy positioning procedures that are based on up-to-date information on vehicle occupant posture and position (33). Further communication with the related SAE committees and NHTSA will be required to develop an implementation plan for safety applications.

Each automaker and supplier will need to determine the best method for implementing the ASPECT manikin into its processes. Seat suppliers may begin using the manikin in comfort and design evaluations prior to its use as the primary seat measurement tool. The new articulated spine and shell contours make the ASPECT manikin more useful than the current H-point manikin for quantifying differences between seats. For example, the new manikin provides a method of quantifying lumbar support prominence that may be related to comfort evaluations. Auto manufacturers may need to use the new manikin in parallel with the current manikin on a pilot program to explore ways in which their in-house practices are affected. Changes underway in other SAE vehicle design practices (J1516: Pedal Reference Points; J1517: Driver-Selected Seat Position; J941: Driver Eye Position; and J1052: Driver Head Location) will provide an opportunity to take advantage of the new ASPECT manikin capabilities (19, 31, 34, 35).

The current SAE J826 manikin is used with several auxiliary tools, such as the belt-fit test device and the head restraint measurement device (9, 10). As noted above, the ASPECT manikin has not been made compatible with these devices, since differences in the posture of the ASPECT and J826 manikins would change the measurement values obtained with these tools. Further investigations will be conducted to determine the best ways of including the functionality of these add-on tools in the ASPECT manikin.

5.0 CONCLUSIONS

The ASPECT manikin builds evolutionarily on the success of the SAE J826 manikin to deliver new, more useful measures of seat and vehicle geometry. The ASPECT manikin measures the vehicle seat independent of the package while providing continuity with previous package-dimensioning practice. The new manikin is easier to use than the current manikin and is more stable and consistent, particularly in seats with prominent lumbar supports. Developed through industry cooperation, the ASPECT manikin is expected to become an important new tool for vehicle and seat design and measurement.

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CHAPTER 3

NEW H-POINT MACHINE APPLICATIONS AND MEASUREMENTS FOR DESIGNING, AUDITING, AND BENCHMARKING[†]

1.0 INTRODUCTION

1.1 Overview

The new H-Point Machine (HPM) and its 3-D descriptive counterpart (HPM-CAD) provide extended capabilities for vehicle seating design, development, and measurement while maintaining continuity with previous SAE Practices. This chapter describes how the HPM is used in the development of new designs, the audit verification of build, and in benchmarking competitive vehicle packages and seats. The measurement procedures are discussed along with a brief description and application of certain seat and package dimensions that are associated with the new tool.

A detailed proposal for the required revisions to SAE J826, now renamed *Devices And Procedures For Defining And Measuring Vehicle Seats And Seating Space*, is found in Annex 1 at the end of this report. The content of SAE J826 is expanded to include certain passenger car packaging procedures that are presently in SAE J1516, Accommodation Tool Reference Points. Annex 2 contains a detailed proposal for the required revisions to SAE J1100, *Motor Vehicle Dimensions.*

1.2 Manikin Applications

Procedures and tools developed by committees of the Society of Automotive Engineers (SAE) and documented in SAE recommended practices are used extensively during the vehicle design process (1).[*] The H-point manikin described in SAE J826 provides the H-point, a reference point used to predict the location of occupants in vehicles. The seating reference point (SgRP) defined in SAE J1100 locates the H-point in the vehicle workspace for drivers and passengers. Pedal plane angle (θ) and the 95th-percentile selected seat position curve described in SAE J1516 and J1517 are used to position the SgRP and manikin thigh, leg, and shoe. Additional measures provided by the H-point manikin and defined in SAE J1100 describe seat characteristics and the spatial relationships for seated occupants (the seating package). Assessment tools for spatial accommodation are provided by SAE J1517 (Driver Selected Seat Position), SAE J941

[†] Portions of this chapter were previously published in SAE Technical Paper 1999-01-0965.

[*] Numbers in parentheses denote references at the end of the paper.

(Drivers' Eye Location), SAE J1052 (Driver and Passenger Head Location), and SAE J287 (Driver Hand Controls Reach).

The SAE J826 H-point manikin is used in three general application categories during the development of seating packages. In *design*, the H-point and associated reference points and measurement definitions are used to specify seating package geometry for a proposed vehicle. After a prototype of the design is constructed, it is *audited* using the H-point manikin to determine build accuracy in relation to design specifications. The H-point manikin is also used to measure vehicles from other manufacturers for which the design intent is not known, an application commonly called *benchmarking*. Audit and benchmarking differ in that the design intent and specifications are known prior to beginning an audit evaluation, while benchmarking is conducted without any previous information about the vehicle or seat design specifications. The ASPECT manikin, also known as the ASPECT Physical Manikin or APM, is referred to in this chapter as the HPM (H-Point Machine) to prepare for its introduction in SAE J826. The HPM provides improvements over the current H-point manikin in its ability to measure the postural support characteristics of seats (2-5). Figure 1 shows a schematic of the HPM. The H-Point is retained as the primary reference point, and a new articulated torso measures the longitudinal contour of the seatback, expressed as Lumbar Support Prominence. The manikin also simultaneously measures seat Cushion Angle and Back Angle.

Unlike the current H-point manikin, the HPM measures H-point location in a seat without being connected to the vehicle package through leg segments. The HPM includes supplemental thigh, leg, and shoe segments that can be used to measure the package geometry, but these segments are not needed for the basic H-point measurement of the seat. This separation between seat and package measures simplifies use of the manikin and allows seats to be measured independent of the rest of the vehicle.

In this chapter, proposed procedures for using the HPM in vehicle design, audit, and benchmarking are presented. The manikin procedures are integrated with other tools developed in the ASPECT program, as well as with new accommodation models developed in coordination with ASPECT (5). These procedures and tools may be revised as they are incorporated into SAE recommended practices. The proposed procedures are intended to facilitate application and evaluation of the new tools.

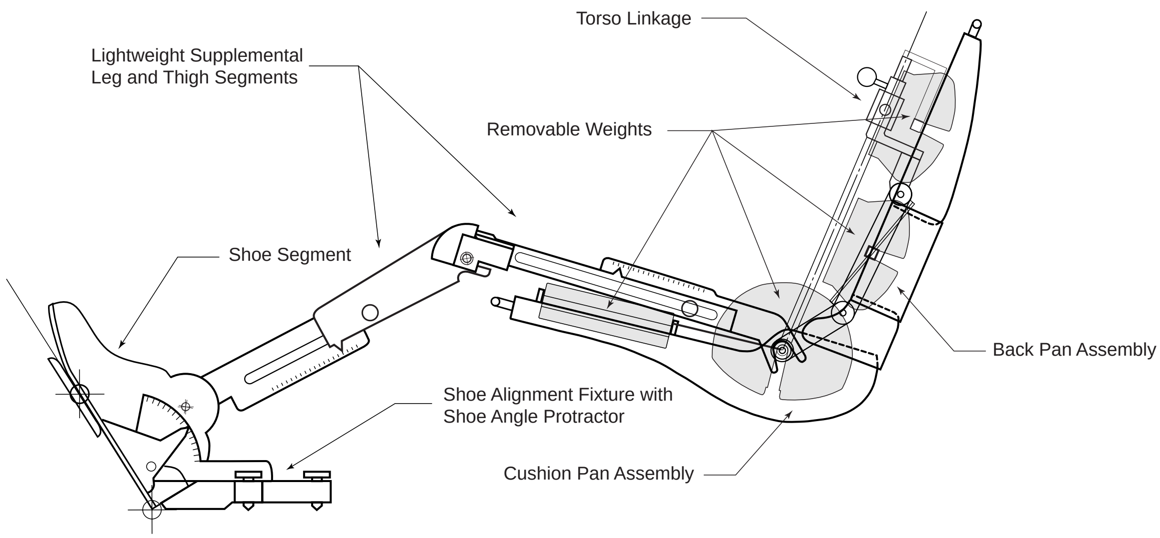

Figure 1. HPM schematic, showing supplemental thigh, leg, and shoe segments.

2.0 METHODS

2.1 HPM Seat Measures

The HPM is intended primarily as a seat measurement tool with additional capability for measuring certain package dimensions. Figures 2 and 3 shows a schematic of the tool in a seat, illustrating the four primary seat characteristics measured by the manikin.

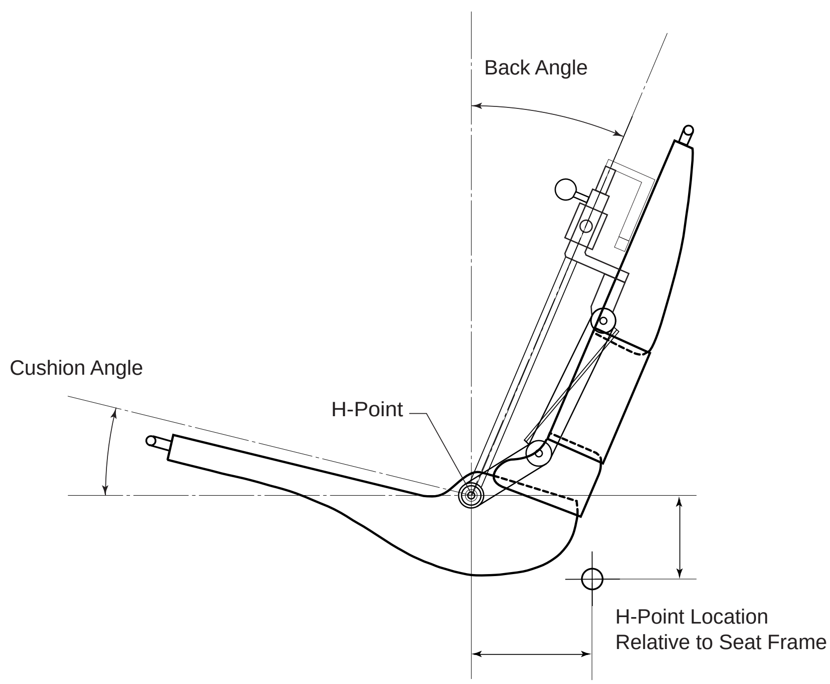

Figure 2. HPM schematic, showing measures of H-point location, Back Angle and Cushion Angle.

2.1.1 Lumbar Support Prominence

One of the limitations of the current J826 H-point manikin that motivated the development of the HPM is the rigid torso, which is often unstable when the manikin is installed in seats with prominent lumbar support. The HPM torso section includes a two-joint, articulated lumbar spine that mimics human lumbar-spine flexibility, creating a torso comprised of pelvis, abdomen (lumbar), and thorax segments. Each internal segment is attached to a contoured shell section collective called the Back Pan. A connecting rod across the lumbar joints synchronizes the motion of the thorax and pelvis segments so that spine flexion is distributed approximately equally across the two joints (3). When installed in a seat, this flexible linkage allows the manikin torso to conform to the longitudinal shape of the seatback. The external shell profile of the HPM torso conforms closely to the profile of the current manikin torso when the linkage is in its neutral position, depicted in Figure 2. However, in a seat with a prominent lumbar support, the manikin lumbar spine extends as the torso shells conform to the shape of the seatback, as shown in Figure 3.

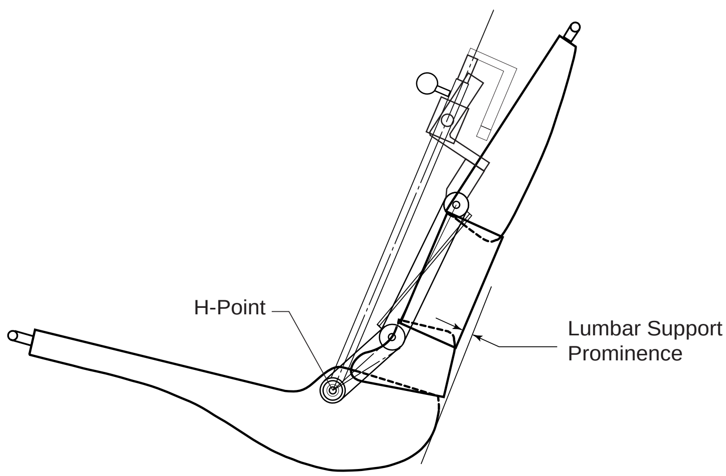

Figure 3. Illustration of Lumbar Support Prominence measurement with the HPM, showing a positive LSP.

The change in spine flexion is interpreted as Lumbar Support Prominence (LSP). The LSP is expressed in millimeters, corresponding to the displacement of the external lumbar shell of the manikin relative to the neutral, straight-back condition. Positive LSP indicates that the HPM linkage is extended, giving a lordotic or inward-curving shape to the external profile. Negative LSP indicates an outward-curving or kyphotic external profile, and the lumbar prominence reading is zero when the seat produces a manikin profile that corresponds to the flat profile of the current SAE J826 manikin.

2.1.2 Seat Back Angle

The HPM includes a Back Line that replicates the function of the Torso Line on the current J826 manikin and two-dimensional (2D) template for defining and measuring seat Back Angle (L40). The HPM Back Line is parallel to the surface profile in the lumbar area of the HPM when installed in a seat with zero Lumbar Support Prominence, just as the Torso Line of the current manikin is parallel to the external shell profile. For other levels of LSP, the Back Line remains approximately parallel to the external shell section connected to the lumbar segment of the tool. Note that the HPM Back Line does not connect the H-point with another point having an anatomical correlate, such as the shoulder. When installed in a seat, the angle of the HPM Back Line with respect to vertical defines the seat Back Angle. Combined with the Lumbar Support Prominence measure, seat back angle measures the deflected surface contour of the seatback in a way that can be related to human posture.

2.1.3 Seat Cushion Angle

SAE J826 was recently amended to include a technique for measuring seat Cushion Angle (L27). In the J826 procedure, the current manikin is installed without legs and with a modified weight distribution to obtain a measure of the orientation of the deflected seat cushion surface. This measure is a factor affecting driver-selected seat position and driver posture (6, 7). The HPM produces a similar measure as part of the normal installation process. A Cushion Line is defined on the HPM at an orientation designed to replicate the seat Cushion Angle measure obtained with the J826 manikin. This is approximately the orientation of a line connecting the hip and knee joints of a midsize male sitting with his thighs fully engaged with the seat cushion. The thigh orientations of sitters will usually differ from the measured seat Cushion Angle because thigh angle is affected by factors other than seat Cushion Angle, such as Seat Height.

2.1.4 H-Point Location

The distances from the HPM H-point to the bottom and rear of the manikin buttock/thigh shell profile are designed to be the same as the corresponding dimensions on the current J826 manikin. As with the current manikin, the H-point is intended to approximate the hip joint location of a human in the seat. When the HPM is installed in a seat with a Lumbar Support Prominence that measures zero, the HPM H-point is intended to be coincident with the SAE J826 H-point (3). However, in seats with more- or less-prominent lumbar supports, differences between the manikins in H-point location are expected. The H-point location will not generally replicate the hip joint location of any particular category of sitter. Hip joint locations are affected by a number of factors, only some of which are measured by the HPM. The HPM H-point is one of the inputs to posture prediction models that are used to locate human hip joints relative to the vehicle and seat (4).

2.2 HPM Package Measures

When the HPM is installed in a vehicle with the seat positioned so that the HPM H-point is at the seating reference point (SgRP), the supplemental thigh, leg, and foot tools can be used to measure the package geometry. Figure 4 shows the tool with the supplemental segments used to measure both driver and rear seats. The measures obtained using these procedures are essentially the same as those obtained with the current J826 manikin, so only a few will be discussed here.

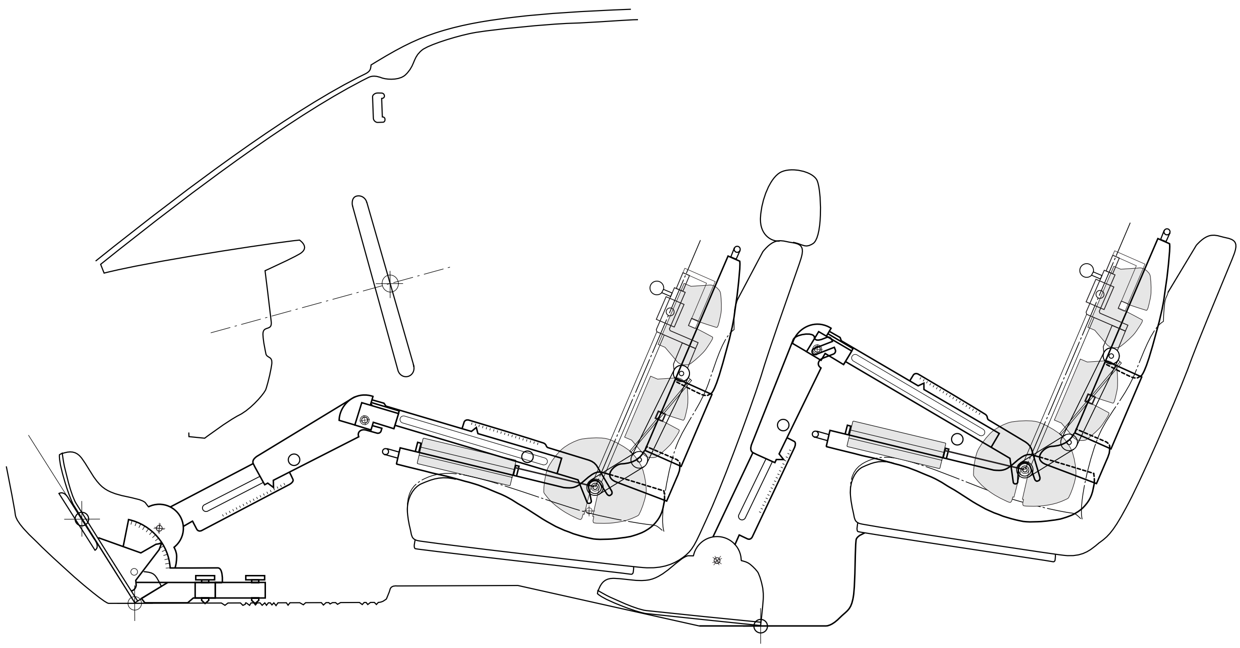

Figure 4. HPM used to measure driver and rear seat package geometry.

2.2.1 Thigh Angle

The vertical distance from the SgRP to the heel rest surface, denoted H30 in SAE J1100 for the driver seat, is the Seat Height. Because the HPM thigh segment is independent of the weighted manikin buttock/thigh shell, the HPM measures a Thigh Angle (relative to horizontal) that is generally greater than the Cushion Angle. The Thigh Angle is determined by the package geometry, specifically the Seat Height. In fact, using the practices described in this chapter for locating the Pedal Reference Point (PRP), Pedal Plane Angle, and SgRP, Thigh Angle can be calculated directly from Seat Height. A new measurement definition for Thigh Angle will be provided in SAE J1100.

2.2.2 Knee Angle

Knee Angle is the included angle between the thigh and leg segments, and is essentially identical to the measure denoted L44 in SAE J1100 using the present SAE J826 manikin. The angle is measured in a vertical plane only. Because the Knee Angle is measured with the seat located at the SgRP and with defined leg and thigh segment lengths, it does not necessarily represent the knee angles of any particular occupants.

2.2.3 Hip Angle

The Hip Angle is measured between HPM Thigh Line and the Back Line (Back Angle). As with the Knee Angle it is essentially the same as the current dimension (L42) in SAE

J1100. The Back Angle is either set to design or to a default value used for benchmarking, and the Thigh Angle is determined by Seat Height.

2.2.4 Foot Angle

The Foot Angle is measured between the HPM Leg Line and reference line on the shoe that defines the bottom of a foot profile on the shoe. This angle is defined as L46 in SAE J1100. As with the other angles measured using the manikin lower extremities, the Hip Angle and Foot Angle do not necessarily represent typical posture measures for any occupant category. Rather, these angles provide dimensions that can be used to compare geometry across vehicle seat packages. Because the angles for the driver seating position are direct functions of the manikin geometry, the SgRP, and the Pedal Plane Angle (or Floor Plane Angle for passengers), the angles of the thigh, leg, shoe segments are likely to be more useful for quantifying rear seat packages. Table 1 lists some of the vehicle and seat dimensions for the driver defined and measured using the HPM. Measures shown in *italics* are redefined or not currently in SAE J1100. Also note that measures discussed are for the driver and have 2nd and 3rd seat counterparts.

2.2.5 New Definitions for SgRP and Pedal Reference Point

In conjunction with the ASPECT program, new proposals have been developed to improve the definitions of SgRP and Pedal Reference Points. These new methods are presented in detail elsewhere (5). Using the new procedures, a Pedal Reference Point (PRP) is defined on the pedal independent of the rest of the package, using only the local pedal and floor geometry. The new SgRP locator line determines the SgRP location aft of the PRP as a function of seat height. The intersection between the SgRP locator line and the H-point travel path defines the SgRP.

2.3 Use of the HPM in Occupant Packaging and Seat Design

2.3.1 Occupant Packaging

The HPM is used in vehicle design mainly through reference to its geometry and measurement capability. Since the HPM is primarily a seat measurement tool, most of the design tasks involving the tool concern the seat, but the supplemental manikin leg, thigh, and shoe can be used to establish clearance specifications. HPM-CAD can be used to depict these dimensions. For example, knee and shin clearance guidelines based on the current J826 2D template can be readily adapted for use with the HPM-CAD geometry. As part of the package design, the HPM/HPM-CAD measures of the seat can be specified. In fact, some seat measurements, such as seat Cushion Angle, must be specified for use with the new accommodation models (5, 7).

Table 1
Measures Used to Define Vehicle Seats And Packages
(New measures are shown in italics.)

HPM Measures - Driver (New SAE J826 measures to be defined in SAE J1100)	Application in Design Development	
	Seat	Package
Back Angle L40*	x	x
Cushion Angle L71*	x	x
*Lumbar Support Prominence L81**	x	x
Seat Height H30		x
SgRP Y Coordinate W20		x
*AHP to PRP Lateral Offset W14**		x
*AHP Y Coordinate W8**		x
*PRP Y Coordinate W1**		x
*Pedal Plane Angle L2**		x
*PRP X Coordinate L1**		*x*
*AHP X Coordinate L8**		x
*AHP Z Coordinate H8**		x
SgRP X Coordinate L31		x
SgRP Z Coordinate H70		x
*Thigh Angle LXX**		x
Hip Angle L42 (similar to old L42)		x
Knee Angle L44 (similar to old L44)		x
Foot Angle L46 (similar to old L46)		x
*Seat Cushion Length to Seat Back SL9 **	x	
*Maximum Seat Cushion Width SW3**	x	
*Seat Back Thickness SL65**	x	
*Maximum Seat Back Width SW55**	x	

*New dimension codes are shown. The S prefix designates a specific seat dimension. Additional seat and package measurement definitions are presented in Annex 2 of this report, *Proposed Revisions To SAE J1100*.

2.3.2 Seat Design

Measurements that can be made with the HPM correspond to a potential specification for seat design. The H-point location relative to the seat frame is specified, as are the seat Cushion Angle and Lumbar Support Prominence. A particular seat back frame orientation is selected that corresponds to a specified HPM measured (seat) Back Angle. In addition, the H-point, Back Line, and Cushion Line can be used as references to define many additional seat measures. The proposed revision to SAE J1100 (Annex 2 of this report) describes a large number of seat dimensions, many of which are referenced to the HPM.

2.4 Use of the HPM for Audit and Benchmarking

The primary use of the HPM is measuring vehicle seats and packages. The measurement is considered an audit if the primary purpose is to assess the extent to which a seat or vehicle meets with design intent. In an audit measurement, the design positions of the vehicle and seat components to be used during the measurement have been previously specified by the vehicle manufacturer. Benchmarking with the HPM uses very similar procedures to measure a vehicle for which the design intent is not known. Consequently, the positions and settings of vehicle components and adjustments must be determined using standardized guidelines to ensure compatibility of the measurements across vehicles. To simplify the discussion, the audit procedures will be described first, followed by the changes to the procedures necessary for a benchmarking measurement.

2.4.1 Seat Measurement

A seat measurement begins by setting the seat components to the designated configuration. The seat cushion frame angle and seatback frame angle are set to the design position, meaning the default values set by the vehicle designer. Any other adjustments, such as lateral bolsters or adjustable lumbar supports, are set to their design positions. In effect, the seat components are placed in the positions and orientations that are expected to produce particular manikin measurements. The audit determines if the seat build has met the intent.

The manikin is then installed in the seat, using the procedure in Appendix 2 of the new SAE J826 Proposal (Annex 1 of this report). A muslin cloth identical to the one currently specified in J826 is laid on the seat to standardize the friction under the manikin. The HPM is placed on the seat and the torso linkage is unlocked to allow the torso to conform to the shape of the seatback. If desired, the HPM Cushion Pan (buttock/thigh segment) can be placed on the seat first, followed by the Back Pan (torso segments), which connects to the Cushion Pan at the H-point. Weights are added to the Cushion Pan first, then to the Back Pan. After each loading step, a calibrated loading device is used to push the HPM into the seat and built-in bubble levels are used to ensure alignment with the seat. After all of the weights have been added, the torso linkage is locked to prevent movement during measurement, completing the installation. The locations of reference points on the HPM can be recorded using coordinate measurement equipment, and the seat Cushion Angle, Back Angle, and Lumbar Support Prominence can be read from scales on the HPM.

2.4.2 Package Measurement

For package measurement, the HPM is used with the supplemental thigh, leg, and shoe segments. Because these segments do not interact dynamically with the vehicle or seat, most of the package measurements can be performed in CAD after measuring the seat with the HPM, as described above, then recording the locations of a few points on the accelerator pedal and floor. However, the entire procedure can also be conducted physically, in a vehicle or mockup. Appendix 2 in the SAE J826 Proposal describes the entire procedure using parallel steps for physical measurement and CAD measurement.

For the driver seat, the first step is to establish the Pedal Reference Point (PRP) on the accelerator pedal, as shown in Figure 5. The PRP is defined on the undepressed accelerator pedal. On a physical pedal, the PRP may be located by positioning the HPM shoe tangent to the pedal at the Ball Of Foot. Usually the pedal will be blocked to keep it from moving during measurement, and pivoting pedals must be measured in their rest position. A shoe alignment fixture provided with the HPM holds the shoe in place against the pedal, simultaneously locating the PRP and shoe rest surface on the floor. On a curved pedal, the tangent point can be difficult to locate physically, although it is no more difficult than the current procedures for locating AHP and BOF. The procedure is straightforward in CAD. Figure 5 shows the PRP and AHP established with the manikin shoe and shoe alignment fixture.

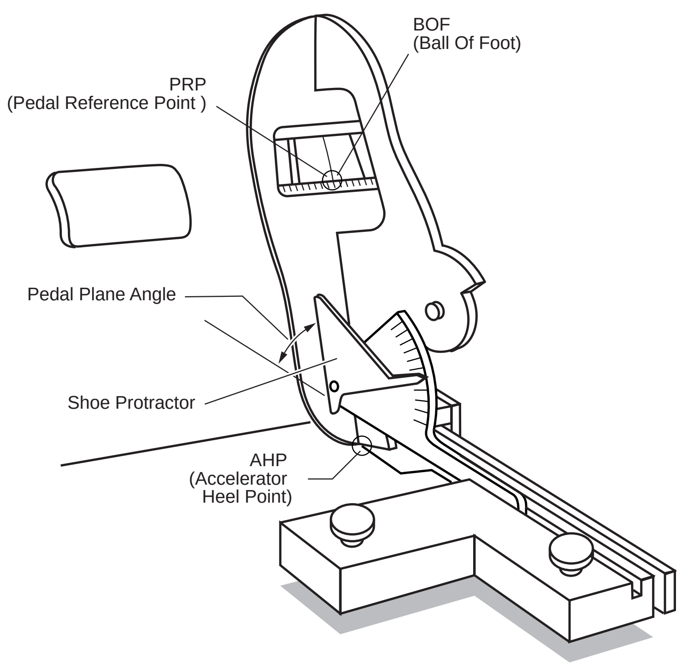

Figure 5. Establishing PRP and AHP.

Next, the HPM is installed in the seat, following the procedures described above and in Appendix 2 of Annex 1. The seat may be positioned anywhere within its track travel range, provided that the seat cushion and seatback have the appropriate orientations with respect to vertical. For an audit measurement, the seat track, seatback recliner, and any other seat adjustments would be placed in their design positions. Seat position will typically be specified with regard to seat track position, such as three detents forward of full rear. Alternatively, the positions of some fiducial points on the seat frame could be specified with respect to other reference points on the vehicle. For an audit measurement, this detailed information is commonly provided.

With the HPM and shoe in place, adding the lightweight thigh and leg segments completes the installation. The thigh and leg are adjusted to 452-mm and 436-mm lengths, respectively, which are based on average lower extremity dimensions for men matching the SgRP reference stature (3, 5). Coordinate measurement equipment, portable inclinometers, or other equipment can then be used to record the manikin segment positions and orientations. Figure 6 shows some of the package-related dimensions that can be measured using the supplemental thigh, leg, and shoe tools. These dimensions are often quantified in CAD rather than with physical measurements.

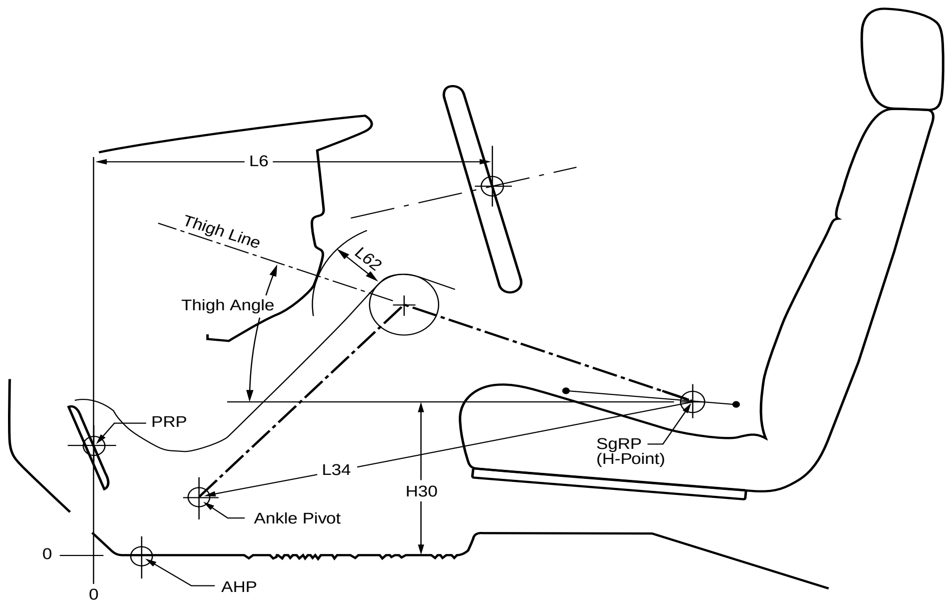

Figure 6. Driver package dimensions.

Use of the HPM for benchmarking is similar to the audit installation process, except that the appropriate positions of the seat and its components are not known in advance. As part of the process of developing HPM usage procedures, a preliminary set of guidelines for setting adjustable components in benchmarking applications has been developed. Table 2 lists some of the proposed settings, which specify that components be set to the least restrictive settings or to the middle of the adjustment range. Lateral bolsters, for example, are set to the least restrictive position. Some pneumatic lumbar support adjusters are difficult to set to a middle position, so a minimum-prominence setting is proposed for all adjustable lumbar supports. Lumbar support height adjusters are set to the middle of the travel range. Seat cushion angle is set to the middle of the travel range for seats without height adjustment and to the orientation obtained in the full-down, full-rear position for seats with adjustable height and angle. Seatback angle must be set using the manikin. A typical average value of driver-selected Back Angle (22 degrees) has been chosen as the default for Class A vehicles, and a more upright angle (17 degrees) for Class B vehicles. Recommended settings for other seat adjustments will be developed as needed for potential standardization in SAE J826. If manufacturers use these settings as the design position, a benchmarking measurement of a vehicle will yield measurements that are close to the design intent, fulfilling the purpose of standardized, industry-wide measures.

After the seat components are set to their default positions, the HPM is installed using the procedures described in Appendix 2 from the SAE J826 Proposal (Annex 1). The location of the H-point is measured relative to one or more targeted reference points on the seat. The targeted reference points should maintain a constant dimensional relationship with the H-point throughout the range of seat track travel. Usually these points are on a part of the seat frame above the track adjuster.

Table 2
Proposed Default Seat Adjustments
for Use in Benchmarking Measurements*

Adjustment	Setting
Vertical	Mid-height
Seat Cushion Angle (independent)	Middle of range
Seat Cushion Angle (dependent, related to seat adjuster movement)	Seat H-Point at SgRP
Driver seat Back Angle (Class A vehicles: passenger cars, station wagons, MPVs and light trucks)	Adjustable backs: 22 degrees, as measured with the HPM Fixed backs: as measured
Driver seat Back Angle (Class B vehicles: heavy trucks and buses)	Adjustable backs: 17 degrees, as measured with the HPM Fixed backs: as measured
Lumbar Support Prominence	Minimum setting
Lumbar Support Height	Middle of range
Seat Bolsters	Minimum, least restrictive setting

*A similar table is provided for audit application where certain adjustments are specified according to proposed SAE design procedures set forth in the SAE J826 proposal (Annex 1).

The seat is exercised through its full range of travel, including vertical and angle adjustment. The targeted seat reference point locations are measured at the extremes of travel. Using the measured relationship between the H-point location and the seat reference points, the H-point travel path can be determined. For a two-way, linear seat track, two measurements are sufficient to define the H-point travel path. For a typical “six-way” seat adjuster, which can move horizontally, vertically, and change seat cushion angle, the H-point travel path has a rectangular appearance. Figure 7 shows a typical H-point travel path for a height-adjustable driver seat. In general, the H-point travel path should not be determined by tracking the actual HPM H-point as it moves with the seat, because the H-point measurement is defined, for packaging purposes, only with the seat at the design or default orientation. Further, during the time required to move the seat through its range of motion, the loaded HPM position may change due to compression of the seat foam. However, it may be useful to measure the seat track movement with the HPM in the seat, because the HPM weight may produce small deflections in the seat mounting hardware.

Next, the SgRP position within the H-point travel path must be determined relative to the PRP and AHP previously established. For a linear seat track, the SgRP location is the intersection between the previously described SgRP locator line and the H-point travel path. For a height-adjustable seat, SgRP is defined as the midpoint between the intersections of the SgRP locator line with the top and bottom of the H-point travel path, putting the SgRP at the middle of the height adjustment range. Note that the a manufacturer may specify the height to be set for an *audit*. For a linear track, the SgRP location is determined by finding the intersection of two lines, a problem readily solved using a spreadsheet or a hand calculator. Determining SgRP location for a height-adjustable seat is more complex, but can be readily accomplished graphically, either on paper or in CAD.

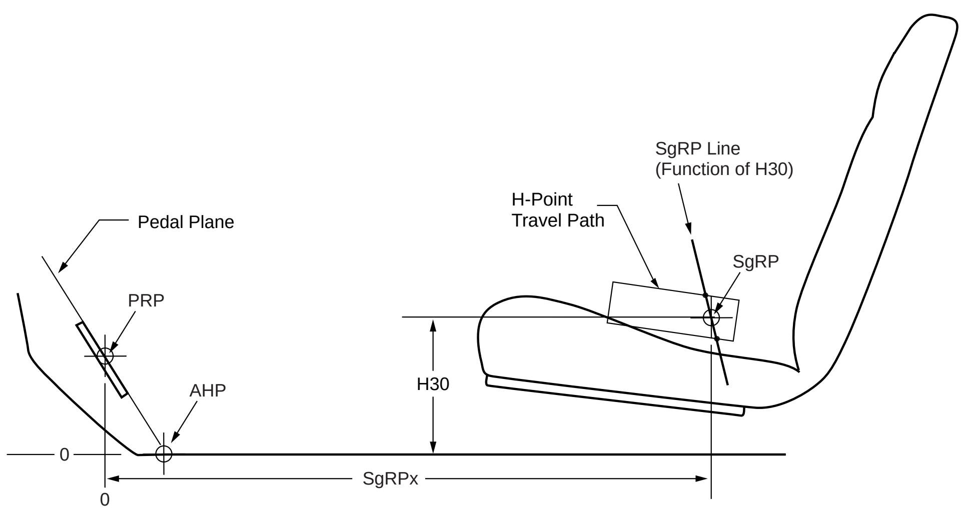

Figure 7. Illustration of H-point travel path with SgRP location.

Using the targeted seat reference points, the seat is moved into a position such that the HPM H-point is located at the SgRP. The HPM is installed as before, and the H-point location is measured to verify that it is positioned at the SgRP. For seats with discrete seat track adjusters, the positioning of the track detents may preclude accurate positioning, in which case the nearest detent should be used. Small changes in seat position to accurately locate the H-point on the SgRP are appropriate if they can be accomplished quickly without changing the HPM position relative to the seat. With the HPM positioned so that the H-point is located at the SgRP, the leg and thigh segments are added to complete the installation.

Most benchmarking measurements can be made without physically positioning the seat with the H-point at SgRP by performing the thigh and leg segment installation in CAD.

On the physical seat, the H-point location is measured relative to reference points on the seat, and the H-point travel path is determined by moving the seat while tracking the reference points. Recording the locations of a few points on the accelerator pedal and floor completes the necessary data collection from the vehicle. In CAD, the PRP can be determined and the SgRP locator line positioned appropriately. Using the H-point travel path, the SgRP position is determined and the corresponding seat height is used to determine the shoe angle. The thigh and leg segments are then added, completing the virtual installation.

Passenger seat procedures are similar to those used for the driver seat. For front seat passengers, no fore-aft shoe position is specified in SAE J1100, however the new SAE J826 does provide a shoe location procedure. For 2nd and 3rd seating positions, the driver shoe is used in multiple positions. When measuring a rear seat, the seat in front of the measured location, if adjustable, is set to the SgRP (design) position. The shoe is then placed on the floor in front of the seating position, typically centered on the occupant centerline, and moved forward until its forward progress is stopped by the front seatback or other components. In certain seating packages, the resulting position is marked, and the front seat is moved forward to facilitate access. The HPM, including the thigh and leg segments, is installed to measure the package geometry.

2.5 Additional Seat Measurements

SAE J1100 defines hundreds of dimensions, but few of these are seat dimensions. In an effort to develop a standardized terminology for seat design similar to the package dimensions that have facilitated vehicle interior design practices, an ASPECT-IAP task group developed a set of seat dimensions. These dimensions include some that are measured using the ASPECT manikin, and others that can be measured without a manikin. Figure 8 illustrates some of the proposed dimensions. The SAE J1100 Proposal (Annex 2 of this report) contains a complete description of the newly defined measures that will be considered for future approval.

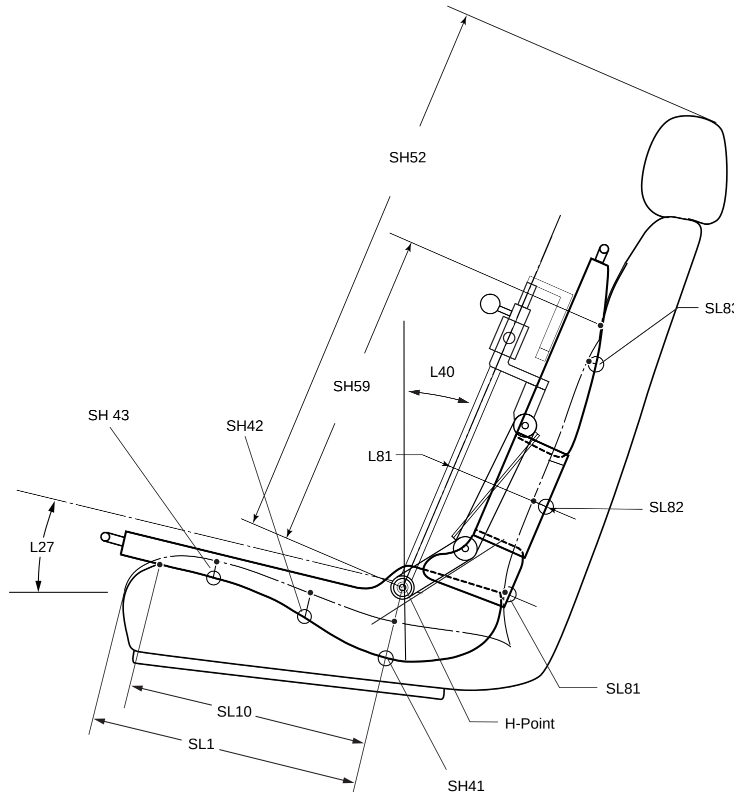

Figure 8. Some proposed seat dimensions based on HPM geometry.

The HPM can also be used to obtain measures of seat stiffness that may be more closely related to the experience of the vehicle occupant than measures obtained using conventional techniques. The HPM weights are designed to be installed incrementally. For example, the twelve weights in the Cushion Pan can be installed in three equal distributions of four weights. If the H-point and Cushion Line are measured at each step in the process, curves can be plotted showing the deflection Cushion Pan reference points as a function of the fractional manikin load. The slopes of these curves provide measures of local seat cushion stiffness and can be used to compare and specify these properties of seats. Similar seat stiffness measures can be obtained on the seatback, where the change in the lumbar support prominence reading during loading is a useful measure of the stiffness of the lumbar support.

3.0 DISCUSSION

The HPM was developed as an improvement on the current SAE J826 H-point manikin, preserving many of the important performance features while providing improved ease of use and additional measurement capability. The HPM is integrated into a new set of vehicle design and evaluation practices that include new pedal reference points and a standardized SgRP location (3, 5). The installation and usage procedures described in this chapter represent an evolution of the current design practice incorporating the additional functionality of the new tools. The HPM, HPM-CAD and proposals for SAE J826 and SAE J1100 revisions were produced in the context of a research program that substantially expanded the available information concerning the influence of vehicle, seat, and anthropometric factors on occupant posture. Drawing on these research results, the new measures obtained with the HPM can be used to represent human occupants more accurately during the design process. The use of the HPM in design is facilitated by related HPM-CAD tools, including occupant posture-prediction models and three-dimensional human body reference forms (5).

During the course of the ASPECT program, the research team examined a number of applications for which the current J826 manikin is used that go beyond its basic role in defining vehicle and seat reference points. These include modified procedures, such as the techniques used in crash dummy positioning (9), and the use of the manikin with add-on devices, such as the Head Restraint Measuring Device (10) and the Belt Fit Test Device (11). These techniques use the J826 manikin as a surrogate for human positioning information and as a platform for mounting measuring tools. Because the HPM performance in vehicle seats is different from that of the current manikin, the *current* add-on tools, such as the head-restraint and belt-fit measuring devices, cannot be used directly with the HPM. However, the extensive vehicle occupant posture data collected during the ASPECT program can be used to develop similar tools to perform these measurements using the HPM, with potentially greater accuracy and ease of use (4, 5, 8). A head model is included in the proposed revisions to SAE J826.

The procedures described in this chapter are proposals based on information available at the conclusion of the ASPECT program. Additional evaluations of the HPM and its associated procedures will be required of the companies participating in the ASPECT program. After these evaluations of the HPM are completed, the SAE Design Devices Committee will consider the manikin for incorporation into SAE J826 and new measurement definitions for SAE J1100.

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CHAPTER 4

NEW CONCEPTS IN VEHICLE INTERIOR DESIGN USING ASPECT[†]

1.0 INTRODUCTION

Automobile interior package design practices have been greatly aided over the past thirty years by the development of a variety of standardized tools to represent the behavior of vehicle occupants, particularly drivers. Committees of the Society of Automotive Engineers (SAE) have developed a set of interrelated physical and statistical tools that define human-centered reference points and capture anthropometric and postural variability in simple equations and design templates.

SAE Recommended Practices provide support for vehicle interior design in three primary areas. First, SAE J826 describes the H-point manikin, a weighted, contoured manikin that defines and measures the H-point, an estimate of human hip joint locations in a seat that is the primary reference point for occupant accommodation assessment. The geometry of the H-point manikin's leg and shoe define pedal reference points (Ball of Foot and Accelerator Heel Point) that create the origin for a driver package coordinate system. Second, SAE J1100 defines vehicle dimensions, many of which are defined with reference to the H-point and pedal reference points measured using the H-point manikin. Headroom, legroom, and vision angles are measured with reference to these human-centered points. Third, a number of SAE practices describe task-oriented percentile accommodation models that encapsulate a large amount of human anthropometric and behavioral data in simply formulated equations. The development of these models, beginning in the early 1960s, represented a fundamental change in the way vehicle interiors are designed.

Two current research programs will lead to a new set of substantial changes in the SAE practices that underlie the vehicle design process described above. For more than a decade, the American Automobile Manufacturers Association (formerly the Motor Vehicle Manufacturers Association) has supported research at the University of Michigan Transportation Research Institute (UMTRI) leading to the development of new statistical models to predict the distributions of driver-selected seat positions and driver eye locations (1-3).[*] In a separate but related effort, a group of eleven auto companies and seat suppliers has supported the four-year ASPECT program, the goals of which are the development of new vehicle design and measurement tools (4-9). The foremost objective

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[†] Portions of this chapter were previously published in SAE Technical Paper 1999-01-0967.

[*] Numbers in parentheses denote references at the end of the chapter.

of the ASPECT program has been the development of a new H-point manikin to replace the current SAE J826 manikin.

Both of these research programs are based on extensive investigations of the effects of vehicle and seat design factors on driver and passenger posture and seat position. Both programs have included studies conducted in vehicles and laboratory vehicle mockups (seating bucks). The AAMA-funded research has focussed on seat position and eye location, while the ASPECT studies have emphasized whole-body posture measurement and prediction. The AAMA work has led to the development of two new driver accommodation models for driver seat position and eye location. The ASPECT program has produced a new H-point manikin and associated whole-body posture-prediction models. Together, these new tools have the potential to improve substantially the process of vehicle interior design.

1.1 Overview of Population-Based Design Tools

Prior to the development of task-oriented percentile accommodation models in the early 1960s, the leading method for designing vehicle interiors could be referred to as the boundary template approach. In-depth studies of the human skeletal articulation in the 1950s by Dempster and others (10, 11) led to the widespread use of two- and three-dimensional mechanical templates illustrating the human form as an articulated linkage of contoured segments. Small and large templates were constructed, typically representing women who are fifth-percentile by stature and men who are ninety-fifth-percentile by stature. The two-dimensional templates were manipulated on full-size, side-view drawings to determine, for example, if the small female template could “see” over the steering wheel and if the knees of the large male template could fit below the instrument panel.

The template approach to vehicle design assumes that anthropometric variability is the key determinant of accommodation. That is, if the physical dimensions of small and large people will fit in the vehicle interior space while preserving the necessary reach envelopes and sight lines, then the population of people with anthropometric dimensions intermediate to the tested templates are assumed to be accommodated.

However, postural variability is nearly as important as anthropometric variability for vehicle occupant accommodation. The strength of task-oriented percentile accommodation models is that they provide a way to include both anthropometric and postural variability in the design process.

The best known example, and the first applied widely in vehicle design, is the eyellipse (12-14). The eyellipse (the word is a contraction of eye and ellipse) was developed in the early 1960s to address the problem of accurately predicting driver eye locations. In a project sponsored by SAE, visitors to Ford Motor Company facilities were invited to sit in one of three convertibles positioned in front of road scenes. Two photographs taken of each person from perpendicular angles were used to determine eye locations relative to the vehicle. A total of 2355 people were measured, each in one of the three cars. Statures of the subjects (with shoes) were measured to the nearest inch. The resulting distributions of stature within gender were judged to be representative of the U.S. driving population.

The vehicles used in the original eyellipse study were different in a number of ways from contemporary vehicles, notably because the seat tracks were shorter and because the seatback angles were fixed at about 25 degrees. Compared to current vehicle seats, the seats used in the original eyellipse study were less contoured and probably lacked substantial lumbar support.

Observing that the distributions of driver eye locations were approximately multinormal, a statistical method was devised to represent eye locations relative to vehicle landmarks. The eyellipse is a second-order ellipse constructed such that tangents to the ellipse (or planes tangent to the corresponding ellipsoid in three dimensions) separate the spatial distribution of eye locations according to the percentile specification of the ellipse. For example, a tangent to the two-dimensional 95^{th}-percentile eyellipse cuts off five percent of the population eye locations, while the same ellipse encloses 74 percent of the eye locations (12).

Because the eyellipse directly predicts the distribution of eye locations for a U.S. driving population, it accounts for variability in eye location due to both anthropometric and postural variability. The eyellipse is therefore a much more useful tool for determining vision requirements than the template-based approach. Following on the success of the eyellipse, other task-oriented percentile models have been developed for head space (J1052), hand reach (J287), and driver-selected seat position (J1517). Each provides a way for designers to consider the distribution of particular, task-oriented postural characteristics with reference to population, rather than individual, anthropometry.

One minor limitation of the task-oriented percentile models is that they are difficult to reconcile with template-based approaches, because there is no information in the eyellipse that specifies the anthropometry of people whose eyes lie in some region of the ellipse. Further, they cannot be readily linked together. SAE J1517, which specifies the distribution of driver-selected seat positions, cannot be used to identify a seat position that corresponds to a particular point in the eyellipse. Thus, the task-oriented percentile models provide no information that can be used for template-based analyses, except broad guidelines bounding the range of reasonable postures.

The major limitation of the current task-oriented percentile models is that they are only applicable to certain well-studied, essentially static characteristics of driver posture. The current models are also formulated in such a way that they apply only to a specific occupant population, namely a U.S. driving population (some of the models provide for variation in the population gender mix). Considerable judgement is required to apply the models to different populations, and the models are not generalizable to other important analyses (e.g., assessing clearances in the shoulder area).

Because of the strengths of the task-oriented percentile models, template-based approaches are now used relatively infrequently for primary vehicle design tasks. However, template-type tools, such as the SAE H-point manikin and the J826 2-D template, have retained an important function in vehicle design. The H-point manikin and its 2-D representation create a standardized, uniform, schematic representation of a vehicle occupant. Key reference points on the template, such as the H-point, are used to position accommodation models and to measure interior dimensions for comparison across vehicles. For example, clearances measured to the knee of the 2-D template are used in some design guidelines. The knee of the template represents only one knee location within the range of possible occupant knee locations, but the standard installation procedure for the template means that the clearance dimensions can be compared across vehicles.

Task-oriented percentile models, such as the eyellipse, have allowed vehicles to be designed without the need for extensive analysis using multiple template sizes. However, in recent years, the movement of design tasks into the computer environment has created opportunity for new applications of the template-based approaches. The templates are now articulated, three-dimensional human models, or CAD manikins, that can be manipulated to simulate a wide range of tasks within a virtual vehicle mockup. New practices are needed to support accurate use of these new CAD tools within the framework of the existing task-oriented percentile models. Further, the percentile models need to be updated and improved to provide greater accuracy and flexibility.

This chapter summarizes the current vehicle design tools defined in SAE recommended practices, then discusses the changes to these practices that are being considered. The development of the new ASPECT H-point manikin provides a natural juncture at which to make these changes, because the current H-point manikin underlies many of the SAE vehicle design practices. Each of the new tools and their interrelations are discussed to illustrate a new framework for vehicle interior design that builds on the existing tools.

2.0 OVERVIEW OF CURRENT DESIGN PRACTICES

2.1 SAE Recommended Practices

Although each company has many in-house procedures and guidelines to design and evaluate vehicles and seats, SAE recommended practices form the basis for many common design procedures. Table 1 lists the SAE Practices that are used for vehicle interior packaging (15, 16).

Table 1
SAE Recommended Practices for
Passenger Car Interior Design (15, 16)

Practice	Title
J182	Motor Vehicle Fiducial Marks
J287	Driver Hand Control Reach
J826*	Devices for Use in Defining and Measuring Vehicle Seating Accommodation
J941*	Motor Vehicle Driver's Eye Range
J1052*	Motor Vehicle Driver and Passenger Head Position
J1100*	Motor Vehicle Dimensions
J1516*	Accommodation Tool Reference Point
J1517*	Driver Selected Seat Position

* Revisions anticipated as a result of the research and new tools described in this chapter.

SAE Recommended Practice J182 establishes the fiducial marks necessary to define a vehicle coordinate system that is used to develop package-specific coordinate systems, e.g., for the driver. J287 defines reach envelopes for drivers that are based on laboratory data (17). J826 describes the H-point manikin and usage procedures, as well as the two-dimensional template based in part on the H-point machine geometry. J941 presents the eyellipse, created using data from a large-scale study of driver eye locations conducted in the early 1960s (12). J1052 contains head location contours based on the eyellipse (14). J1100 defines hundreds of motor vehicle dimensions, many of them interior dimensions, and several defined relative to the other practices listed here (e.g., H30 is seat height, defined using the H-point manikin described in J826). J1516 defines the pedal reference points, Ball of Foot and Accelerator Heel Point, used to define measures of package space. J1517 provides equations predicting the distribution of driver fore-aft seat position for a U.S. driver population with an equal gender mix (18). Figure 1 illustrates the accommodation tools defined in these practices.

These practices have considerable interrelation, illustrated in Figure 2. The H-point machine defines and measures the seat H-point. When the seat is located in the design (manufacturer-specified) position, the H-point is known as the Seating Reference Point (SgRP). The manikin leg and shoe geometry are used to define the Ball-of-Foot (BOF) and Accelerator Heel Point (AHP) reference points, which are used as the X and Z coordinates, respectively, of the vehicle package origin. These definitions are codified in J1516, Accommodation Tool Reference Points, and in J1100.

Many dimensions in J1100 are defined relative to this manikin position. Seat height (H30) is the vertical distance between the H-point (SgRP) and heel (AHP). Fore-aft steering wheel position (L11) is the horizontal distance between the center of the steering wheel and the AHP. Headroom (H61) is measured using a probe from the SgRP oriented eight degrees rearward of vertical. In effect, the H-point manikin defines the primary reference points that are used to measure interior dimensions related to occupant accommodation. Some of these dimensions are used to position the driver reach envelopes described in SAE J287. The eyellipse (J941) and head contours (J1052) are positioned with respect to the SgRP, with a recommendation to establish the SgRP using the 95th-percentile population seat position curves defined in SAE J1517. The latter predicts the distribution of driver-selected seat position using second-order functions of seat height (H30). Thus, the SAE J826 H-point manikin is important to all of the other interior design practices.

2.2 A Simplified Example

The design process will be illustrated using the packaging of a hypothetical vehicle. For this illustration, a seat height of 220 mm and some predefined pedal geometry are assumed. Figure 3 shows the tools on a side view of the package. First, the pedal plane angle is calculated using the equation in J1516, in the process defining the BOF and AHP locations. Next, using the 95th-percentile driver-selected seat position curve, an SgRP location is established. The 2.5th percentile and 97.5th-percentile curves from J1517 are laid in, along with a seat-track (H-point) travel line, to define the seat track travel length necessary to accommodate preferred seat positions of 95 percent of a U.S. driver population with an equal gender mix. With the SgRP and pedal reference points established, the other accommodation models may be positioned. The eyellipse (defined in J941 for a U.S. driving population with an even gender mix) is positioned relative to the SgRP using the design seatback angle (defined in J1100 as L40). Head contours from J1052 are positioned in a similar manner. Positioning the hand-control reach envelopes requires calculation of the "G" factor from a range of vehicle interior dimensions, including H30, L11, and others.

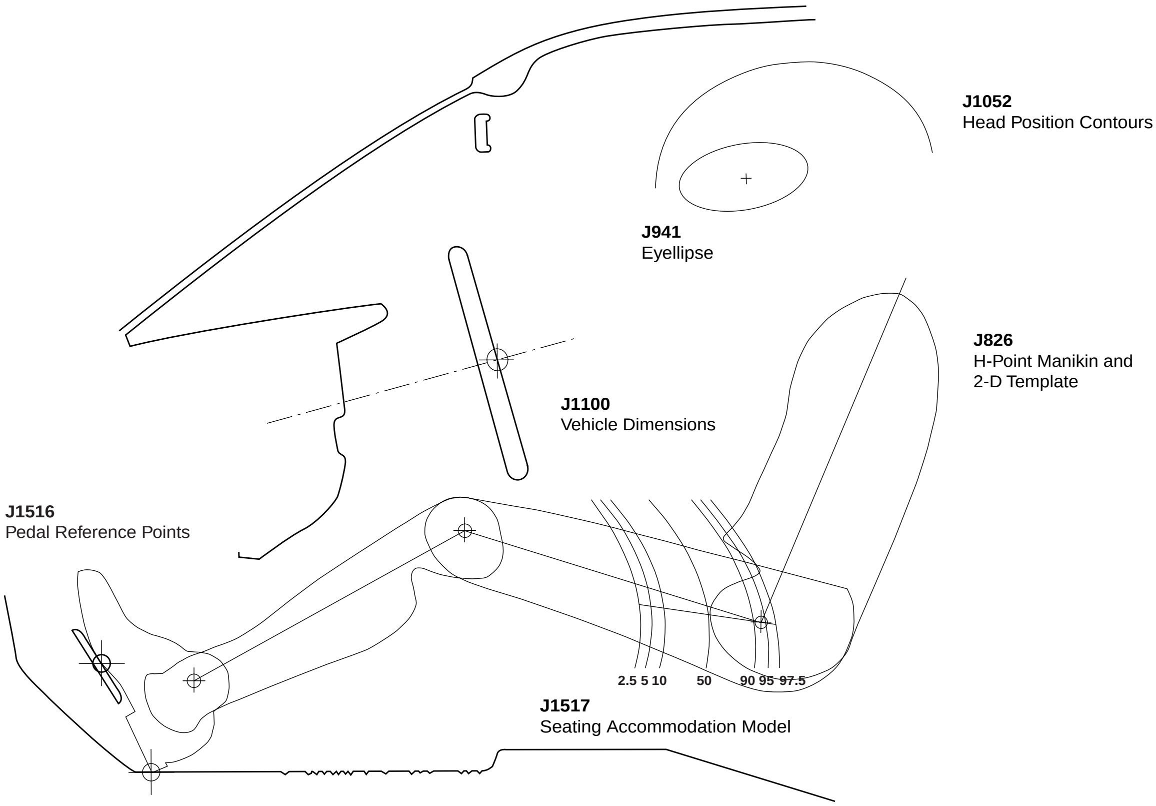

Figure 1. Accommodation tools defined in SAE recommended practices.

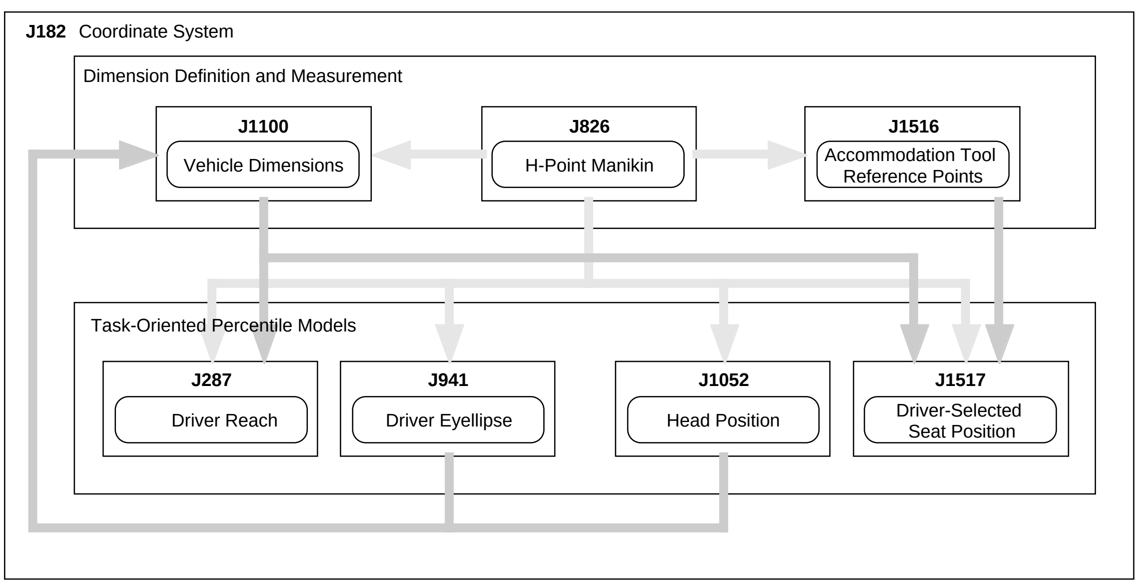

Figure 2. Schematic of relationships among SAE recommended practices.

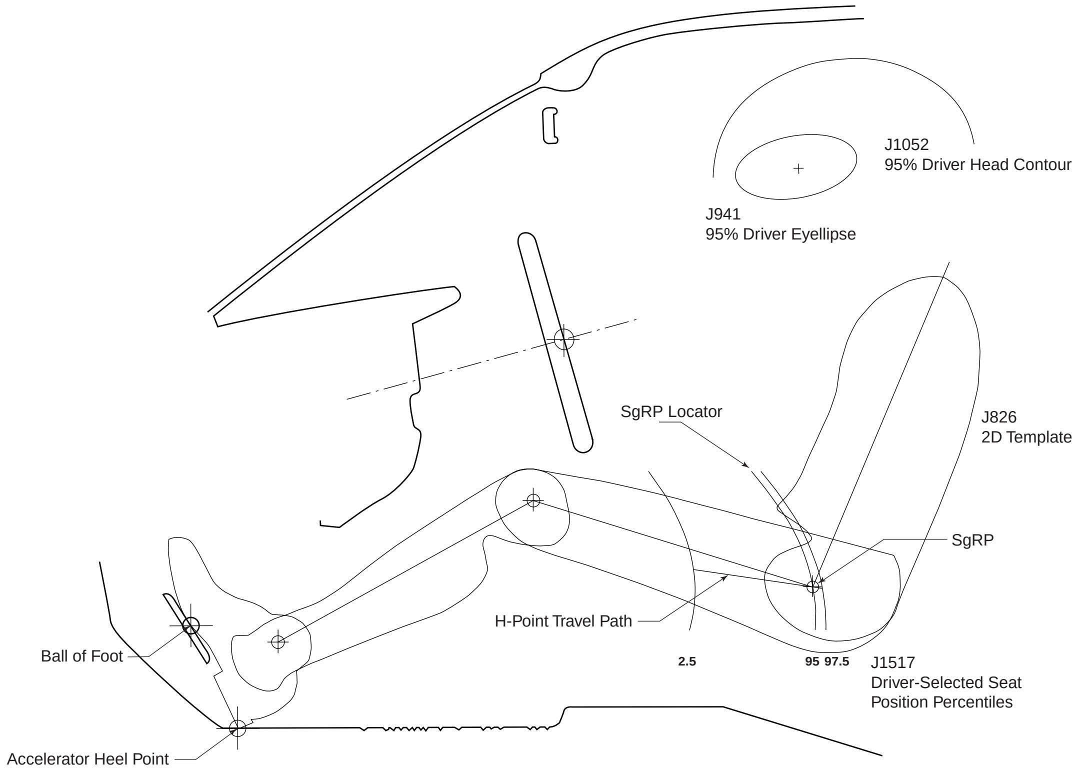

Figure 3. Illustration of hypothetical driver station layout procedure using SAE recommended practices.

The resulting accommodation tool locations can then be used to assess the vehicle interior design. Display locations and steering wheel obscuration can be evaluated using sight lines or planes constructed tangent to the eyellipse. Head clearance can be quantified using procedures defined in J1100 based on translation of the head contours toward the roof. In addition, many other design guidelines developed by individual companies that reference the SAE accommodation models can then be applied.

2.3 Human CAD Models

In recent years, vehicle interior designers are increasingly turning to computer-aided-design (CAD) manikins to assess prototype layouts (19). These CAD manikins represent a human figure that can be scaled to match a wide range of human anthropometry, and can be positioned in the simulated vehicle to explore a wide range of possible occupant postures. Vision tasks can be evaluated by examining the view from the manikin's eye locations, and reach tasks can be simulated by manipulating the manikin's limbs. In spite of rapid advances in the quality and capability of these models in recent years, their use in the vehicle development process has been hampered by a lack of integration with the now-standard tools described in the SAE practices. The new tools described in this chapter include methods for positioning CAD manikins so that their postures and body landmark locations have a quantitatively defined relationship to the population distributions, providing the needed linkage between the population-based task-oriented percentile models and the CAD manikins.

3.0 NEW TOOLS FOR VEHICLE INTERIOR DESIGN

3.1 Overview

The research described here and elsewhere (1-9) has led to the development of a set of new design tools that are intended to be more closely integrated than the current practices. Table 2 lists the new tools along with the relevant SAE recommended practices. The following sections discuss the source and application of each tool. Several general principles have guided the development of these tools.

Accuracy – The primary motivation behind the new tools is a desire to improve on the accuracy of the current practices, defined as correspondence between the model predictions or tool measurements and the analogous values for human occupants.

Population Configurability – Many of the current tools are formulated solely for a particular U.S. population, generally one defined using anthropometric data that are decades old. The new tools are designed to be used for any population of interest and can be applied equally well to the U.S. or other populations.

Ease of Use – Some of the current practices and tools, notably the H-point machine, are difficult to use, whether physically or in CAD. Where practical within the constraints imposed by improved accuracy, the application methods have been simplified. The ASPECT manikin, in particular, contains many changes in features and procedures intended to simplify its use.

Continuity with Current Practice – There is a large body of information that has been accumulated over the preceding decades using the current tools. The need to preserve the applicability of these data was considered along with the other primary priorities in creating the new tools. As a result, the changes in the tools are evolutionary, and many of the current dimensions and measurement conventions will remain applicable under the new system.

Table 2
New Vehicle Interior Design Tools

Tool/Model	Relevant SAE Recommended Practice
UMTRI Seating Accommodation Model	J1517
UMTRI Eyellipse Model	J941
Head Contours	J1052
ASPECT Manikin	J826
Pedal Reference Points	J1516
SgRP Definition	J1100
Human Body Reference Forms	*
ASPECT Posture Prediction	*
Application Guidelines for Human Models	*

* No current SAE recommended practice

3.2 UMTRI Seating Accommodation Model

The initial goal of the MVMA/AAMA research conducted at UMTRI was the development of a more accurate model for predicting the distribution of driver-selected seat positions. Beginning in 1985, SAE J1517 provided curves to predict the various percentiles of a fifty-percent male U.S. driver seat position distribution (18). However, data from studies at UMTRI suggested that the curves were substantially in error in some vehicles (1). Seat positions of hundreds of drivers of widely varying anthropometry were measured in 44 vehicles with a wide range of vehicle interior geometry after driving on a local road route. In addition, a detailed laboratory investigation was conducted, in which package geometry was varied over a wide range to determine the effects on seat position. These studies led to a model that predicts the distribution of driver-selected seat positions as a function of seat height, horizontal steering-wheel-to-Ball-of-Foot distance, seat cushion angle, transmission type (clutch/no clutch), and population anthropometry (1, 2).

The new Seating Accommodation Model (SAM) goes beyond adding three new vehicle and seat variables as predictors, however. The most valuable addition to SAM is the use of population anthropometry as input to the model. The current SAE J1517 seat position curves for passenger cars are applicable only to a specific, U.S. driver population. SAM allows the user to specify the anthropometry of the user population, including the gender ratio, average stature for each gender, and the stature variance within gender. This new feature provides considerably greater flexibility for designing seat track layouts. For example, designers of a sports car aimed at a 65-percent-female target market could locate their seat track to accommodate 95 percent of the target population without unnecessarily restricting rear seat legroom.

SAM also provides the ability to predict mean selected seat positions for any specified driver stature. This feature was recently exploited to propose new crash dummy positioning procedures that would place the dummies in positions more representative of similarly sized human occupants than current procedures (20). Another application of this feature of SAM is in positioning CAD manikins for vehicle design.

3.3 UMTRI Eyellipse Model

Along with the new Seating Accommodation Model, the UMTRI research team has developed a new eyellipse model (3). Eye location distributions observed in contemporary vehicles differ in important ways from the SAE eyellipse. Figure 4 compares the UMTRI eyellipse with the SAE eyellipse for one vehicle geometry. The new eyellipse centroid is generally behind and slightly above the current SAE centroid, and the fore-aft axis is longer.

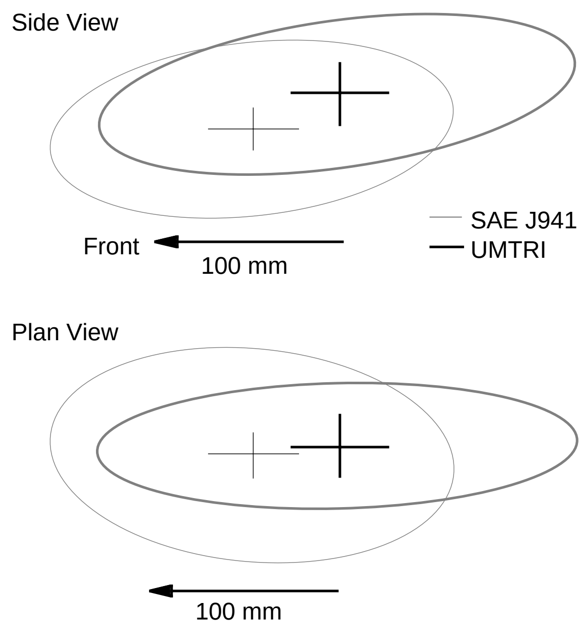

Figure 4. Comparison of SAE J941 and new UMTRI 95th-percentile eyellipses for a typical vehicle geometry and 50-percent-male U.S. driving population.

More important than the shape changes, however, are the changes in the way the eyellipse is positioned in vehicle space. In current SAE practice, the eyellipse is positioned with respect to the SgRP using a function of design (seat) back angle (L40). SAE J941 suggests using the SAE J1517 95th-percentile driver-selected seat position curve to determine the SgRP as a function of seat height. Design back angle is a manufacturer-specified value, usually a value between 21 and 28 degrees, selected to meet a variety of design goals, such as visibility, headroom, and safety performance.

The research conducted to develop SAM demonstrated that the J1517 95th-percentile seat position curves did not consistently predict driver seat positions; consequently, the SgRP defined in that manner does not represent an optimal point from which to reference the eyellipse position (1). The eye position research also demonstrated that design seatback angle is not a good predictor of driver-selected seatback angle or torso posture (3, 20). The new eyellipse model positions the eyellipse centroid with respect to the pedal reference points, rather than with respect to the SgRP, and does not include design seatback angle in the centroid location calculations. As with SAM, the new eyellipse provides the capability of specifying the target driver population anthropometrically. For example, a light truck intended for a population that is taller, on average, than the population used to define the current SAE eyellipse can be designed using an appropriately specified eyellipse.

3.4 Head Space Contours

The current SAE Recommended Practice J1052 presents head space contours created by moving an average-size headform around the perimeter of the SAE J941 eyellipse. These cutoff contours are intended to be used as reference surfaces for determining headroom dimensions. Contours are specified for both fixed seats and those with adjustable seat tracks.

The new eyellipse model provides an opportunity to revise the shape of these contours and to provide a new, more accurate method of positioning them in the vehicle. Using similar procedures, a new ellipsoid model will be developed that provides head space cutoffs for any population of interest. Additionally, new data on head turn kinematics will allow the space required for volitional head movement to be accounted for more fully than is the case in the current J1052 models. As with the eyellipse, the removal of design seatback angle from the head space contour locating procedure for seats with adjustable seatback angles will improve the accuracy of the model.

3.5 ASPECT Manikin

The new ASPECT manikin is intended to replace the current SAE J826 manikin (4, 9). The manikin, shown in Figure 5, is designed to measure the seat independent of the vehicle package. The new manikin has an articulated lumbar spine that allows the manikin to measure the longitudinal contour of the seatback, expressed as lumbar support prominence. The ASPECT manikin measures an H-point location that can be directly related to the J826 H-point location (9), and simultaneously measures seat cushion angle and seatback angle. The manikin includes supplemental, lightweight legs that can be attached after the manikin is installed in a seat without altering the H-point location, providing the ability to measure the knee and hip angles used in some accommodation assessments. Details of the manikin design and associated application procedures are presented elsewhere (7, 9).

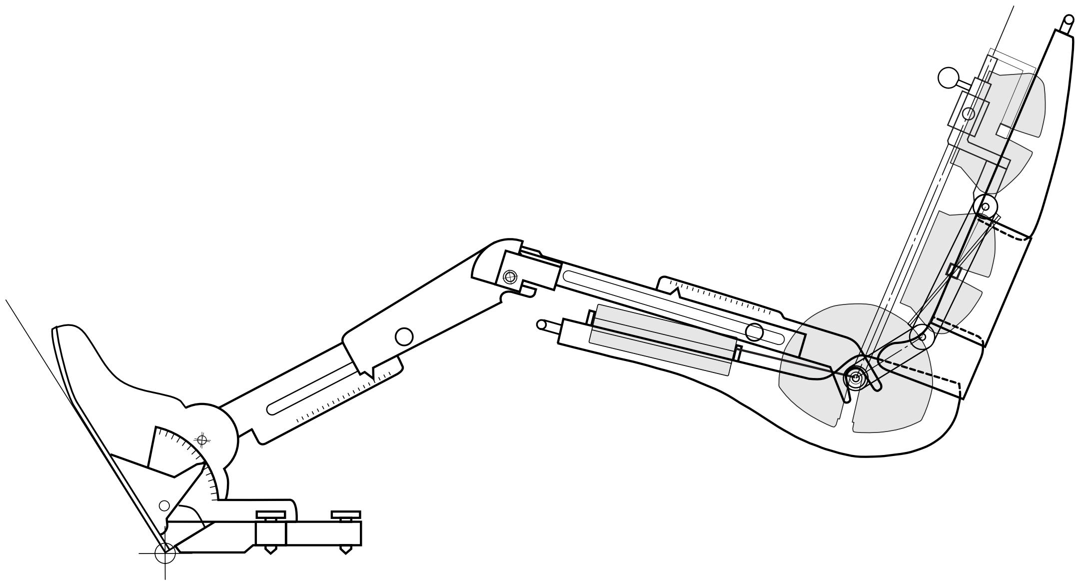

Figure 5. New ASPECT manikin, shown with supplemental thigh, leg, and shoe components (9).

As noted above, the current SAE J826 manikin is closely interwoven into many contemporary design practices, including those described in the SAE recommended practices. These relationships were among the foremost considerations in the design of the ASPECT manikin. The new manikin was created from the start to be integrated into the design process more consistently than the current manikin.

The primary purpose of the H-point manikin, from the vehicle and seat design perspective, is the definition and measurement of the H-point. Yet, in most cases, the physical manikin is not needed until after the interior is designed and the first prototypes are constructed. The H-point, or more specifically, the particular H-point location at the SgRP, is a key starting point for the package layout and seat design. The physical manikin is used only to verify that the seat and package, as constructed, have met the design dimensions.

However, the current J826 manikin geometry is closely tied into the current design process because a two-dimensional template based, in part, on the manikin geometry is widely used in vehicle package development. The template, having the same link lengths and approximately the same profile as the J826 manikin thigh, leg, and shoe, is used with the procedures in J1516 to establish the Ball of Foot and Accelerator Heel point. These points are the reference locations for determining the SgRP position and locating the accommodation tools, such as the eyellipse.

In the current SAE J826, H-point location is intrinsic to the seat, but the SgRP is a specific H-point location, intrinsic to the workspace (15, 16). However, because H-point verification is done with the legs attached, changes in the J826 manikin leg posture can change the H-point location. In contrast, the ASPECT manikin isolates the H-point measurement from the package by using no leg segments for the standard H-point measurement. With the seat cushion and seatback at design attitude, the H-point measurement (relative to the seat) can be made with the seat at any fore-aft seat position, or even without any vehicle components other than the seat.

The ASPECT manikin thereby provides a set of measures of seat geometry that can be used to specify a seat more fully, and to predict the effect that seat geometry will have on occupant posture and position. In addition to the H-point location relative to the seat frame, the vehicle package designer can specify the seat cushion angle, lumbar support prominence, and seatback angle at a particular seat frame orientation. The effects of these parameters on occupant posture can then be accounted for in both the population-based accommodation models (such as SAM) and in the use of CAD manikins. After the seat is constructed, the ASPECT manikin is used to verify compliance with the specifications.

3.6 New Pedal Reference Points

One of the goals of the ASPECT manikin design was to remove the dependence of the pedal reference points on the manikin linkage geometry. Because the Ball-of-Foot and Accelerator-Heel-Point reference points are related by a pedal plane angle derived from the SAE J826 manikin leg geometry, fixed foot (ankle) angle, and seat height (see J1516), any change in seat height, or SgRP location generally, changes the pedal reference point locations. This is contrary to the results of human posture studies, which suggest that if the pedals do not change, the pedal reference point should also remain fixed. Further, this definition of pedal reference points introduces iteration into the design process, so that a change in SgRP location leads to changes in the positions of all of the design tools located using Ball of Foot or Accelerator Heel Point. Identical pedals in vehicles differing in seat height by 20 mm would have different pedal reference points.

In conjunction with the ASPECT program, a new pedal reference point proposal has been developed that defines a new point, called the Pedal Reference Point (PRP), based only on floor and accelerator pedal geometry. Figure 6 illustrates the proposed procedure for locating the PRP. A tangent to the accelerator pedal is constructed such that it contacts the pedal a distance of 200 mm along the tangent line from the depressed floor surface. For a flat accelerator pedal, the measurement is made along the plane of the pedal. The PRP is always on the pedal, unlike the Ball of Foot point on the current manikin shoe. The floor contact point, called the Accelerator Heel Point (AHP), defines the Z reference plane for package dimensions, and the PRP defines the X reference plane. The process of determining the PRP location can be readily performed in CAD or on a physical accelerator pedal. (For more details on the PRP-locating procedure, see Annex 1 of this report.)

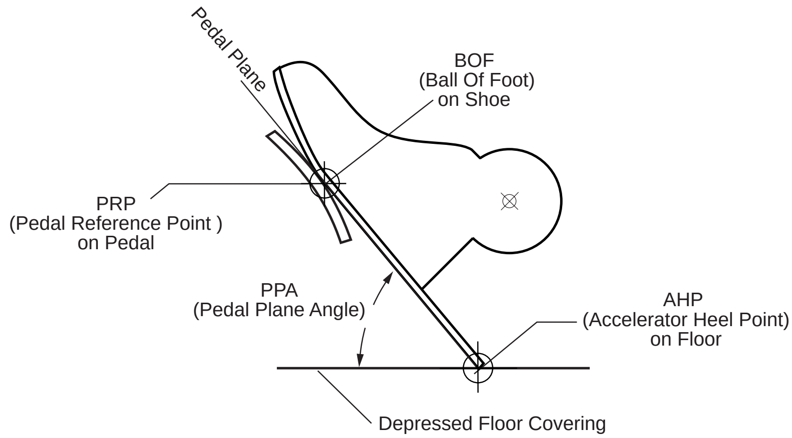

Figure 6. Proposed procedure for locating a pedal reference point (PRP) on the accelerator pedal. The bottom of the shoe is tangent to accelerator pedal at the Ball of Foot reference point on the shoe, which is 200 mm from the heel of the shoe. The heel contact is the Accelerator Heel Point (AHP).

When the ASPECT manikin thigh, leg, and shoe segments are installed, the shoe is positioned tangent to the accelerator pedal. If the pedal is curved, the shoe is located so that the Ball of Foot (BOF) reference point contacts the pedal at the point of tangency.

For pedal design purposes, a pedal plane angle analogous to the current theta angle given in SAE J1516 can be obtained from the following equation:

$$\alpha = 76 - 0.08\ \mathrm{H30} \qquad [1]$$

where H30 is the height of the SgRP above the heel rest surface (AHP). Compared with the pedal plane angles given by the current J1516 equation, pedal plane angles given by equation 1 are flatter (closer to horizontal), change more slowly with seat height, and better represent actual shoe angles observed in studies of driver posture.

3.7 Standardized SgRP Definition

One of the notable problems with the current set of SAE practices is that the most important reference point for driver packaging, the Seating Reference Point, is ambiguously defined. Currently, the SgRP is defined in SAE J1100 as the "rearmost normal design driving or riding position." This would seem to specify the most rearward position on the seat track, but such a definition would prevent the SgRP from being used as a standard reference for locating accommodation models, since seat track lengths and locations vary considerably. Recognizing this limitation, SAE J941 recommends, but does not require, that the SgRP position be determined using the 95^{th}-percentile driver-selected seat position curve from SAE J1517. Although discussions among industry representatives suggest that this practice is routinely followed, a standardized, unambiguous definition is needed because of the importance of the SgRP in vehicle design.

One of the problems with changing the SgRP definition (or creating an unambiguous definition that conflicts with current practice) is that there are a large number of dimensions in SAE J1100 that are affected by the SgRP location. These dimensions, many of them also related to the SAE J826 manikin geometry, are routinely used to compare vehicles and to specify interior space. The simplest example is seat height (H30), defined as the height of the SgRP above the heel rest surface (AHP). For a vehicle with an inclined seat track, a change in fore-aft SgRP location would change the seat height, which would in turn affect many other accommodation models, such as the driver-selected seat position curves and the eyellipse locations.

These considerations indicate that a new SgRP definition will be most easily incorporated into the design process if the dimensional changes relative to the old system are small. One possibility for a new definition would be to codify the practice of using the SAE J1517 95th-percentile seat position equation. However, as noted above, plans are underway to revise SAE J1517, replacing the current equations with a more accurate and flexible system (i.e., SAM). Therefore, a proposal for a new SgRP locator equation has been developed that removes the ambiguity of the preceding definition while preserving reasonable continuity with current practice. The newly developed Seating Accommodation Model (SAM), described previously, provides a way to develop such a system.

One of the equations in SAM predicts the mean selected seat position of a single-gender population having a specified mean stature (2). This equation is equally applicable to a diverse population of women or a hypothetical subpopulation of men who are all exactly the same stature. Besides stature, the other inputs to the equation are seat height, steering-wheel-to-Ball-of-Foot distance, and seat cushion angle.

The current practice of using the SAE J1517 95th-percentile seat position equation to establish SgRP makes SgRP location a function of seat height. This is a reasonable approach, since seat height is an important determinant of occupant position. To create a similar relationship in the new system, the SAM equation was reconfigured to express seat position as a function of only seat height and stature. Seat cushion angle and steering wheel position were approximated using regressions of these variables on seat height. An optimization procedure was then used to determine the stature that produced the best agreement (least squared error) between the predicted seat position in 26 vehicles and the seat position given by the 95th-percentile J1517 equation. Figure 7 shows the predicted seat position for drivers 71.1 inches (1806 mm) tall as a function of seat height, compared with the J1517 equation now commonly used to determine SgRP location. The new linear equation,

$$\text{SgRPx} = 1038.2 - 0.3945\ \text{H30} \qquad [2]$$

crosses the J1517 curve at two points within the range of seat heights typical of passenger cars, and differs from the J1517 curve in fore-aft position by a maximum of about 7 mm for seat heights from 180 to 340 mm. For many vehicles, the difference is within the range of one seat track detent. This equation, which predicts fore-aft seat position as a function of seat height for people who are 1806 mm in stature, is suggested as a new SgRP definition.

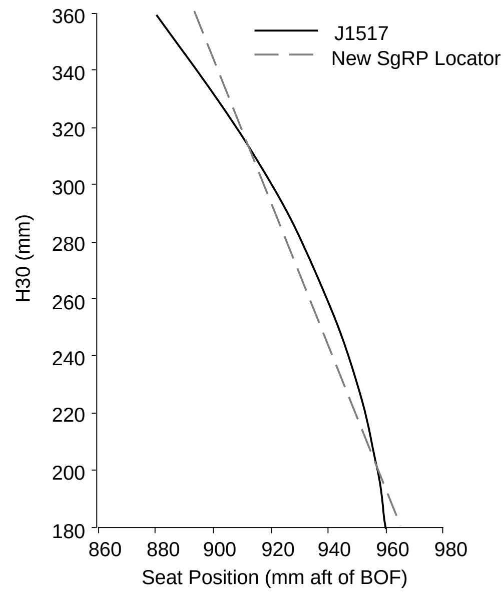

Figure 7. Comparison of proposed SgRP locator function with currently used SAE J1517 95th-percentile driver-selected seat position curve.

The new equation has a number of advantages over standardizing on the current SAE J1517 equation. First, the J1517 equation will be superceded soon by revisions to the practice based on SAM. Second, the J1517 equation was developed for a fifty-percent-male U.S. driving population, using anthropometry that may be out of date. Ideally, the SgRP equation should be population independent, to provide uniform applicability to international populations and consistency over time.

The proposed new SgRP equation overcomes both of these limitations and also provides an opportunity to create new leg and thigh segment lengths for use with the manikin that are anthropometrically consistent with the SgRP seat position. In current practice, the SgRP location is determined using an estimate of the location of the 95th percentile of the driver-selected seat position distribution. As has been noted before (18), this location does not correspond to the average seated position of people who are 95th percentile on any anthropometric variable, such as stature. Yet, in current practice, the J826 manikin and template are positioned with the H-point on this locator curve and then installed using “95th-pecentile” leg and thigh segment lengths. These segment lengths are based on 95th-percentile values for external leg dimensions from the U.S. HES study, dating from the early 1960s (21). Because both segments are designed to be 95th percentile individually, the combined leg and thigh length is larger than the 95th percentile for the original target population. Thus, the current practice uses a leg length, thigh length, and seat position that are inconsistent from anthropometric perspective. Consequently, the resulting manikin lower extremity posture bears, at best, an unclear relationship to actual human postures.

The new proposal would replace the leg and thigh segment lengths with lengths that are consistent with the SgRP reference stature. Using data from a large-scale anthropometric survey (22), the average knee height and buttock-to-knee lengths for men matching the SgRP reference stature of 1806 mm were calculated. Preserving the same offsets between the knee surface and knee joint, ankle and bottom of shoe, and H-point and the posterior of the buttock/thigh shell, new segment lengths were calculated to match these external dimensions. Table 3 shows the SgRP reference segment lengths, along with the current J826 95th-percentile segment lengths. The proposed thigh length is only slightly smaller than the J826 95th-percentile segment length, but the leg segment is about five percent shorter.

To measure a vehicle package, the ASPECT manikin is installed with the seat positioned such that the manikin H-point lies at the SgRP, as calculated by equation 2. The shoe is installed tangent to the accelerator pedal, and the leg and thigh segments set to the SgRP-reference segment lengths given in Table 3 are installed. The resulting knee and hip angles are generally within one degree of those measured with the current practices. Figure 8 shows a typical vehicle package comparing the current and new systems for locating SgRP, along with the corresponding tools (SAE 2D template and ASPECT manikin) adjusted to the appropriate lower-extremity segment lengths.

Table 3
Comparison of SgRP Reference Segment Lengths with SAE J826 95th-Percentile Segment Lengths (mm)

Segment	SAE J826 95th Percentile	New SgRP Reference
Thigh	456	452
Leg	459	436

* Segment lengths appropriate for male matching the SgRP reference stature of 1806 mm.

Overall, the effects on vehicle package dimensions of the new SgRP proposal are small. Yet, the new proposal would:

- standardize the SgRP definition,
- create a single reference anthropometry for SgRP definition that is independent of any particular population,
- provide consistency with the new Seating Accommodation Model, and
- introduce consistency between manikin segment lengths and SgRP locations.

This proposal remains subject to further discussion and potential modification by the industry through the SAE Design Devices Committee. Assessments of current vehicle packages using the proposed system support the conclusion that most changes will be minor and that the large body of data collected under the current system will remain applicable.

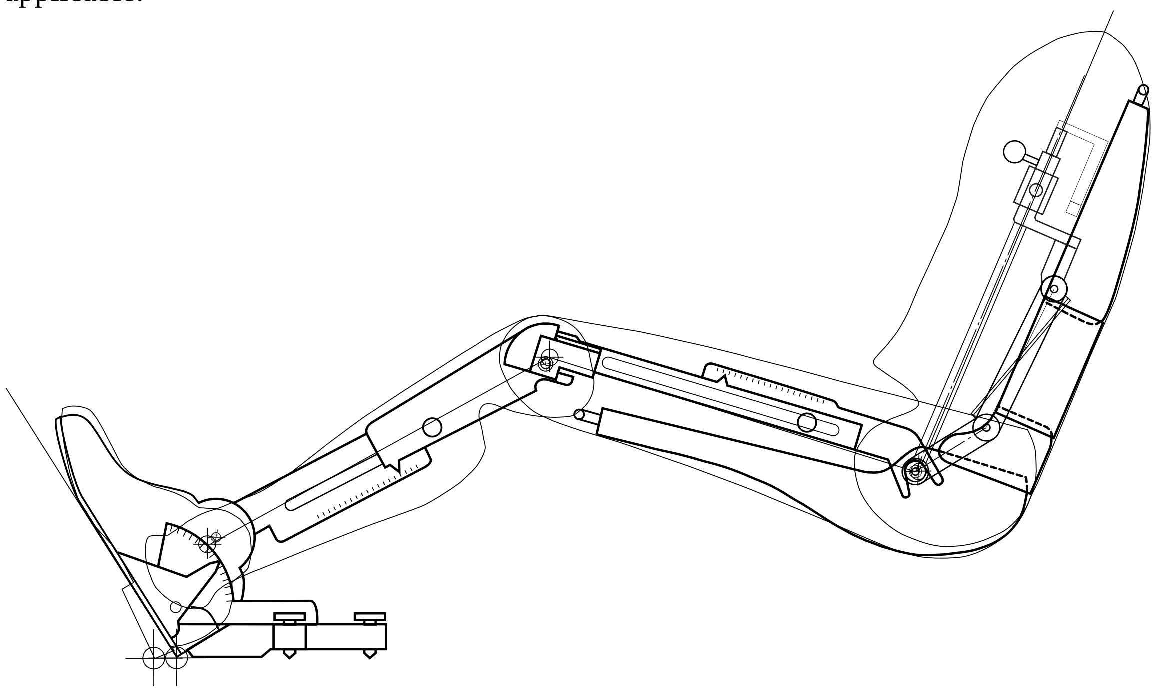

Figure 8. Comparison of current (light lines) and new (ASPECT manikin) packaging practices for a 220-mm seat height.

3.8 Human Body Reference Forms

Industry representatives to the ASPECT program raised the concern that, in current design practice, there are no standard three-dimensional representations of the human body other than the SAE J826 manikin and the crash dummies. The SAE J826 manikin, as noted above, represents an amalgam of dimension percentiles, and crash dummies have been designed primarily for dynamic performance, not for the representational accuracy of their external geometry. Particularly in the shoulder and neck areas, the current standard Hybrid-III crash dummy does not have accurate contours.

Although collecting new whole-body contour data was beyond the scope of the ASPECT program, whole-body contours were available that were based on detailed anthropometric measurements. As part of an effort funded by the National Highway Traffic Safety Administration (NHTSA) to develop anthropometric specifications for a new generation of crash dummies, researchers at UMTRI developed full-size, physical, three-dimensional shells representing the average anthropometry and posture of small-female, midsize-male, and large-male drivers (23). The anthropometric specifications for the subjects were selected based on 5^{th-}-, 50th-, and 95th-percentile stature and weight for men and women, based on the 1974 U.S. NHANES study (24).

As part of the ASPECT program, high-resolution surface scan data from the three physical shells were used to fit parametric (splined) surfaces. These three-dimensional figures, shown in Figure 9, can be rendered in CAD environments and manipulated in virtual vehicle mockups. These body surface descriptions may be considered for standardization in a new SAE practice.

There are a number of potential uses for these three-dimensional representations in vehicle design. First, they provide a way of visualizing vehicle occupants of three different sizes in a vehicle package. If the representations become part of a recommended practice, companies could use them to make comparative measurements, much as the current SAE J826 manikin and two-dimensional template are used now. Second, the reference forms provide a way of ensuring a degree of consistency in body contour among CAD manikins. Currently, CAD manikins from different companies configured to the same overall anthropometry often have considerably different body contours. This difference complicates use of the CAD manikins to make accommodation assessments. CAD manikins that matched the external surfaces of the reference forms developed in the ASPECT program would provide comparable measurements independent of the software.

Third, the standardized body surfaces would provide three-dimensional tools for conducting some of the analyses that are currently performed using the two-dimensional SAE J826 template. The SAE 2-D template has a torso height and shape that are different from the three-dimensional manikin. The “shoulder” height of the 2-D template is intended to be approximately representative of the 99th-percentile U.S. male shoulder height, and is used for such things as assessing shoulder belt anchorage locations. The new large male 3-D body surface could be used as a reference tool for measuring a number of vehicle interior clearance dimensions. The front torso and leg surfaces of the reference forms may provide more useful steering wheel and knee bolster clearance measures than are provided by the current two-dimensional template.

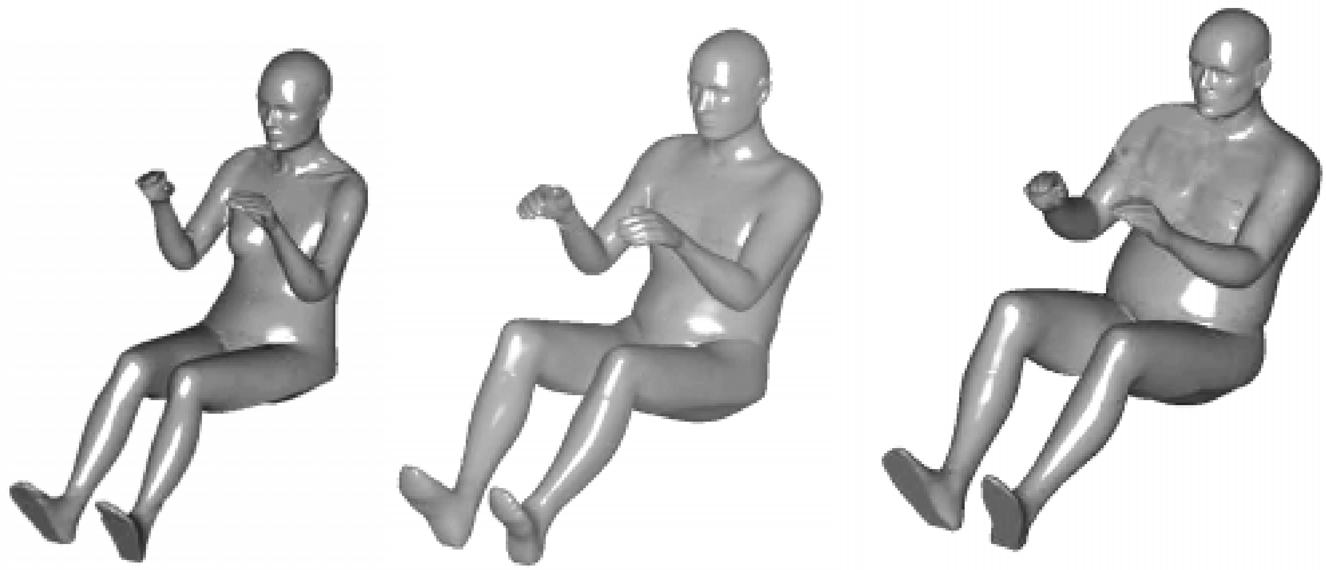

Figure 9. Small female, midsize male, and large male body surface contours for representing humans in CAD environments

3.9 ASPECT Posture Prediction

Early in the ASPECT program, the research team solicited extensive input from industry concerning the current and anticipated uses of the ASPECT manikin. One common sentiment was that use of the physical device was expected to diminish as more vehicle design and assessment tasks were conducted in CAD. While it was clear that a physical tool would always be needed to verify that the seat and vehicle were constructed as intended, new tools to facilitate the use of computers in the design process were also desired.

In addition to CAD models of the ASPECT manikin, companies participating in ASPECT indicated that future vehicle designs would make extensive use of computerized human models. These CAD manikins are capable of representing people with widely varying anthropometry and can be manipulated to simulate tasks within the vehicle. A review of existing CAD manikins demonstrated that the biggest impediment to effective use of the models is a lack of accurate posture prediction. While the anthropometric scaling of the available models is sophisticated, the posturing and position of the models is commonly left to the discretion of the vehicle designer. Of the models surveyed for ASPECT in 1995, only RAMSIS contained any posture prediction validated for vehicle occupants (25).

Consequently, a major objective of the ASPECT program was to develop a large database of vehicle occupant postures, covering a wide range of anthropometry, vehicle, and seat geometry. The data were analyzed to determine the effects of these factors on occupant posture and position. The resulting statistical models provide a means of predicting the posture and position of drivers or passengers with a wide range of body dimensions in almost any passenger car geometry. The models have been validated using data from large-scale posture studies conducted in vehicles. Details of the occupant posture research and posture-prediction model development are presented elsewhere (6, 8).

The ASPECT posture prediction models will provide ways of using CAD manikins with known quantitative accuracy. For example, a manikin positioned using the ASPECT techniques has an eye location with a specified accuracy relative to the distribution of eye locations for people who match the manikin anthropometry. The ASPECT posture-prediction models allow CAD manikins to be used to make more accurate assessments of accommodation than were possible using other posture-prediction methods (8).

The ASPECT posture-prediction models also provide a way of ensuring compatibility between different CAD manikins. Ideally, a manikin with a specified anthropometry provided by one software publisher will sit in the vehicle environment in the same way as an identically sized manikin from another software company, that is, in a way that represents the average posture of people matching the specified anthropometry. Any discrepancies can be resolved by reference to the available data and models from the ASPECT program and other studies. Much as SAE J1517 and J941 have provided standardized predictions for population distributions of some postural degrees of freedom, a new SAE practice could be developed that would standardize prediction of a number of postural degrees of freedom for individuals.

3.10 CAD Manikin Usage and Postural Variability

The analyses of posture data collected in the ASPECT program leading to the development of posture prediction models have emphasized the need to consider carefully the importance of residual postural variability when applying CAD manikins to design analyses. In many ways, the current use of CAD manikins in vehicle design approximates in three virtual dimensions the template-based design practices that preceded the development of the task-oriented percentile models, such as the eyellipse. That is, large and small manikins are selected to represent the occupant population. These manikins are positioned in the simulated vehicle space, and their accommodation is assessed, using vision, reach, and comfort analyses (the latter usually based on joint angles). In the old template-based procedures, the work was performed in two dimensions using physical templates, and the time-consuming manual procedures meant that only a few templates were applied. With CAD manikins, many different occupant sizes can be rapidly evaluated, and the analyses can include full three-dimensional assessment. However, these assessments are still limited by the primary assumption underlying the approach, which is that body dimensions are the primary determinants of occupant accommodation.

The central difficulty in applying physical or CAD manikins to accommodation assessment is that occupant positions are affected both by anthropometric variability and by postural variability that is not related to anthropometry. For example, consider the case of using manikin-based procedures to determine the appropriate range of fore-aft seat track adjustment. Using data from recent studies at UMTRI (1, 2, 20) the mean selected seat position for men who are 95th percentile in the U.S. driver population by stature (1870 mm) is 953.5 mm aft of the Ball-of-Foot reference point for a typical midsize sedan. Figure 10 shows this mean position, which represents the most accurate prediction available for a male driver of this size. However, Figure 10 also depicts the *distribution* of seat positions for male drivers with this stature, approximated by a normal distribution with a standard deviation of 30 mm (20). Because of differences not associated with stature, men who are 1870-mm tall select seat positions over a fairly wide range. Among a hypothetical population of people 1870-mm tall, a fore-aft range 117.6 mm would be required to span 95 percent of their preferred seat positions.

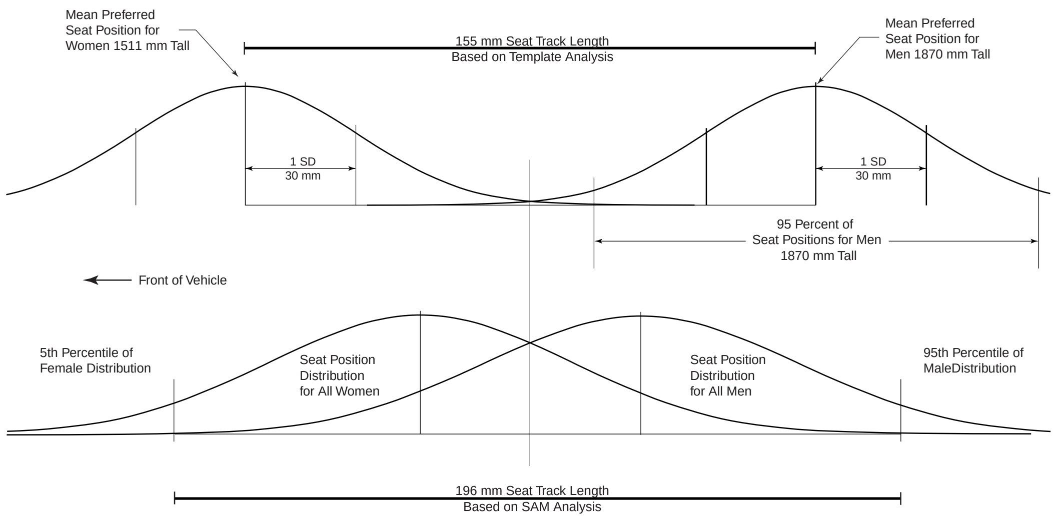

Figure 10. Illustration of seat position distribution. The top curves show predicted seat positions for large men (right) and small women (left). The bottom curves show distributions of seat positions for all men and women, along with the seat track length necessary to accommodate 95 percent of the combined population.

For comparison, consider the mean predicted seat position in the same vehicle for a small woman whose stature is equivalent to the 5th percentile for U.S. women. Figure 10 illustrates the mean predicted seat position for people of this stature, along with the residual variance. (Analyses at UMTRI have shown that men and women of the same stature select the same average seat position.) The residual variance in seat position for small women is approximately the same as for large men (2). The difference in mean selected seat positions between 5th-percentile women and 95th-percentile men (by stature within gender) is 155 mm, only about 37 mm (32 percent) more than the horizontal window containing 95 percent of individuals of either stature.

Suppose that these accurate posture prediction models were used with a family of CAD manikins to determine the necessary range of seat track adjustment. Selecting the 5th-percentile female and 95th-percentile male statures in an attempt to span 95 percent of a 50-percent-male driver distribution, the mean predicted positions for these two body sizes, shown in Figure 10, would define the needed range of seat track travel.

However, such an analysis would neglect the postural variability not accounted for by accurate posture predictions based on anthropometry. In contrast, a task-oriented percentile model for seat position, like that presented in SAE J1517 or the recently developed Seating Accommodation Model (SAM), includes both anthropometric and postural variability in determining accommodation ranges. Figure 10 shows the predicted 2.5th and 97.5th percentiles of the target driver population using SAM, approximated by the 5th percentile of the female distribution and 95th percentile of the male distribution (2). Compared to the manikin-based approach, SAM indicates that an additional 41 mm of seat track travel is needed to accommodate the desired percentage of the population.

Previous studies have demonstrated similar findings, showing that the distance between the mean seat positions of 5th-percentile women and 95th-percentile men is smaller than the range of adjustment needed to accommodate 95 percent of the driving population. These observations formed part of the justification for developing the driver-selected seat position model in SAE J1517 (18). However, the issue of residual variance in posture prediction for individuals has not previously been explored in the context of CAD manikin usage.

One might expect that the performance of the manikin assessment approach could be improved by specifying anthropometric variables in addition to stature. For example, using the ratio of sitting height to stature (or leg length) as well as stature might improve the prediction of seat position. Four manikins could be used, representing the same two statures, but with a range of leg lengths within stature. The idea could be carried further, sampling a family of manikins to span a wide range on several variables. Unfortunately, this procedure does not substantially improve the performance of the technique, because the use of additional anthropometric variables does not substantially improve the posture prediction.

Accuracy in posture prediction can be defined as agreement between the predictions and the average value for the same measure obtained with a large group of people matching the specified anthropometry, in the specified vehicle conditions. Since it is impossible to sample people who are anthropometrically identical, and it is likewise impossible to manipulate the anthropometry of an individual experimentally, the “true” posture values for a specified anthropometry are determined by statistical analysis of the postures of people who span a range of anthropometry. The experimentally measured postures are analyzed to determine the anthropometric variables that are associated with posture differences, and mathematical models are constructed to determine the average posture for a specified anthropometry (8, 26).

In research conducted for ASPECT, a diverse population of drivers selected their preferred driver seat positions in a vehicle mockup adjusted to a wide range of vehicle package conditions. Stepwise regression analysis demonstrated that about 76 percent of the variance in fore-aft seat position can be accounted for using package and seat variables along with stature (adjusted $R^2 = 0.763$). Adding two other posture variables (the ratio of sitting height to stature, and body mass index, defined as the body mass divided by the stature squared) improves the percentage of variance predicted (adjusted R^2 value) to 0.767. Importantly, the root mean square error, a measure of the residual variance, decreases only from 38.8 to 38.5 mm, indicating that the additional variables have not substantially improved the posture prediction. Using leg length (stature minus sitting height), rather than stature, yields slightly poorer results ($R^2_{adj} = 0.735$, RMSE =

41.0). Similar findings have been reported elsewhere, in work to develop the new Seating Accommodation Model (1, 2)*.

These analyses indicate that most of the residual postural variance is not related to primary anthropometric variables, such as leg length or weight, that would be useful for positioning manikins. Instead, the residual variance represents the range of driver preference independent of anthropometry. This variance is likely to be essentially unpredictable; that is, the variance is not related to the small number of descriptors, such as gender, stature, and weight, that are useful for describing target vehicle occupant populations.

Although the examples given here use seat position, the general observations apply to any other postural variable. For example, eye location shows a three-dimensional residual variance distribution after taking into account vehicle, seat, and anthropometric factors (8, 26). The resulting uncertainty in posture prediction is important for assessments that are dependent on CAD manikin posture and position, such as reach and vision evaluations.

It is difficult to represent the posture variance not attributable to anthropometry in CAD human models. Yet, these models have important applications in vehicle design. If accurately postured, they can be used to visualize people of a wide range of sizes sitting in the vehicle interior. Often, these visualizations will reveal design problems that were not identified using the standard statistical tools. Dynamic tasks, such as reaches, that are difficult to describe kinematically with task-oriented percentile models, are usefully examined with human models. Further, accommodation dimensions that are limited almost entirely by anthropometry are assessed well using CAD manikins. For example, lateral hip and shoulder room can be usefully studied using an appropriately selected family of manikins. However, the uncertainty regarding the postures and positions of drivers of these sizes must be kept in mind when assessing fit.

The knowledge gained from recent occupant posture research could be used to develop new methods for CAD manikin application that would broaden the applicability of these models for accommodation assessment. In particular, automated procedures could be developed to conduct vehicle evaluations using virtual sampling of a large number of manikins from the target population. In such a procedure, the posture and anthropometry of each CAD manikin instance would include random components accounting for the residual postural variability that cannot be predicted from primary anthropometric factors. Research is now underway to determine the efficacy of this approach for manikin-based accommodation assessments.

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* The residual variance in this analysis is larger than the variance used in Figure 11, which was taken from SAM calculations. The SAM calculations are based on in-vehicle data, whereas these calculations are based on laboratory data. The smaller variance in the vehicle data may indicate the influence of posture restrictions not present in the laboratory, but the overall effects of anthropometry and other variables are similar in vehicle and laboratory studies (1).

3.11 Design Process Using the New Tools

Table 4 contrasts the current SAE practices with the new methods. The new methods provide considerable continuity with existing practice, but with greater accuracy and generality. The application of the new tools to vehicle interior design can be illustrated using a hypothetical example. As in the preceding illustration, a seat height of 270 mm and some predefined pedal geometry are assumed. Figure 11 shows the new tools on a package layout.

First, the Pedal Reference Point (PRP) location is determined by constructing a plane tangent to the accelerator pedal extending 200 mm from the depressed floor surface. This defines the horizontal (PRP) and vertical (AHP) reference points for laying out the vehicle package. The new SgRP locator line is placed on the drawing, referenced to the PRP and AHP locations. Using the specified seat height, the SgRP location is now defined.

The SAE task-oriented percentile models for eye location and seat position can now be added. The new version of the eyellipse requires information on steering wheel position and the anthropometry of the target population, obtained using in-house procedures. For this illustration, a population matching the general U.S. adult population defined in the 1974 NHANES survey (24), but with a 60-percent-female gender mix, will be used. Note that this type of configurability is not available with the current eyellipse. The eyellipse centroid location is calculated relative to the PRP and AHP reference points, using the fore-aft steering wheel position and seat height. The eyellipse is not positioned relative to the SgRP, as in the old procedure, and design seatback angle is not used. The new head contours can be positioned in the same way as the eyellipse.

Next, the seat track is laid out using the new Seating Accommodation Model (SAM). In addition to steering wheel position and seat height, seat cushion angle and transmission type are required. For this two-way seat track vehicle, a design cushion angle of 14 degrees is chosen, based on in-house guidelines, and the vehicle is designed for automatic transmission (no clutch). The same population used to define the eyellipse is used to determine the 2.5th and 97.5th percentiles of the driver-selected seat position distribution, defining a seat track adjustment (H-point travel) range that will accommodate 95 percent of drivers in their preferred seat positions. Using the SgRP location and a design seat track angle of six degrees (defined from in-house practice), the H-point travel path is defined. Driver reach envelopes can be added for further design analysis. Although J287 is not directly affected by the new procedures described in this chapter, it is currently under review by the SAE Design Devices Committee.

Table 4
Comparison of Current SAE Recommended Practices with New Methods

Practice	Topic	Current	New
J1517	Driver Selected Seat Position	U.S. 50%/50% male/female driver population Function of seat height Equations for 7 percentiles	Any population stature and gender mix Function of seat height, steering wheel position, seat cushion angle, and transmission type Solutions for any desired percentile of the distribution
J1516	Accommodation Tool Reference Points	Pedal Plane Angle Theta Ball of Foot Accelerator Heel Point – –	Shoe Plane Angle Alpha Ball of Foot Accelerator Heel Point Pedal Reference Point
J1100	Motor Vehicle Dimensions	Ambiguous SgRP Definition Many dimensions relative to H-point manikin	New SgRP Definition Revised definitions relative to ASPECT manikin
J826	Devices for Use in Defining and Measuring Vehicle Seating Accommodation	H-point manikin 2-D template – –	ASPECT manikin CAD ASPECT Manikin 3-D CAD human reference forms
J941	Driver's Eye Range	U.S. 50%/50% male/female population Function of SgRP location and design seatback angle 95th- and 99th-percentile cutoff ellipses – –	Any population stature and gender mix Function of seat height and steering wheel position Solutions for any desired percentile ellipse New eyellipse shape
J1052	Driver and Passenger Head Position	U.S. 50%/50% male/female population Function of SgRP location and design seatback angle 95th- and 99th-percentile cutoff ellipses No head turn	Any population stature and gender mix Function of seat height and steering wheel position Solutions for any desired percentile ellipse Includes space for head turn

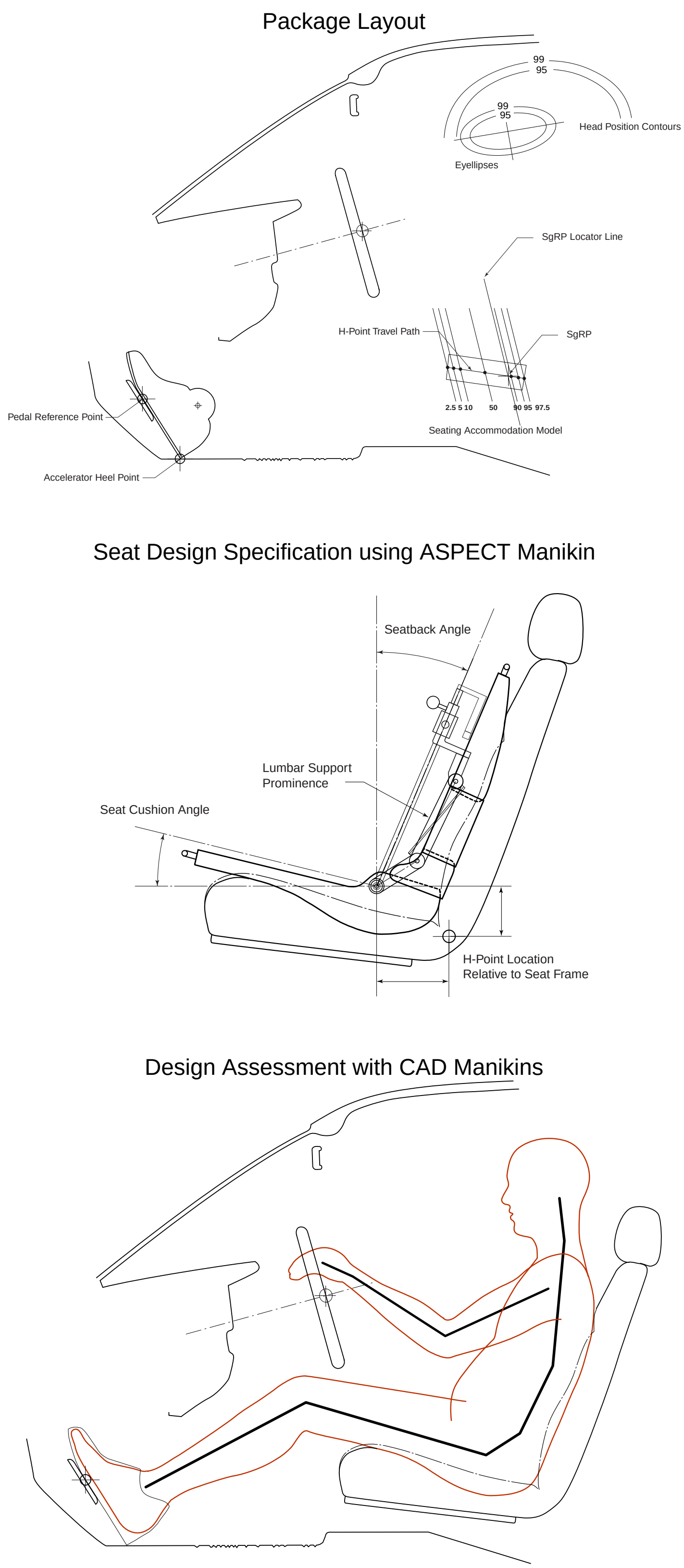

Figure 11. Illustration of hypothetical driver station design procedure using the new methods.

The ASPECT manikin is not directly used in the design process up to this point. However, there are a number of assessments that are currently made using the SAE 2D template that may be carried over. For example, knee clearances are sometimes assessed using the 2D template knee and shin locations. To facilitate this type of analysis, a 3D CAD version of the ASPECT manikin can be installed in the new design, placing the H-point at the SgRP. The shoe is placed tangent to the accelerator pedal. The leg and thigh segments, adjusted to the SgRP reference length, complete the installation. Note that it is not necessary to include the entire ASPECT manikin for this application. Only the geometry of the thigh, leg, and shoe segments are needed.

When the vehicle designer begins to consider seat design, the ASPECT manikin measures of the seat can be used as specifications. For example, the location of the H-point relative to the seat frame, the seat cushion angle, seatback angle, and lumbar support prominence can be specified for a particular seat frame orientation. This information, along with other dimensional guidelines, can be forwarded to the seat supplier to guide the seat design. When a seat prototype is available, the seat can be tested using the ASPECT manikin for conformance with these specifications without having to install the seat in a vehicle mockup. Only the correct seat frame attitude with respect to vertical is required.

For additional design assessments, CAD manikins can be used with posture prediction models developed in ASPECT. Inputs to the posture prediction models include basic package dimensions such as seat height and steering wheel position, but also include ASPECT manikin seat measures, such as seat cushion angle, lumbar support prominence, and (for fixed seatbacks) seatback angle. The posture prediction models include the appropriate offsets between the manikin hip joint and seat H-point as a function of anthropometric, seat, and package variables. The standard human body reference forms (small female, midsize male, and large male) can also be used to make interior assessments. Using appropriate posture prediction, the three-dimensional CAD forms can be placed in the vehicle interior for visualization or to make comparative clearance measures.

4.0 DISCUSSION

The SAE recommended practices for vehicle interior design represent a substantial body of knowledge concerning vehicle occupant posture and position. These tools, developed and modified over several decades with contributions from many people in the auto industry, have been very successful in providing uniform methods for designing, evaluating, and comparing vehicles. The new methods described in this chapter represent only evolutionary changes to the current vehicle design practices, and provide considerable continuity with respect to measurement definitions and applications techniques. Yet, the new tools will provide vehicle designers with better accuracy, consistency, and flexibility. Seat position and eye location distributions can be customized for the specific vehicle occupant population of interest. The new ASPECT posture prediction models, combined with a quantitative understanding of postural variability, can be used to improve the effectiveness and validity of analyses with CAD manikins. Finally, the ASPECT H-point manikin provides new measures of the seat that will allow more complete specification of seats to meet comfort and performance goals.

The research leading to the development of these new tools has been conducted in close cooperation with industry, including the participation of many people from the corresponding SAE committees. This cooperation ensures that the tools are likely to meet the requirements of industry, but there will be additional opportunities for feedback as the committees prepare the revisions to the recommended practices. Evaluations of these tools are currently underway at a number of companies.

The implications of changes in the current recommended practices are broader than can be addressed in this chapter. Notably, several of the practices and definitions are cited in vehicle safety standards, such as the U.S. Federal Motor Vehicle Safety Standards. The H-point manikin is used in dummy positioning procedures, and the eyellipse and associated points are used in vision standards. The SAE practices have also been cited and adapted for a number of international standards. Changes to these other practices, if necessary, will require additional actions by the associated committees and governing bodies. However, the considerable effort required to change the current practices should not dissuade the industry from moving ahead with improvements that will result in better-designed, more comfortable, and safer automobiles.

While the previous task-oriented percentile models were limited to descriptions of a particular U.S. driver population, the new models can be configured to represent any population of interest. The ASPECT manikin and the new SgRP locating procedure have been developed using anthropometric reference standards so that they can be applied equally well for any particular population. However, the extension of the task-based models to non-U.S. populations is based solely on anthropometry. These models do not take into account the potential for other sources of difference between populations in vehicle occupant posture.

The research leading to the development of these tools has clarified the complicated issues regarding anthropometric and postural variance. While both sources of variability in vehicle occupant positioning are addressed by the task-oriented percentile models, current CAD manikin procedures address only the anthropometrically related variance. New application procedures will be necessary to integrate them fully into the vehicle design process.

5.0 CONCLUSIONS

A new set of tools has been developed that improves on the current SAE recommended practices for vehicle interior design, including new versions of:

- H-point manikin (J826),
- driver-selected seat position model (J1517),
- driver eyellipse (J941),
- pedal reference points (J1516),

- seating reference point definition (J1100), and
- vehicle interior dimensions (J1100).

New methods and models have also been developed for:

- three-dimensional human body surface definition, and
- whole-body posture prediction.

Through the activities of the associated SAE committees, these new methods will be considered in revising the current SAE recommended practices. Continued participation of industry representatives throughout the process will ensure that the resulting practices are appropriate for current and future needs.

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CHAPTER 5

HUMAN SUBJECT TESTING IN SUPPORT OF ASPECT†

1.0 INTRODUCTION

Detailed knowledge of how anthropometric, vehicle, seat, and task factors affect occupant posture and position is essential to the development of valid physical and computer models to represent humans in the automotive environment. A large database of driver posture and position has been collected and compiled by UMTRI researchers over the past ten years, particularly with regard to the effects of vehicle package factors (1-4).* The ASPECT program provided an opportunity to collect additional posture data to answer some of the remaining questions about the effects of vehicle package factors on occupant posture, but particularly to establish relationships between seat and task factors and posture. These data were collected in a wide range of vehicle and seat configurations for both passenger and driver situations. The effects of vehicle, seat, and task factors on occupant posture and position have been used in the ASPECT program to formulate posture-prediction models for use with CAD manikins, and to guide the design of the ASPECT manikin and usage procedures.

Anthropometric criteria for selecting subjects for these studies were examined carefully during the initial phases of the ASPECT program. Existing anthropometric databases were analyzed to determine both subject selection criteria and the sizes of sample populations needed for the various phases of posture testing. The primary data collected in all the studies were occupant posture and position, but some studies also included subject comfort ratings and measurement of seat pressure distributions. The test facilities included vehicles that were driven by the subjects or, in the case of passenger testing, by another person, as well as laboratory vehicle mockups. The latter allowed for independent variation of vehicle interior geometry or seat factors and included testing of a wide range of vehicle seats.

This chapter provides an overview of the important considerations for this posture research, including subject selection criteria, test protocol, sampling strategies, and test facilities. A summary of each of the eight different posture studies conducted in the ASPECT program is provided.

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* Numbers in parentheses designate references provided at the end of this chapter.

2.0 ANTHROPOMETRIC FACTORS

Human body dimensions vary among individuals and populations and are known to affect occupant posture and position within the vehicle package space. Consequently, any study of occupant posture must consider anthropometry in the experimental design. In most cases, subjects are selected in large part based on anthropometric factors, so that the data adequately represent the targeted user population. An understanding of the relationships among anthropometric variables is therefore necessary to select subjects effectively.

Although a large number of anthropometric measurements can be taken on any one subject, many of these measurements are highly correlated (i.e., a small person has small measurements on most body dimensions). As a result, the number of measures needed to characterize a person's size and proportions is fortunately relatively small. By identifying those key measurements that best account for the variance in body dimensions, the selection of subjects for testing can be greatly simplified.

In the ASPECT program, data from several sources were analyzed to identify a set of primary anthropometric measurements that could be used for selecting and defining subjects. These sources were the Anthropometric Survey of U.S. Army Personnel from 1988 (5), the U.S. Health Examination Survey from 1965 (6), and an UMTRI database of measurements gathered from test subjects over the past seven years. Each of these databases was analyzed using factor analysis to identify the set of anthropometric measurements that best explain the variance in the complete dataset (7). These analyses used the set of measures shown in Table 1 and produced very similar results for both males and females on all three datasets. It should be noted that leg length and aspect ratio (sitting height/stature) could not be included in the analysis for the two published surveys because individual subject data were not available.

In each case, three groups of anthropometric "factors" were identified. In this context, a factor corresponds to a group of correlated variables. These include a measure of torso length, such as erect sitting height, a measure of limb length, such as leg length, buttock-knee length, or forearm length, and a measure of girth or weight, such as hip breadth or total body mass. Variables strongly associated with each factor are given in Tables 2 and 3. These three factors account for about 75 percent of the variance in the selected anthropometric measures for both males and females.

Table 1
Measures Selected for Analysis from Anthropometric Databases

Anthropometric Measure	U.S. Army	HES	UMTRI
Age	x	x	x
Stature	x	x	x
Weight	x	x	x
Arm Reach	x		x
Forearm Length	x		x
Shoulder-Elbow Length	x		x
Sitting Height	x	x	x
Seated Eye Height	x		x
Knee Height	x	x	x
Popliteal Height	x	x	x
Buttock-Knee Length	x	x	x
Buttock-Popliteal Length	x	x	x
Shoulder Breadth	x	x	x
Seated Shoulder Height	x	x	x
Hip Breadth	x	x	x
Leg Length (Stature - Sitting Hgt)		x	x
Aspect Ratio (Sitting Hgt/Stature)		x	x

Table 2
Anthropometric Variable Correlation Groupings for Males

Factor 1 (Limb length)	Factor 2 (Torso length)	Factor 3 (Weight)
Leg Length†	Sitting Hgt	Hip Breadth
Popliteal Hgt	Eye Hgt	Shoulder Breadth
Knee Hgt	Seated Shoulder Hgt	Weight
Forearm Length	Stature	
Shoulder-Elbow Len.	Aspect Ratio	
Stature		
Aspect Ratio		
Butt-Popliteal Len.		
Butt-Knee Length		
Arm Reach		

† Leg length calculated as stature minus sitting height.

Table 3
Anthropometric Variable Correlation Groupings for Females

Factor 1 (Limb length)	Factor 2 (Torso length)	Factor 3 (Weight)
Leg Length†	Sitting Hgt	Weight
Aspect Ratio	Eye Hgt	Hip Breadth
Popliteal Hgt	Seated Shoulder Hgt	Shoulder Breadth
Knee Hgt	Stature	Butt-Knee Len.*
Shoulder-Ebw Len.		Butt-Popliteal Len.*
Forearm Length		
Stature		
Butt-Knee Length		
Arm Reach		
Butt-Popliteal Len.		

† Leg length calculated as stature minus sitting height.

*These variables are not included in the weight factor in the analysis of Army data. That data set is restricted to Army personnel, who may be more fit and less overweight on average than the populations in the other two studies.

There are two interesting observations from the results of this factor analysis. First, stature appears in both the limb length and torso length factors. Given that stature is a combination of leg length and torso length, it makes sense that it would be correlated with both. Second, the results for males and females are very similar, except for two components of the weight factor. For males, buttock-knee and buttock-popliteal lengths appear only on the limb-length factor. For females, weight is associated with these measures as well, suggesting that extra weight in females may be more likely to affect measures involving the buttocks.

From these analyses, stature, sitting height, and weight were chosen as the primary anthropometric measures. Sitting height and weight represent the torso and body mass factors, respectively. Leg length can be used to represent limb length, but since leg length was calculated by subtracting sitting height from stature, the measured variable is essentially the same as stature. It is not important that the three variables be strictly orthogonal (as the factors are constrained to be). These three variables make a good set for subject selection because they account for much of the variance in anthropometry, they can be used to predict most other anthropometric measurements with reasonable accuracy, they are easily measured, and they are familiar. If necessary, they can be orthogonalized by using variables related to ratios of sitting height or weight to stature (e.g., body mass index).

Other similar analyses have reached equivalent conclusions. RAMSIS, a computer model of human occupants developed for automotive design applications, uses similar variables, namely stature, waist circumference, and aspect ratio (limb length/torso length) to describe the anthropometric space (8). Because waist circumference is highly correlated with weight, the three primary measures selected for ASPECT do not differ in any important way from the three anthropometric axes used in RAMSIS.

3.0 SUBJECT SAMPLING CONSIDERATIONS

Potential strategies for choosing test subjects for vehicle occupant posture studies can be divided into three categories: random selection, representative selection, and stratified selection. These strategies differ in the extent to which one or more subject factors is used to guide the selection of subjects. Gender can be used as a simple example of a subject factor. Assume that about half the drivers are male and half female in the target population for a particular study of driving posture. With random sampling, subjects are sampled as they are available, without regard to gender. Given a large enough sample, a random sample will accurately represent the larger population from which it was taken, with close to half of the subjects being males and half being females. With representative sampling, subjects are chosen to make sure that the number of male and female subjects in the completed subject population matches the proportion in the target population -- in this case 50% males and 50% females. In contrast to random sampling, the experimenter does not rely on chance to produce a sample that represents the larger population on the specific characteristic.

Representative sampling is a specific case of stratified sampling. In the more general form of stratified sampling, defined subject groups are sampled in any designated proportion that is determined by the goals of the study. In the gender example, it may be that data for females are more critical to the outcome of a particular study and females would be oversampled (i.e., a greater number of females would be recruited than males). The final subject population might include, for example, 75% females and 25% males.

The primary advantage of random sampling is that the resulting data conform to the assumptions of most statistical tests without requiring weighting of the data. The disadvantage is that random sampling requires more subjects to ensure that the sample is appropriately matched to the target population. As an illustration, it is not particularly unusual to have seven heads out of ten flips of a fair coin, an event with a probability of 0.17 (i.e., 17%). However, it would be very surprising to see 70 heads out of 100 flips of the same coin, an event which has a probability of 0.0000393 (i.e., 0.004%). A larger sample will be more likely to match the distribution in the target population.

In contrast, stratified sampling provides a way of controlling the sample and ensuring that all groups are adequately sampled. It can also be used to emphasize groups that are more crucial to the results, and that might not be well represented by random or representative sampling. Fewer subjects are required than for random sampling, but accurate analysis of the data relies on the validity of the weighting scheme, which is necessary to calculate statistics that appropriately estimate parameters of the target population. Representative sampling does not require weighting, but it does not have the flexibility to reflect the relevance of the different groups to the study. For example, extreme stature groups (short females and tall males) were often of particular interest in ASPECT studies. Representative sampling requires a larger sample size than other stratification schemes to ensure good estimates of behavior in extreme groups.

In the ASPECT research, stratified sampling was typically used, with the stratification groups based on a combination of stature and gender. The specific stratification scheme depended on the goals of the study. A typical stratification scheme used equal sampling in each of several stature/gender groups. Such a scheme was used for studies in which the goal was to measure behavior (posture or position) across the range of vehicle occupants and to predict that behavior of occupants of any size. Often, the most extreme groups (tall males and short females) are of particular interest because a goal of several studies was to develop accommodation models, which are used to define limits for vehicle design criteria. Such limits are typically most relevant in the extremes, or tails, of a distribution.

In other cases, the stratification scheme emphasized one group, often midsize males, because they match the ASPECT manikin reference anthropometry (9). Other stature/gender groups were also sampled to verify that driver behavior across a range of statures is consistent. However, such a strategy typically does require large samples at the extremes of the stature distribution.

3.1 Sample Sizes

The number of subjects in each ASPECT study depended on the objectives of the study. For several studies, the primary goal was to generate a point estimate of posture or position for a specific stature (typically the reference stature for the manikin). Another common goal was to model posture or position across the entire range of statures (e.g., for posture-prediction models). Because central-point estimates are easier to obtain with a specified degree of accuracy than are estimates of variability and/or estimates of extreme behavior, the first type of study usually required fewer subjects.

The power of the test is one criterion often used to determine the appropriate sample size. Power is the probability that a given difference (between two groups) will be detected, and depends primarily on sample size and random variability in the dependent variable. The primary limitation of power as a determiner of sample size is that it can be calculated only for a specific difference in one dependent variable. Studies for ASPECT were typically aimed at a number of dependent and independent measures, so one of these was chosen to determine the sample size required to achieve a particular level of power. By combining power calculations with general heuristics, sample sizes selected for ASPECT studies of posture or position of midsize males generally ranged from 15 to 30, while sample sizes for studies designed to understand behavior across the stature range were 24 to 68 subjects.

3.2 Stratification Schemes

Having chosen stratified sampling as the best approach to subject sampling for ASPECT, the next step was to determine a specific stratification scheme for each study. As described previously, three anthropometric measures (stature, weight, and sitting height) are sufficient to account for most of the variance in anthropometry within gender. Any or all of these could be used to define the strata, or groups from which subjects are sampled. Across all ASPECT studies, however, stature is used to define such groups. Sitting height and weight were allowed to vary randomly within the groups and were inspected to confirm that the sample was not unusual relative to norms for these variables.

While stature, weight, and a sitting height comprise a key set of anthropometric variables, there are two primary reasons for using stature alone to determine sampling groups. The first reason is that sampling on two or more characteristics simultaneously makes finding subjects to fit the categories difficult, especially since people usually know their stature better than they know their sitting height or even their weight. It is difficult enough to find short and tall volunteers without adding requirements for their sitting height and weight.

The second reason is that adding other variables to the stratification scheme provides minimal additional value to the posture results. Previous research at UMTRI has shown that sitting height and weight add little predictive power to that of stature when modeling most posture and position variables (4). In analyses of those few variables in which weight or sitting height is a better predictor than stature, stratifying the sample on the basis of stature ensures an adequately wide range of sitting heights and weights as well.

The only sample characteristic not guaranteed by stratification on stature is a range of sitting heights or weights *within* each stature group. In other words, sitting height *relative* to stature is sampled randomly, but actual sitting height is correlated with stature such that stratification on stature guarantees a wide range of sitting heights. Sitting height and weight relative to stature do not provide sufficient additional value to predicting occupant posture and position to justify the increased sampling complexity required to fill specific gender/stature/weight categories.

Subject age was not a subject selection criterion and was allowed to vary over a normal range. The subjects who participated in the ASPECT studies ranged from 20 to 73 years of age. Analyses of the UMTRI data collected previously have indicated that age does not affect driver preferred seat position or seatback angle, and, in the ASPECT studies, subject age has not been found to have an effect on occupant posture.

Twelve stature groups were defined for ASPECT studies. Table 4 below describes the stature ranges for each of the groups, along with the number of subjects sampled in each group for the eight studies summarized later in this chapter. When posture behavior across the range of statures was of primary interest (e.g., the driver posture study, in-vehicle passenger posture study), all groups were sampled relatively evenly. For studies in which midsize-male behavior was of primary interest (e.g., midsize-male passenger posture study), midsize males were oversampled relative to other groups. Other studies represent a compromise between these goals. For example, seat factor study III emphasized male behavior (to estimate midsize-male behavior), but included data from all groups so that the data would be applicable to any population.

4.0 TEST FACILITIES

4.1 Vehicles and Laboratory Seating Bucks

Subject testing for ASPECT was conducted both in vehicles and in carefully designed laboratory vehicle mock-ups, depending on the data collection requirements of the study. Testing in actual vehicles provides the most realistic situation and was used in a portion of the studies of driver and passenger posture. However, testing in vehicles often limits the types of measurements that can be safely and accurately made, and also present limitations in the vehicle package and seat conditions. Occupant posture is measured by digitizing palpated bony landmarks on the subject, and only a subset of the required set of body landmarks can be feasibly measured in vehicles. Studies that required a complete set of landmarks were therefore conducted in seating bucks. The laboratory vehicle mock-ups also allowed seat and package features to be independently adjusted over wider ranges of conditions than is possible in vehicles.

Table 4
Subject Sampling Strategy for ASPECT Studies

Subject Groups				ASPECT Study							
Group	Gender	Percentile Stature Range by Gender (10)	Stature Range (mm)	Driver Posture	Seat Factors I & II	Seat-Factors III	Kinematic Model Validation	Midsize Male Passenger Posture	In-Vehicle Passenger Posture	Manikin Validation	Total of All Studies
0	Female	< 5th	Under 1511	6	2	3	0	0	2	0	15
1	Female	5-15	1511 - 1549	5	2	3	1	0	2	0	15
2	Female	15-40	1549 - 1595	6	2	3	2	0	2	0	17
3	Female	40-60	1595 - 1638	5	2	3	2	0	2	0	16
4	Female	60-85	1638 - 1681	6	2	3	2	0	2	0	17
5	Female	85-95	1681 - 1722	6	2	3	1	0	2	0	16
6	Male	5-15	1636 - 1679	6	2	5	1	0	2	5	23
7	Male	15-40	1679 - 1727	6	2	5	2	0	2	5	24
8	Male	40-60	1727 - 1775	5	2	5	2	15	2	5	38
9	Male	60-85	1775 - 1826	6	2	5	2	0	2	5	24
10	Male	85-95	1826 - 1869	5	2	5	1	0	2	5	22
11	Male	> 95th	Over 1869	6	2	5	0	0	2	5	22
	Total			68	24	48	16	15	24	30	249

The fidelity of the UMTRI laboratory test environment was assessed in earlier studies by comparing posture and position data obtained in the laboratory with equivalent data collected in actual vehicles (1, 2). These analyses ensure that the UMTRI laboratory bucks produce results that are comparable to in-vehicle conditions. Each buck is equipped with actual automotive seats, pedals with realistic force-deflection properties, a steering wheel with typical movement and feel, a driving scene or simulator to provide a visual task, and an appropriately positioned instrument panel. In some cases, a roof liner was used to provide realistic head and vision constraints. The position and orientation of these components were adjusted through ranges typical of automotive package designs.

All subject test environments were calibrated and measured to document the test conditions before and after the study. Multiple SAE J826 H-point drops and seat cushion angle measurements were made, and the position and travel range of all vehicle features were recorded using a FARO arm or sonic digitizing system as discussed below. The contours of the vehicle and buck surfaces were also scanned to document their positions and shapes and to facilitate visualization in CAD programs. Fixed hardware targets were incorporated into each test environment and were digitized with every subject tested to verify component positions.

4.2 Hardware for Measuring Driver Posture

4.2.1 Sonic Digitizer

A Science Accessories Corporation sonic digitizer, shown in Figure 1, was used to measure subject position and posture in five of the eight studies. The system uses a fixed array of four microphones to detect the three-dimensional locations of sonic emitters with an accuracy of 2 mm. A sonic probe is placed on a palpated body landmark and the two emitters on the probe are fired in rapid sequence. The three-dimensional coordinates of the probe tip are calculated from the measured locations of the probe emitters.

Figure 1. Sonic digitizer hardware.

4.2.2 FARO Arm

A portable, articulated arm for coordinate measurement, manufactured by FARO Technologies, Inc. and shown in Figure 2, was used to measure occupant position in three of the eight studies. The FARO arm is a three-link mechanical coordinate measurement device instrumented at each of six joints with rotary transducers. The joint angles and the lengths of the three articulated links are used to calculate the position of the probe tip. To measure subjects' positions and postures, the subjects were asked to maintain their driving or riding posture while the FARO arm apparatus was aligned to the data collection coordinate system by digitizing three reference points on the vehicle or laboratory mockup. The FARO arm was then used to record the driver's posture and position by measuring the locations of the key body landmarks. Digitization of all body landmarks was completed in approximately thirty seconds. The FARO arm accuracy under data collection conditions was determined to be ± 2 mm.

Figure 2. FARO arm digitizer hardware.

5.0 GENERAL TEST PROTOCOL

Subjects were recruited for testing from the greater southeastern Michigan area through the use of classified advertisements. An effort was made to recruit subjects from both inside and outside the University community and to recruit subjects of all ages. The subjects were paid $10-$20 per hour for their participation. All subjects were required to have four years of driving experience and to wear comfortable, non-bulky clothing and low-heeled shoes. Information on the subjects' current vehicle and driving habits were collected and each driver was screened using a health questionnaire. Informed consent was obtained from every subject, according to the University of Michigan protocols for research involving human subjects.*

Subjects selected were naive to the specific conditions of the study and were told that the experimental goals were to determine comfortable automotive seated positions. They were not informed of any of the specific test configurations or differences between test conditions nor were they allowed to observe the changing of test conditions. No manufacturers or brand names were used when identifying the different seats or vehicles.

Prior to posture testing, each subject was measured to determine their body size and dimensions. These measures were taken using a calibrated GPM anthropometer. The anthropometric measures included: stature, weight, age, sitting height, eye height,

* The rights, welfare, and informed consent of the volunteer subjects who participated in this study were observed under guidelines established by the U.S. Department of Health and Human Services on Protection of Human Subjects and accomplished under medical research design protocol standards approved by the Committee to Review Grants for Clinical Research and Investigation Involving Human Beings, Medical School, The University of Michigan.

shoulder height, buttock-to-knee length, knee height, arm length, forearm length, hip breadth and shoulder breadth. These measures are illustrated in Figure 3. The full set of palpated bony landmarks shown in Figure 4 were also digitized on each subject seated in a specially designed hardseat, shown in Figure 5. This documented each subjects' torso shape and the relationship between the body landmarks, including back and spine landmarks that are inaccessible while the subject is seated in a vehicle seat.

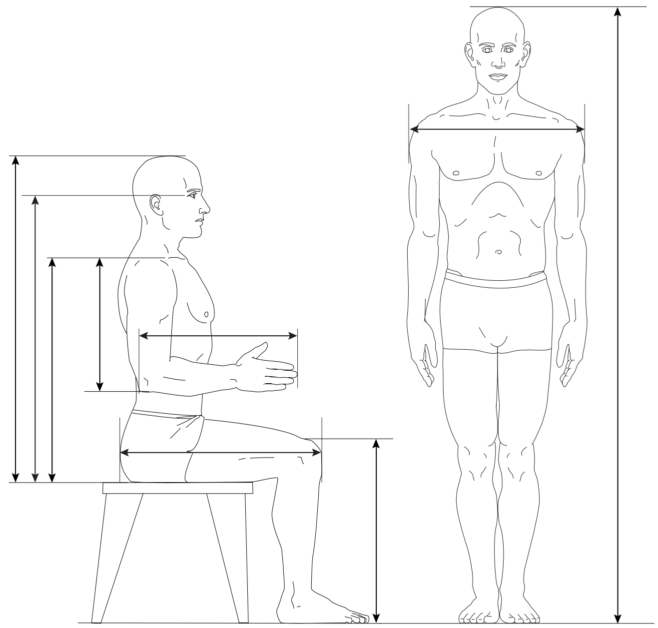

Figure 3. Illustration of anthropometric measures (age and weight not illustrated).

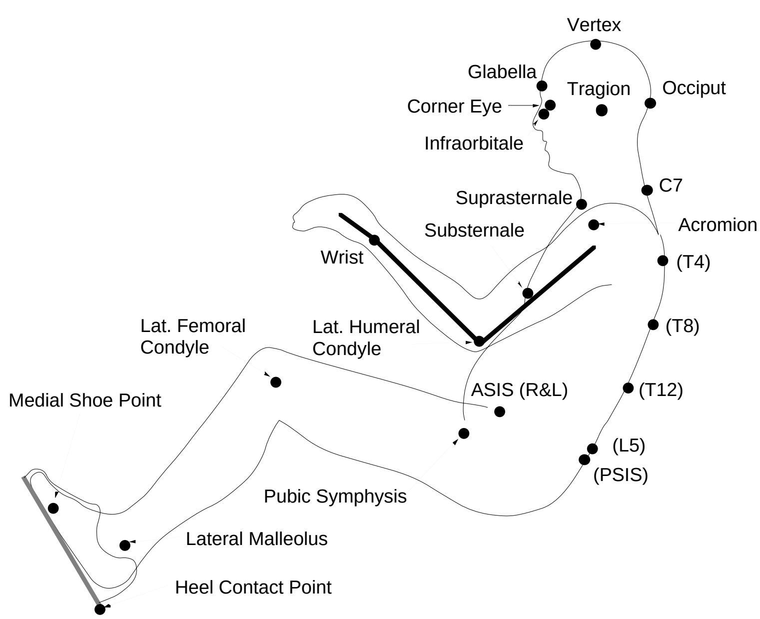

Figure 4. Digitized body landmarks.

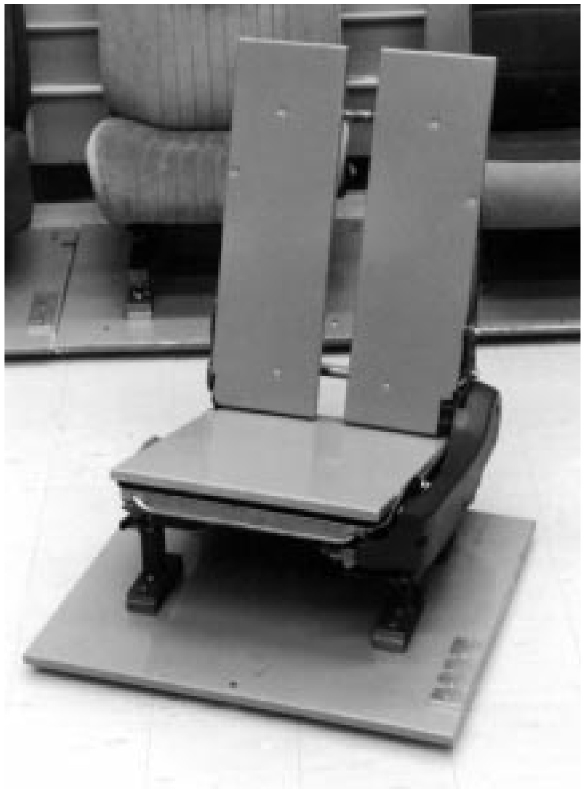

Figure 5. Hardseat.

Many steps were taken to eliminate potential sources of error or bias associated with the test protocol. Test sessions were limited to a maximum of 2-1/2 hours to maintain the subjects' motivation level. The order of the test conditions was randomized for each subject and conditions were identified by a configuration number rather than descriptive terms (i.e., "configuration 10" rather than "high cushion angle"). Prior to the subject entering the vehicle or laboratory mockup, the initial positions of the seat and seatback were set to a standardized position representing the expected mean positions in order to minimize bias associated with the initial positions. Subjects were instructed to find a comfortable driving or riding position using the adjustments provided, experimenting with their position while driving/riding.

Data were collected immediately after a 10 to 20 minute drive or after the subject had found a comfortable driving or riding position in the laboratory buck. Previous UMTRI studies have shown differences of less than 2 mm in preferred seat fore/aft position between pre- and post-drive measurements, suggesting that short exposure testing is acceptable for collecting driver preferred position and posture data (11,12). Also, analysis of National Personal Transportation Survey data indicates that 60% of all vehicle trips are 15 minutes or less in duration, and that 80% of vehicle trips are 30 minutes or less (12). This suggests that 10-20 minutes is an adequate drive time for characterizing occupant seated posture.

In every study, data collected included driver preferred seat fore/aft position, driver preferred seatback angle, driver preferred steering-wheel tilt position (if applicable), and the 3D locations of body landmarks. The landmark data were used to calculate driver posture measures, using a process described by Reed et al. (13). In most cases, driver comfort ratings and subject evaluations of the positions of the controls were also collected. In the manikin validation study, pressure-distribution data were collected for every subject using an X-Sensor pressure mapping system. Figure 6 shows the mats installed in the laboratory buck setting.

Figure 6. Pressure mapping system installed in test seat.

6.0 OVERVIEW OF ASPECT POSTURE STUDIES

Eight posture studies were conducted in ASPECT. Table 5 summarizes the sample size, test conditions, and data collected. The following sections describe the objectives of each study, the subject pool, and the test conditions. The primary findings and conclusions from each study are reviewed. The implications of the study results for vehicle occupant posture prediction are discussed in detail in Chapter 7.

Table 5
Summary of ASPECT Posture Studies

Study	# of Subjects	Factors	# of Conditions	Setting	Data Collected
Kinematic Model Validation Study	16	Seatback angle Lumbar support prominence	6	Laboratory Mockup	Seat-fore/aft and seatback position Occupant posture
Driver Posture Study	68	Seat height (H30) Steering-wheel-to-BOF distance Seat cushion angle (L27) Lateral bolsters Seat type (sport vs. sedan)	19	Laboratory Mockup	Seat-fore/aft and seatback position Occupant posture
Seat Factors Study I	24	Seat cushion angle (L27) Seat cushion length Lumbar support prominence Task (driver vs. passenger)	16	Laboratory Mockup	Seat-fore/aft and seatback position Occupant posture
Seat Factors Study II	24	Lumbar support prominence Lumbar support height Task (driver vs. passenger)	8	Laboratory Mockup	Seat-fore/aft and seatback position Occupant posture
Seat Factors Study III	48	Seat cushion angle (L27) Seat cushion length Seat cushion stiffness Lumbar support prominence Lumbar support height Task (driver vs. passenger)	44	Laboratory Mockup	Seat-fore/aft and seatback position Occupant posture Subjective rating
Laboratory Passenger Posture Study	15	Seatback angle Lumbar support prominence Seat contour level Task (driver vs. passenger)	12	Laboratory Mockup	Seat-fore/aft and seatback position Occupant posture
In-Vehicle Passenger Posture Study	24	Task (driver vs. passenger) Vehicle type Seating location (frt/rear)	13	Vehicle	Seat-fore/aft and seatback position Occupant posture
Manikin Validation Study	30	Task (driver vs. passenger) Seat type (12 production seats)	24	Laboratory Mockup	Seat-fore/aft and seatback position Occupant posture Subjective rating Pressure distribution
Totals	249		142		

6.1 Kinematic Model Validation Study

This study examined the kinematics of the spine in response to torso recline and lumbar spine flexion. The primary purpose of the study was to quantify the accuracy of the accessible-landmark method for estimating T12/L1 (i.e., upper lumbar) joint location with a seated subject. The accessible landmark method is used in all other ASPECT studies to calculate the measures of lumbar spine posture from the digitized landmarks that are accessible when the subject is sitting in a vehicle seat (13). The study was conducted using the hardseat with passenger postures and enforced spine extensions about the lumbar support. Sixteen subjects were tested, as described in Table 6. Body landmark location data were collected using the sonic digitizing system. Each subject's posture was measured in the hardseat with and without a prominent lumbar support at seatback angles of 19, 23, and 27 degrees. The test conditions are listed in Table 7. The hardseat, shown in Figure 5, has an opening along the center of the backrest that allows direct palpation and measurement of the spinous processes. These data provide for direct comparison between the position of the T12/L1 joint estimated using the accessible-landmark method and a more direct measure of the actual location of the T12/L1 joint by palpation and measurement of spinal landmarks. The results of this study confirmed that the accessible-landmark method is sufficiently accurate for locating the T12/L1 joint of subjects in vehicle seats to achieve the goals of ASPECT.

Table 6
Subject Pool
Kinematic Model Validation Study

Group	Gender	Percentile Range	Stature Range (mm)	n
0	Female	< 5th	under 1511	
1	Female	5-15	1511 - 1549	1
2	Female	15-40	1549 - 1595	2
3	Female	40-60	1595 - 1638	2
4	Female	60-85	1638 - 1681	2
5	Female	85-95	1681 - 1722	1
6	Male	5-15	1636 - 1679	1
7	Male	15-40	1679 - 1727	2
8	Male	40-60	1727 - 1775	2
9	Male	60-85	1775 - 1826	2
10	Male	85-95	1826 - 1869	1
11	Male	> 95th	over 1869	
				16

Table 7
Test Conditions
Kinematic Model Validation Study

Condition	Seatback Angle	Lumbar Support
1	19	Yes
2	23	Yes
3	27	Yes
4	19	No
5	23	No
6	27	No

6.2 Driver Posture Study

6.2.1 Overview

The driver-posture study determined the effects of selected interior vehicle dimensions on driver posture. Vehicle package factors considered as potential predictors of driver posture included seat height (H30), seat-track angle, steering-wheel fore/aft position (relative to pedals), steering-wheel vertical position, transmission type, vision restrictions and head clearance. This experiment benefited from recent UMTRI research on driver seat position (1, 2, 4), which determined that four vehicle dimensions and driver stature are the dominant factors affecting driver seat fore/aft position. This previous work led to the detailed study of two package factors (seat height and wheel-to-ball-of-foot distance) and three seat features (seat-cushion angle, lateral thigh bolstering, and overall seat type). Other seat features were the focus of a set of seat factor studies described below.

The factors studied in the ASPECT driver posture study included seat height: (H30), steering-wheel-to-pedal distance (L6) and seat-cushion angle (L27), as illustrated in Figure 7. Testing was conducted in the reconfigurable buck shown in Figure 8, which allowed the vehicle factors to be varied independently to determine the factor effects and interactions. Sixty-eight subjects (34 men and 34 women) were selected to fill twelve stature/gender groups as described in Table 8. Each subject was tested in 11 to 19 conditions, listed in Table 9. The two seats tested included a mid-contour, moderately stiff sedan seat and a firm sports-car seat with a prominent lumbar support. A Taurus seat was used for phases 1 and 2, and a Neon seat was used for phase 3. The seat-cushion angles tested ranged from 11 to 18 degrees, values spanning the majority of seat-cushion angles observed in the current vehicle fleet. The seat height used in the laboratory buck ranged from that of a typical sports car (180 mm) to that of a typical minivan (360 mm). Steering-wheel-to-BOF distance was varied over a 100-mm range, selected appropriately for each seat height tested. Subjects were instructed to adjust the seat and seatback angle to find a most-comfortable driving position and posture in each test condition. A set of body landmarks were then digitized using the sonic digitizing system previously described. Subject-selected seat fore/aft position and seatback angle were also recorded.

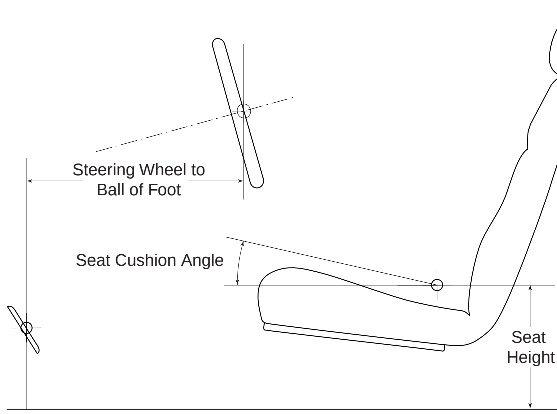

Figure 7. Illustration of vehicle factors.

Figure 8. One of the UMTRI reconfigurable vehicle mockups.

Table 8
Subject Pool
Driver Posture Study

Subject Group	Stature Range (mm)	Gender	Part 1 n	Part 2 n	Part 3 n	All n
0	under 1511	Female		3	3	6
1	1511 - 1549	Female	5	0	0	5
2	1549 - 1595	Female		3	3	6
3	1595 - 1638	Female	5	0	0	5
4	1638 - 1681	Female		3	3	6
5	1681 - 1722	Female		3	3	6
6	1636 - 1679	Male		3	3	6
7	1679 - 1727	Male		3	3	6
8	1727 - 1775	Male	5	0	0	5
9	1775 - 1826	Male		3	3	6
10	1826 - 1869	Male	5	0	0	5
11	over 1869	Male		3	3	6
Total			20	24	24	**68**

Table 9
Test Conditions
Driver Posture Study

Configuration Number	N	Phase 1 (Taurus Seat)	Phase 2 (Taurus Seat)	Phase 3 (Neon Seat)	Seat Cushion Angle (L27) (degrees)	Seat Height (H30) (mm)	SW-BOFX (mm)
1	44	x	x		11	270	450
2	68	x	x	x	11	270	500
3	68	x	x	x	11	270	550
4	68	x	x	x	11	270	600
5	44	x	x		11	270	650
6	44	x	x		18	270	450
7	68	x	x	x	18	270	500
8	68	x	x	x	18	270	550
9	68	x	x	x	18	270	600
10	44	x	x		18	270	650
11*	44	x	x		18	270	650
12	48		x	x	11	180	550
13	48		x	x	11	180	650
14	48		x	x	11	360	450
15	48		x	x	11	360	550
16	24			x	18	180	550
17	24			x	18	180	650
18	24			x	18	360	450
19	24			x	18	360	550

* Condition 11 is identical to 10 except that restrictive lateral bolsters were placed on the seat cushion.

6.2.2 Primary Findings

The Driver Posture study was designed to investigate a number of different two- and three-way interactions between factors, but no important interactions were observed. Of particular importance, the effects of cushion angle and steering wheel position were independent of seat height. All three of the primary factors showed significant effects on several of the posture variables of interest.

Fore-aft Hip Location – Driver fore-aft hip location was affected by seat height, steering wheel position, and seat cushion angle, as well as driver anthropometry. Using data from all trials, the hip location aft of Ball of Foot (BOF) is given by:

$$\text{HipX} = 84.8 + 0.4659\ S - 430.1\ SH/S - 0.1732\ H + 0.4479\ SWX - 1.04\ CA,$$
$$R^2 = 0.78, \text{RMSE} = 35.9$$

where S is driver stature, SH/S is erect sitting height divided by stature, H is seat height, SWX is horizontal steering wheel center position aft of BOF, CA is cushion angle. RMSE is the root mean square error, a measure of the residual variance. The regression model shows that drivers move their hips forward about 44 mm for every 100 mm of forward steering wheel movement. Taller drivers sit further rearward, as expected, but drivers with long torsos relative to their height sit further forward than other drivers with the same stature and shorter torsos.

All of the factor effects were linear – no higher order terms were found to be justified. Figure 9 shows the effect of steering wheel position on HipX for two different cushion angles. The steering wheel position has been normalized within seat height. The steering wheel effect is highly linear, and no interaction with seat cushion angle is evident.

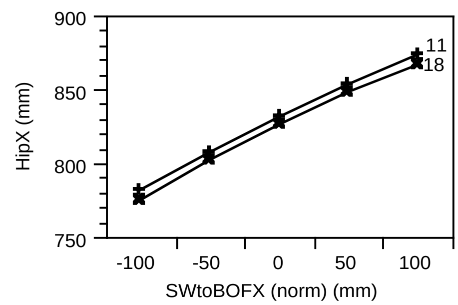

Figure 9. Effect of normalized steering wheel position and seat cushion angle on driver hip location aft of Ball of Foot.

Torso Recline – The side-view hip-to-eye angle rearward of vertical is a useful measure of overall torso recline. Using step-wise regression techniques, the hip-to-eye angle (degrees) is given by:

HiptoEyeAngle = -72.7 + 0.00642 S + 115.7 SH/S + 0.0147 SWX + 0.11,
R^2 = 0.20, RMSE = 3.9

The R^2 value for hip-to-eye angle is low, meaning that torso recline can not be precisely predicted from package, seat, and anthropometric variables. Steering wheel position has a small effect, but the most important effect is the sitting height to stature ratio. People with tall torsos for their stature tend to sit more reclined, probably because their more-forward hip location (see above) results in the steering wheel effectively being more rearward for them (relative to their hips).

Bolsters – One test condition (11) was identical to another (10) except that high, firm lateral bolsters were added to the seat cushion. There was no effect on torso recline, hip position, or other variables except leg posture. Leg splay angle (see Chapter 6 for the definition) was reduced by an average of about 4 degrees when the lateral bolsters were added.

6.3 Seat Factors Study I

6.3.1 Overview

This study quantified the main effects of, and interactions among, three seat design factors and also studied the effects of task constraints (driver versus passenger) on posture. The primary goal was to examine two-way interactions between seat factors to reduce the number of trials necessary for seat-factors study III. The seat factors studied include seat cushion angle, seat cushion length, lumbar support prominence, as illustrated in Figure 10. Twenty-four subjects were selected on the basis of stature and gender, as described in Table 10. Subjects were tested in the laboratory using reconfigurable seat A, shown in Figures 11 and 12, to determine the primary effects and two-way interactions of the three seat factors on measures of driver posture and position. Table 11 lists the test conditions. In each condition, the subjects were asked to use the seat fore/aft and seatback angle adjustments to find a comfortable driving or riding position. Driver posture was measured with the subject's hands on the steering wheel and the right foot resting on the accelerator pedal**,** while passenger posture was measured with the subject's hands in his or her lap and with both feet on the floor.

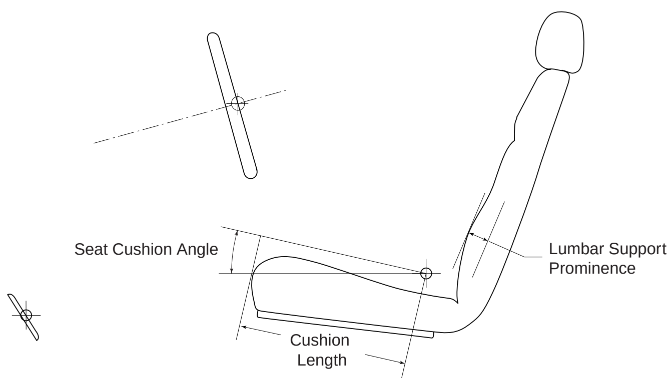

Figure 10. Illustration of factors studied in seat factors study I.

Figure 11. Reconfigurable seat A, front view.

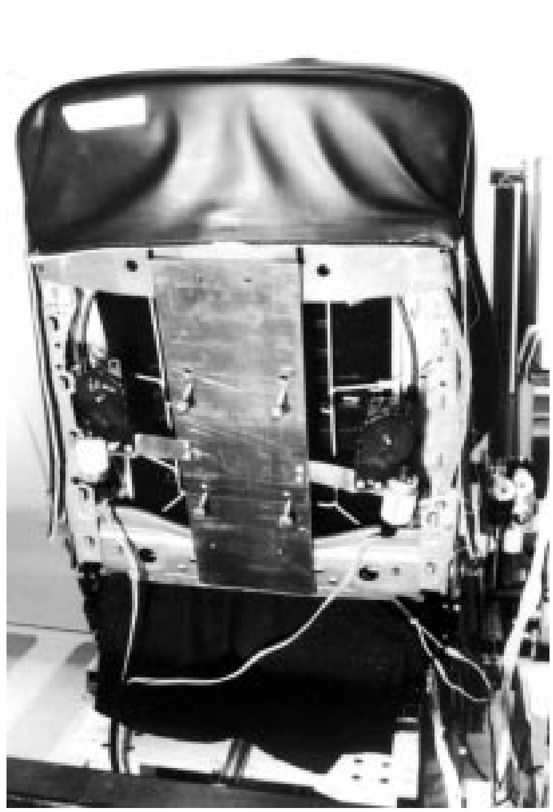

Figure 12. Reconfigurable seat A, rear view.

Table 10
Subject Pool
Seat Factors Study I

Group	Gender	Percentile Range	Stature Range (mm)	n
0	Female	< 5th	under 1511	2
1	Female	5-15	1511 - 1549	2
2	Female	15-40	1549 - 1595	2
3	Female	40-60	1595 - 1638	2
4	Female	60-85	1638 - 1681	2
5	Female	85-95	1681 - 1722	2
6	Male	5-15	1636 - 1679	2
7	Male	15-40	1679 - 1727	2
8	Male	40-60	1727 - 1775	2
9	Male	60-85	1775 - 1826	2
10	Male	85-95	1826 - 1869	2
11	Male	> 95th	over 1869	2
				24

Table 11
Test Conditions
Seat Factors Study I

Condition	Task	Lumbar Prom	Cushion Angle	Cushion Length
1D	Driver	H	L	S
2D	Driver	L	L	S
3D	Driver	H	H	S
4D	Driver	L	H	S
5D	Driver	L	H	L
6D	Driver	L	M	L
7D	Driver	L	M	S
8D	Driver	L	L	L
1P	Pass	H	L	S
2P	Pass	L	L	S
3P	Pass	H	H	S
4P	Pass	L	H	S
5P	Pass	L	H	L
6P	Pass	L	M	L
7P	Pass	L	M	S
8P	Pass	L	L	L

6.3.2 Primary Findings

The primary objective of this study was to determine if there were significant interactions between lumbar support prominence, cushion angle, and cushion length, as well as differences between driver and passenger posture. No significant interactions were observed. Figure 15 shows the effect of cushion angle and lumbar support prominence on the lumbar spine flexion (difference between pelvis and thorax segment angles). None of the effects are significant with $p<0.05$, although there was a trend toward slightly reduced lumbar spine flexion levels with the high lumbar support prominence and high cushion angles. Cushion length similarly had a minimal effect on lumbar spine flexion, and there were no differences between driver and passenger postures.

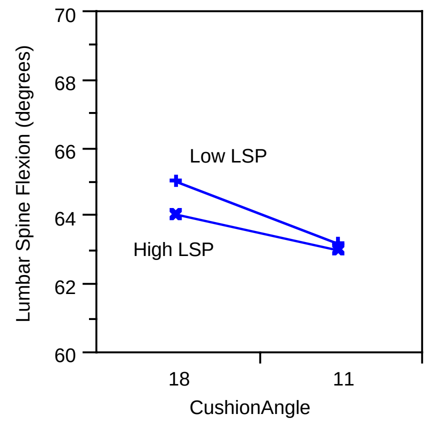

Figure 15. Effects of cushion angle and lumbar support prominence on lumbar spine flexion. Neither the main effects nor the interaction are statistically significantly ($p>0.05$).

This study demonstrated that seat factor effects are subtle and require a larger number of subjects to investigate. Further, there do not appear to be important interactions among the key variables.

6.4 Seat Factors Study II

6.4.1 Overview

This study quantified the main effects of, and interactions among, two seat design factors: lumbar support prominence and lumbar support height. The effects of task constraints (driver versus passenger) on occupant posture were also studied. The primary goal was to study the two-way interaction between lumbar support prominence and lumbar support height to assist in determining the test conditions for seat factors study III. Twenty-four subjects were selected on the basis of stature and gender, as described in Table 12. Subjects were tested in the laboratory using reconfigurable seat B equipped with a Schukra backrest adjuster, shown in Figures 16a and 16b, that allowed the lumbar support height and lumbar prominence to be adjusted independently. Subjects adjusted the seat fore/aft position and seatback angle to find a comfortable driving or riding posture. The driving condition required the subject's hands to be grasping the steering wheel and right foot to be on the accelerator pedal. Figure 17 illustrates the experimental factors. Table 13 lists the test conditions.

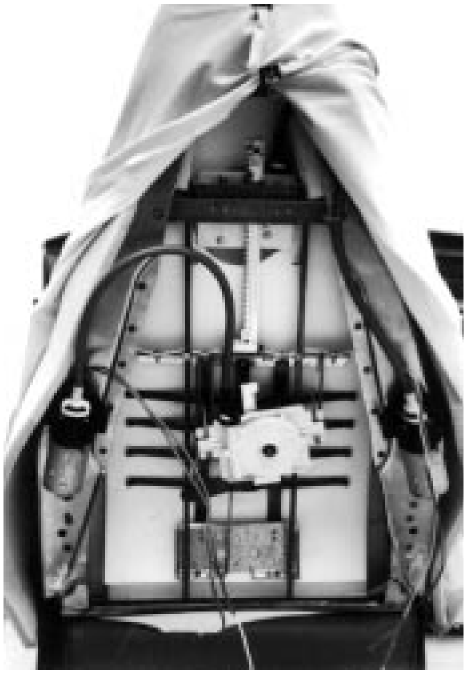

Figure 16a. Reconfigurable seat B
used for seat factors study II.

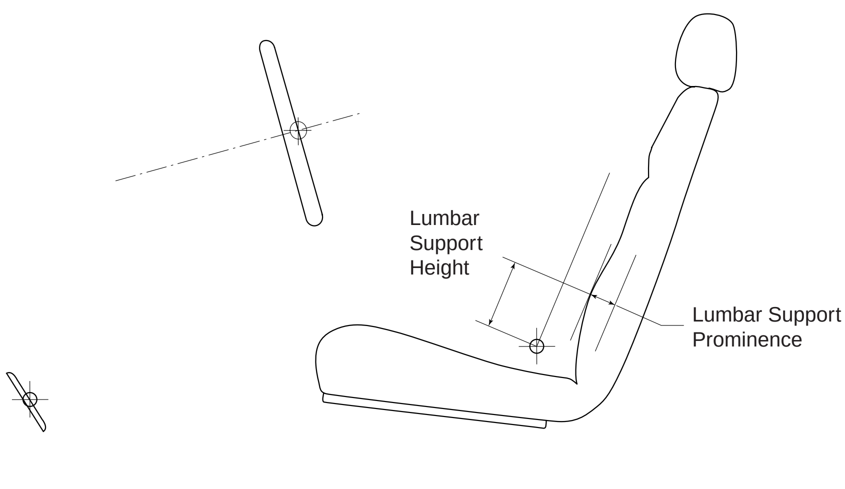

Figure 17. Illustration of factors investigated
in seat factors study II.

Table 12
Subject Pool
Seat Factors Study II

Group	Gender	Percentile Range	Stature Range (mm)	n
0	Female	< 5th	under 1511	2
1	Female	5-15	1511 - 1549	2
2	Female	15-40	1549 - 1595	2
3	Female	40-60	1595 - 1638	2
4	Female	60-85	1638 - 1681	2
5	Female	85-95	1681 - 1722	2
6	Male	5-15	1636 - 1679	2
7	Male	15-40	1679 - 1727	2
8	Male	40-60	1727 - 1775	2
9	Male	60-85	1775 - 1826	2
10	Male	85-95	1826 - 1869	2
11	Male	> 95th	over 1869	2
				24

Table 13
Test Conditions
Seat Factors Study II

Condition	Task	Lumbar Prom	Lumbar Hgt
9D	Driver	H	H
10D	Driver	H	M
11D	Driver	H	L
12D	Driver	L	all
9P	Pass	H	H
10P	Pass	H	M
11P	Pass	H	L
12P	Pass	L	all

6.4.2 Primary Findings

As with Seat Factors I, this study focused on the possibility of interactions between seat factors. In this case, does lumbar support prominence have a different effect on posture depending on the lumbar support height? Figure 18 shows lumbar spine flexion for drivers at three lumbar support heights and with a flat lumbar support (lumbar support height has no meaning with a flat support). Note the large variance in spine flexion between subjects. Lumbar spine flexion was reduced an average of 6.5 degrees by the addition of the lumbar support, but the effect was independent of the lumbar support prominence location. The magnitude of the LS prominence effect is virtually identical to that obtained in a previous study using the same test conditions (18). The larger lumbar support prominence effect observed in this study, compared with Seat Factors I, resulted from a larger difference between test conditions and the fact that the test seat in Seat Factors II was more thinly padded.

As in Seat Factors I, driver postures were not significantly different from passenger postures on most variables, but passenger postures were slightly more reclined. On average, passenger hip-to-eye angle was 1.3 degrees more reclined than for drivers. The lumbar support prominence height also had a small effect on torso recline. Figure 19 shows hip-to-eye angle at each of the lumbar support conditions, showing that higher lumbar support apex locations were associated with more reclined postures.

This study reinforced the findings from Seat Factors I showing only small differences between driver and passenger postures in the tested vehicle packages, and no important interactions between seat factors.

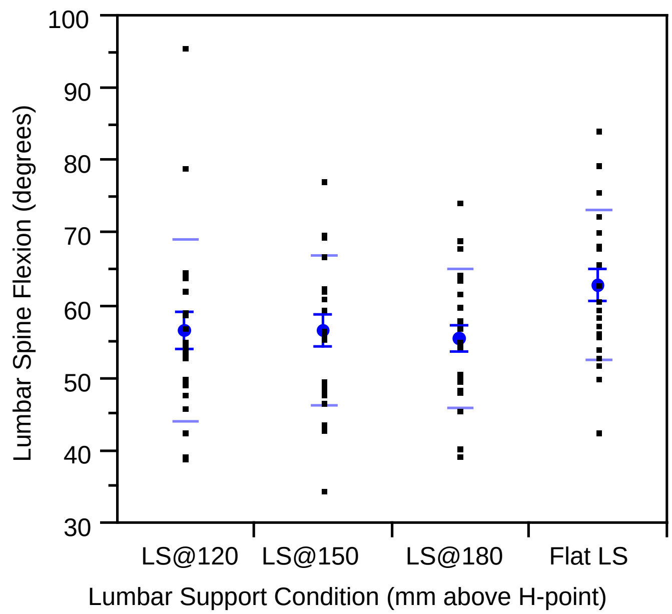

Figure 18. Effect of lumbar support prominence and apex height on lumbar spine flexion. Large dots are condition means. Horizontal bars show ± 1 standard error and ± 1 standard deviation.

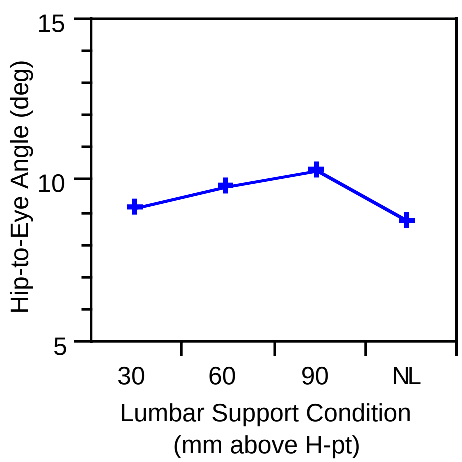

Figure 19. Effect of lumbar support prominence and apex height on overall torso recline. NL = Flat lumbar support.

6.5 Seat Factors Study III

6.5.1 Overview

Conducted after the data from Seat Factors I and II were analyzed, Seat Factors III quantified the effects of five seat factors on driver and passenger posture and comfort. The factors studied were those identified in the driver posture study and the Seat Factors I and II as those having quantifiable effects on occupant posture. The results were used to determine manikin performance specifications and to integrate seat factor effects into vehicle occupant posture-prediction models.

Forty-eight subjects were selected for testing on the basis of stature and gender, as described in Table 14. Subjects were tested in a reconfigurable seat, shown in Figures 11 and 12, created by installing a Schukra lumbar support that allowed vertical adjustment of the lumbar support and adjustment of the prominence of the lumbar support into a luxury seat already equipped with cushion length and cushion angle adjusters. The seat cushion was modified to allow the foam in the buttock area to be changed to achieve two different foam stiffness levels. Each factor was manipulated independently to determine main effects and factors interactions. The factors studied include seat cushion angle, seat cushion length, lumbar support prominence, and occupant task (driver or passenger), as illustrated in Figure 20. Tables 15 and 16 list the test conditions. The experimental design was aided by the findings from the first two studies concerning a lack of important interactions among some variables. Nonetheless, a number of interactions were included in the experiment design and analysis.

The seat was installed in a laboratory seating buck set to a midsize-sedan package configuration. Subjects were asked to find a comfortable position for each of 40 test conditions outlined in Tables 15 and 16, tested in the course of two sessions. Subjects selected a comfortable seat fore/aft position for the driver posture trials, and adjusted the seatback angle in both driver and passenger posture trials. Certain conditions were tested in both sessions to assess repeatability issues. Subjective comfort data were collected for each subject in each seat configuration.

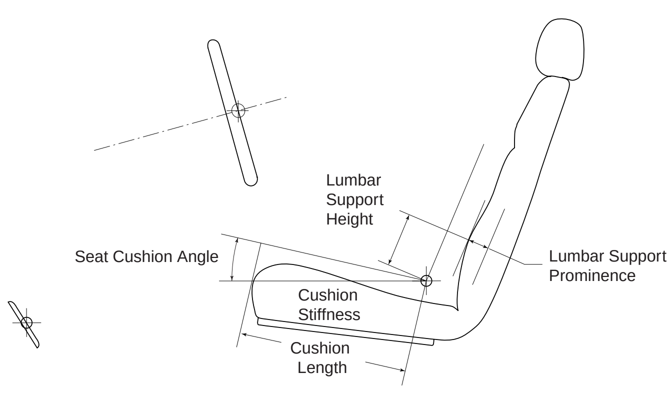

Figure 20. Illustration of factors studied in seat factor study III.

Table 14
Subject Pool
Seat Factors Study III

Group	Gender	Percentile Range	Stature Range (mm)	n
0	Female	< 5th	under 1511	3
1	Female	5-15	1511 - 1549	3
2	Female	15-40	1549 - 1595	3
3	Female	40-60	1595 - 1638	3
4	Female	60-85	1638 - 1681	3
5	Female	85-95	1681 - 1722	3
6	Male	5-15	1636 - 1679	5
7	Male	15-40	1679 - 1727	5
8	Male	40-60	1727 - 1775	5
9	Male	60-85	1775 - 1826	5
10	Male	85-95	1826 - 1869	5
11	Male	> 95th	over 1869	5
				48

Table 15
Test Conditions for Session One
Seat Factors Study III

condition	task	pan angle	lumbar prom	lumbar hgt	pan length	cushion stiffness
1D	driver	12	L	150	M	H
2D	driver	12	H	120	M	H
3D	driver	12	H	150	M	H
4D	driver	12	H	180	M	H
5D	driver	18	L	150	M	H
6D	driver	18	H	120	M	H
7D	driver	18	H	150	M	H
8D	driver	18	H	180	M	H
9D	driver	12	L	150	L	H
10D	driver	12	L	150	H	H
11D	driver	18	L	150	L	H
12D	driver	18	L	150	H	H
1P	passenger	12	L	150	M	H
2P	passenger	12	H	120	M	H
3P	passenger	12	H	150	M	H
4P	passenger	12	H	180	M	H
5P	passenger	18	L	150	M	H
6P	passenger	18	H	120	M	H
7P	passenger	18	H	150	M	H
8P	passenger	18	H	180	M	H
9P	passenger	12	L	150	L	H
10P	passenger	12	L	150	H	H
11P	passenger	18	L	150	L	H
12P	passenger	18	L	150	H	H

Table 16
Test Conditions for Session Two
Seat Factors Study III

condition	task	pan angle	lumbar prom	lumbar hgt	pan length	cushion stiffness
13D	driver	12	L	150	L	L
14D	driver	12	L	150	H	L
15D	driver	18	L	150	L	L
16D	driver	18	L	150	H	L
17D	driver	12	L	150	M	L
18D	driver	12	H	150	M	L
19D	driver	18	H	150	M	L
13P	passenger	12	L	150	L	L
14P	passenger	12	L	150	H	L
15P	passenger	18	L	150	L	L
16P	passenger	18	L	150	H	L
17P	passenger	12	L	150	M	L
18P	passenger	12	H	150	M	L
19P	passenger	18	H	150	M	L

6.5.2 Primary Findings

The complex experimental design and large sample size of Seat Factors III allowed many details of driver and passenger posture to be examined closely. The primary finding, however, echoing the findings from the two earlier seat factors studies, was that vehicle occupant postures are only slightly affected by seat design parameters over the range expected for vehicle seats. This study, which used the same seat as was used in Seat Factors I, showed a similarly small effect of lumbar support prominence on posture. Some interactions were statistically significant (the effect of lumbar support prominence on hip-to-H-point offset differed with cushion angle, for example) but the practical effects of these interactions are minimal because the effect magnitudes are small. (See Chapter 7 for more detailed information on hip-to-H-point offsets.)

Passenger postures were slightly more reclined than driver postures, although the analysis from the Driver Posture study indicates that the steering wheel position has a large enough effect that, in some package conditions, driver postures would be more reclined than passenger postures.

Lumbar Spine Flexion – Figure 21 shows lumbar spine flexion (difference in orientation between pelvis and thorax segments – see Chapter 6) for passengers with two different lumbar support prominences and seat cushion angles. The figure illustrates that both cushion angle and lumbar support prominence have small effects on lumbar spine flexion, but the effects are additive and small.

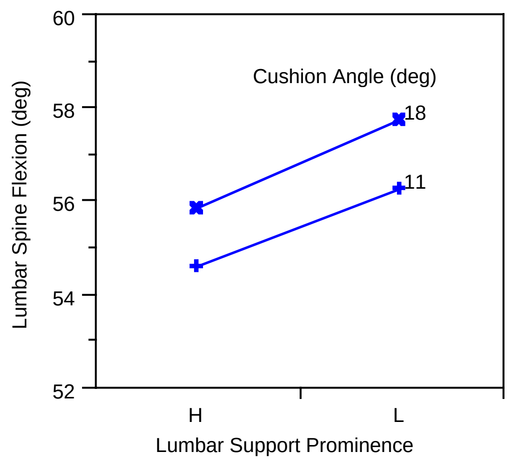

Figure 21. Effects of lumbar support prominence and seat cushion angle on lumbar spine flexion.

Cushion Length and Angle – Figure 22 shows the effects of seat cushion angle and seat cushion length on the fore-aft offset between the sitter's hip and the SAE J826 H-point. Higher seat cushion angles put the sitter's hips further rearward on the seat cushion, closer to the H-point. A long cushion tends to pull sitters forward on the cushion, although, surprisingly, the effect is not dependent on stature.

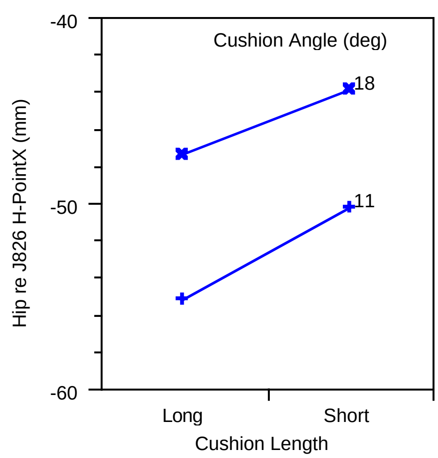

Figure 22. Effects of cushion length and angle on hip-to-J826-H-point fore-aft offset in passenger data.

6.6 Laboratory Passenger Posture Study

6.6.1 Overview

This study collected data on midsize-male passenger postures in three seats at three seatback angles. The conditions tested were identical to those used for the AAMA/UMTRI H-point study of driving postures (14). Comparing these datasets provided insight into the differences in posture that can be attributed to occupant task (driver versus passenger). Fifteen midsize-male subjects (Group 8) were recruited for testing, as shown in Table 17. The subjects were instructed to find comfortable riding positions in the three seats: a soft, noncontoured Caprice seat, a moderately firm, moderately contoured Pontiac seat, and a firm, highly contoured Saturn seat with the lumbar support adjusted to the most prominent position. The seatback angles tested were 19, 23, and 27 degrees, as measured with the SAE J826 H-point machine (15). Table 18 lists the test conditions. Use of a fixed seatback angle condition makes these data particularly applicable to passenger seats without seatback angle adjustment, such as the majority of seats in rear-seat positions. Subject posture was measured by using the sonic digitizer to collect several body landmarks. These data were analyzed to determine the effect of task and imposed seatback angle on occupant posture.

Table 17
Subject Pool
Laboratory Passenger Posture

Group	Gender	Percentile Range	Stature Range (mm)	n
8	Male	40-60	1727 - 1775	15

Table 18
Test Conditions
Laboratory Passenger Posture

Condition	Seat	Seatback Angle
1	Saturn	19
2	Saturn	23
3	Saturn	27
4	Saturn	Subject-Selected
5	Pontiac	19
6	Pontiac	23
7	Pontiac	27
8	Pontiac	Subject-Selected
9	Caprice	19
10	Caprice	23
11	Caprice	27
12	Caprice	Subject-Selected

6.6.2 Primary Findings

Figure 23 shows the effects of (J826-seatback-manikin-measured) seatback angle on passenger hip-to-eye angle. The effect is approximately linear, with a coefficient of 0.6, meaning that hip-to-eye angle changes at about 60% of the change in J826-manikin-measured seatback angle. The effects of seatback angle on passenger posture are included in the ASPECT posture prediction models (Chapter 7).

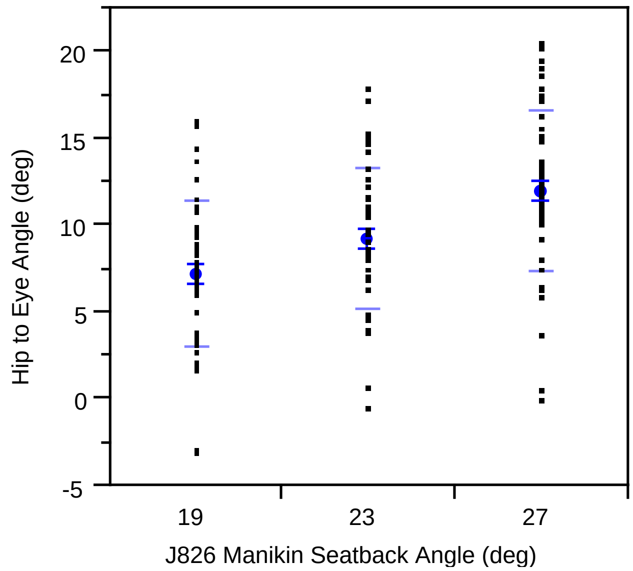

Figure 23. Effect of seatback angle (J826) on overall torso recline. Large dots are condition means. Horizontal bars show ± 1 standard error and ± 1 standard deviation.

6.7 In-Vehicle Passenger Posture Study

6.7.1 Overview

This study compared driver and front-seat passenger postures, and determined the effects of legroom restriction on rear-seat occupants. Twenty-four subjects were selected on the basis of stature and gender, as described in Table 19. Subjects were tested in eight vehicles, including sports cars, sedans, pickup trucks, a minivan, and a sport utility vehicle (SUV). These subjects had already been tested as drivers in the same vehicles for an UMTRI eye-position study (3). The subjects were instructed to find a comfortable front passenger riding posture during a 10-15 minute ride, in which the investigator was the driver. The same midsize-female driver was used for all trials to control the effect of the driver's seat position, which may influence passenger seating position. Table 20 lists the test conditions.

Immediately after the ride, the subject's seat fore/aft position, seatback angle, and riding posture were recorded using a FARO arm coordinate measurement system. Subjects were then instructed to find comfortable riding positions in the back seat of the static vehicle under minimum and maximum legroom conditions (i.e., with the front seat positioned full forward and full rearward). The data collected in this study quantify the effect of task (driver versus passenger) on occupant posture through comparison of the data collected with the driver position data available for the identical subjects from the UMTRI eye position study.

Table 19
Subject Pool
In-vehicle Passenger Posture

Group	Gender	Percentile Range	Stature Range (mm)	n
0	Female	< 5th	under 1511	2
1	Female	5-15	1511 - 1549	2
2	Female	15-40	1549 - 1595	2
3	Female	40-60	1595 - 1638	2
4	Female	60-85	1638 - 1681	2
5	Female	85-95	1681 - 1722	2
6	Male	5-15	1636 - 1679	2
7	Male	15-40	1679 - 1727	2
8	Male	40-60	1727 - 1775	2
9	Male	60-85	1775 - 1826	2
10	Male	85-95	1826 - 1869	2
11	Male	> 95th	over 1869	2
				24

Table 20
Test Conditions
In-vehicle Passenger Posture

Condition	Vehicle	Front	Rear
1	Acclaim	x	x
2	Laser	x	
3	Avenger	x	
4	Peugeot 605	x	x
5	LHS	x	x
6	Grand Cherokee	x	x
7	Voyager	x	
8	Neon	x	
9	Ram	x	

6.7.2 Primary Findings

In the front seat, passenger’s torso recline was very similar, on average, to the passenger postures measured in the laboratory. Passenger-selected seat positions were less extreme than the corresponding driver postures. Short-statured people tended to select passenger seat positions more rearward than their driving positions, while tall subjects sat further forward as passengers than as drivers. In the rear seat, restrictions in legroom (front seat position) changed leg postures but did not affect torso postures. Hip joint height relative to H-point was not affected by leg posture. These in-vehicle findings were used to adapt the laboratory data to prediction of passenger postures (see Chapter 7).

6.8 Manikin Validation Study

6.8.1 Overview

This study generated a database of human posture in twelve different production seats for use in evaluating and validating final prototypes of the ASPECT physical manikin (APM). Thirty men, described in Table 21, were tested in the twelve seats. This set of seats was selected to represent a wide range of seat types and features. A seating buck was constructed to allow each seat to be installed while maintaining the vehicle package dimensions of a midsize sedan in terms of seat height, steering-wheel position, pedal positions, and orientation, and instrument-panel height and location. Subjects were tested in six vehicle seats in each of two sessions, and were instructed to adjust the seat fore/aft position for driver trials and adjusted the seatback angle to find a comfortable position and posture for both driving and riding in each seat. Each subject's driver and passenger postures were recorded with a sonic digitizing system. Subjects also assessed the comfort of each seat using subjective rating forms. Upon completion of the posture testing in each seat, the seat cushion and seatback pressure distributions generated by each subject was measured using the Xsensor system. This study generated a set of human posture data that was used to assess the performance and measures of the ASPECT physical manikin.

Table 21
Subject Pool
Manikin Validation Study

Group	Gender	Percentile Range	Stature Range (mm)	Phase 1
6	Male	5-15	1636 - 1679	5
7	Male	15-40	1679 - 1727	5
8	Male	40-60	1727 - 1775	5
9	Male	60-85	1775 - 1826	5
10	Male	85-95	1826 - 1869	5
11	Male	> 95th	over 1869	5
				30

6.8.1 Primary Findings

The most notable finding from this study was the observation that both driver and passenger postures were very similar across seats, except for the heavy truck seat. The truck seat had a substantial restriction in seatback recline that resulted in considerably different torso postures in that seat. Passenger postures were slightly more reclined than driver postures, but driver postures are influenced by the steering wheel position, so a more rearward steering wheel position would have resulted in identical driver and passenger postures. The data from this study were used extensively in developing the posture prediction models, because these data from actual vehicle seats provide an intermediate level of fidelity between the experiments conducted with modified test seats and actual in-vehicle data. Chapter 7 describes the analyses used to apply these data to occupant posture prediction.

7.0 CONCLUSIONS

The posture data collected in these studies has played a key role in the success of the ASPECT program. The rationale and strategies for selecting study participants assured adequate and efficient subject sampling. The studies enhanced an existing posture database and the combined data set provides a detailed understanding of the effects of package, seat, task, and anthropometric factors on occupant posture. The results have been used to guide the design and performance of the ASPECT physical manikin and the development of new concepts for using the manikin and other design tools (16, 17). They have also been used to develop accurate posture-prediction models for use with a full range of occupant sizes represented by computer models of vehicle occupants (4).

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CHAPTER 6

METHODS FOR MEASURING AND REPRESENTING AUTOMOBILE OCCUPANT POSTURE[†]

1.0 INTRODUCTION

The human body is commonly represented in ergonomic and biomechanical investigations as an open chain of rigid segments. The number of segments and the nature of the joints between segments varies widely depending on the application of the resulting kinematic model. A classic representation of the body for design purposes by Dempster (1)[*] divided the body into 13 planar segments, including a single segment from the hips to the top of the head. A contrasting model is presented by Nussbaum and Chaffin (2) who used multiple rigid, three-dimensional segments to simulate torso kinematics. There are many other whole- and partial-body models in the literature, with a wide range of complexity.

For automotive applications, two kinematic representations of the body have been most widely used. The Society of Automotive Engineers (SAE) J826 H-point manikin (3) provides four articulating segments (foot, leg, thigh/buttocks, and torso) to represent a vehicle occupant's posture. A two-dimensional template with similar contours is used with side-view design drawings. The joints of the H-point manikin and the two-dimensional template have a single degree of freedom, pivoting in a sagittal plane. These two tools are the standard occupant representations of vehicle interior design (4).

The other widely used kinematic representation of vehicle occupants is that embodied in the Anthropomorphic Test Devices (ATDs), or crash dummies, used to assess impact protection. The current standard ATD, the Hybrid-III, has many more degrees of freedom and body segments than the SAE H-point manikin or two-dimensional template, including three degrees of freedom at each hip, shoulder, and ankle (5). The lumbar and cervical spine are represented by flexible structures that allow flexion or extension in any plane. In a more recent development, Schneider et al. (6) presented new anthropometric data for an advanced family of crash dummies that were subsequently used in the development of a new ATD thorax that adds additional complexity to the shoulders, thoracic spine, and ribcage to obtain a more realistic interaction with restraint systems (7).

[†] Portions of this chapter were previously published in SAE Technical Paper 1999-01-0959.

[*] Numbers in parentheses denote references at the end of this chapter.

Software representations of both the SAE J826 and ATD linkages are now widely used in the vehicle design process. The design tools are intended for kinematic analysis only, but models of the ATDs are intended for dynamic use, i.e., crash simulation. In both vehicle ergonomics and impact protection, commercial human body representations are now available that provide models with additional complexity (8-10). The JOHN model, a three-dimensional kinematic tool intended for use in auto seat design, uses a six-joint lumbar spine to provide complex spine motions linked to changes in external contour (11). Bush (12) developed a two-dimensional seat design template with similar kinematics using a fixed motion distribution between two lumbar joints.

The objectives of the current work are:

1. to develop a kinematic representation of vehicle occupant posture for vehicle interior ergonomics applications relating to normal riding and driving postures while providing continuity with existing occupant protection tools, and
2. to develop techniques for measuring and representing posture using the kinematic model.

This work is primarily a review and synthesis of previous studies. The emphasis here is on the efficient representation of vehicle occupant posture, using the smallest amount of information necessary to describe the posture to a level of detail sufficient for vehicle ergonomic applications relating to normal riding and driving postures.

It is useful to define "normal driving posture" as sagittally symmetric, with the sagittal plane aligned with the vehicle or seat side-view (XZ) plane. A large body of experimental data in vehicles and laboratory vehicle mockups has demonstrated that drivers, when instructed to sit with a "normal, comfortable driving posture," choose a torso posture that largely conforms to this definition. Asymmetric limb postures are resolved by recording the posture of only the right side of the body, since the right foot interaction with the accelerator pedal ensures that the right-leg posture is related to the driver's adaptation to the workspace. The techniques presented here are readily applied to either or both legs or arms, so that the sagittal symmetry requirement for the limbs can be relaxed if desired. By accepting this somewhat restrictive definition of normal driving (or riding) posture, the resulting kinematic constraints can be exploited to reduce the amount of body position information that is necessary to describe the posture.

As noted above, one of the objectives of the current work is to provide continuity between ergonomic applications and impact protection. This process has been facilitated by extensive use of the data and analysis on which the new family of frontal crash dummies is based. Robbins (13, 14) used three-dimensional surface landmark data from seventy-five drivers in three size categories to estimate the locations of anatomical joints that define a kinematic linkage. In the current analysis, ambiguities among various sources relating to joint locations have been resolved in favor of consistency with Robbins' analysis, except where the preponderance of evidence suggests that an alternative approach will significantly improve the location estimate.

Unfortunately, there is much less publicly available data for determining the relationship between surface anatomical landmarks and interior skeletal geometry than one might expect, given the importance of these calculations for so many ergonomic and biomechanical studies. The landmark studies in this area include Dempster (1), who used cadaver dissections to propose a kinematic model for human factors analysis, and Snyder et al. (15), who used cadaver dissection and radiographs of male volunteers in a variety of postures to obtain data on surface-landmark-to-skeleton transformations. The risks of radiography for healthy people have made such investigations unlikely to be performed today. Recently, Reynolds (16) conducted radiographic studies with a small number of human cadavers, but additional useful linkage data from healthy people in normal postures will probably have to be derived from MRI or other low-risk imaging techniques.

2.0 METHODS

2.1 Kinematic Model

The choice of the segments and joints for the kinematic model was based on an assessment of the needs for posture data in vehicle interior design. A vehicle occupant's posture can be represented in a number of ways, each of which has some advantages and disadvantages for use in vehicle design. In current SAE practice, the distribution of drivers' eye locations is predicted from vehicle geometry using statistical summaries of eye position data collected from a large number of people (3). The distribution of drivers' selected seat positions, which is closely related to their hip locations, is similarly predicted using a statistical summary of a large body of data (3). Both of these currently used models predict the spatial distribution of a single body landmark for an occupant population. The data on which they are based are, of course, the measured locations of these landmarks for a suitable population of drivers. Hence, one of the ways of representing vehicle occupant posture data is by statistical summaries of the locations of body landmarks for appropriately selected subjects. If these data are collected for a carefully selected range of vehicle interior geometries, then the resulting percentile accommodation models can accurately predict these landmark locations for a range of vehicles (4).

Recently, however, the use of three-dimensional software manikins to represent occupants in the vehicle design process has made more complete and integrated techniques necessary for representing occupant posture. To be useful in design, these manikins must not only represent appropriate combinations of anthropometric variables, but also must accurately represent the likely posture of an occupant with the specified body dimensions. Most currently available statistical summaries of driving posture, such as those represented by the SAE eye position (J941) and driver-selected seat position (J1517) practices, are severely limited for use in positioning CAD manikins, because they predict parameters of the population distribution of landmark locations, rather than the most likely landmark locations for a specific size of occupant. So, for example, the J941 eyellipse centroid represents a prediction of the average eye position for the U.S. population, but does not provide useful information about the most likely eye location for a person who is 1650 mm tall.

A primary emphasis in the current work is the representation of posture data in a way that can be readily interpreted to determine appropriate postures for CAD manikins of different sizes. There are many different ways of representing body posture, including body landmark locations, external body contours, and kinematic-linkage-model representations. While body landmark data are directly useful, particularly for prediction of eye and hip location, independent, simultaneous prediction of many individual landmark locations is inadequate for posturing CAD manikins, because the relative positions of the predicted landmark locations can be inconsistent with the kinematic constraints imposed by the manikin's internal linkage. A method for interpreting postures in terms of a kinematic linkage is required.

Seidl (9) developed an innovative approach to representing posture using a kinematic linkage that is aligned using a person's external body contours in video images. The resulting posture analysis techniques were used to develop the RAMSIS software manikin, which is currently the only CAD manikin primarily intended for auto interior design that includes significant posture prediction capability. A limitation of the external contour fitting approach is that it does not generate external body landmark locations. Instead, the only representation of posture is in terms of the specific kinematic linkage used in the model. In the case of the RAMSIS model, the joints in the torso of the RAMSIS manikin are not intended to relate to specific anatomical joints, so the posture data from this approach cannot be readily generalized to other manikin linkages.

In the current work, a posture representation method has been developed that uses external body landmark locations to estimate the locations of joints that define the end points of body segments. The joints and segmentation scheme have been chosen because they provide the minimum complexity believed to be necessary to simulate the motions typical of changes between different vehicle occupant postures, while preserving an anatomical relationship between the external landmarks and the internal joints that define the linkage. This procedure is believed to allow findings reported using these techniques to be readily generalized to CAD manikins with a wide range of kinematic complexity. Using fewer segments would provide inadequate mobility, and using more segments, or using segments without explicit anatomical referents, would increase the difficulty in presenting and using posture data.

The kinematic model is depicted in Figures 1 and 2. The choice of the limb segments is straightforward. Individual hand, forearm, arm, thigh, leg, and foot segments are joined on each side of the body. In practice, the hand and forearm segments are considered as a single segment for representing normal riding and driving postures, since the complexities of hand movement relative to the arm are unimportant in that context. In the torso, the lumbar and cervical regions of the spine are each represented by a single segment and two joints. It appears from analysis of changes between different vehicle occupant postures that this approach represents sufficient kinematic complexity for representing normal riding and driving postures, and corresponds to the linkage most commonly used for dynamic crash victim simulation (10). The key determinant of model complexity for this application is that the linkage must adequately represent within-subject posture changes resulting from changes in vehicle layout and seat design within the rotational degrees-of-freedom of the linkage, i.e., without changing segment lengths. This is a necessary condition for interpreting the data using a limited-degree-of-freedom CAD manikin.   For example, eye-to-hip distance varies significantly with changes in lumbar support prominence (17). The selected linkage must allow this change in distance without violating the kinematic constraints. Analyses have demonstrated that the model presented here is kinematically adequate for representing normal driving postures (16).

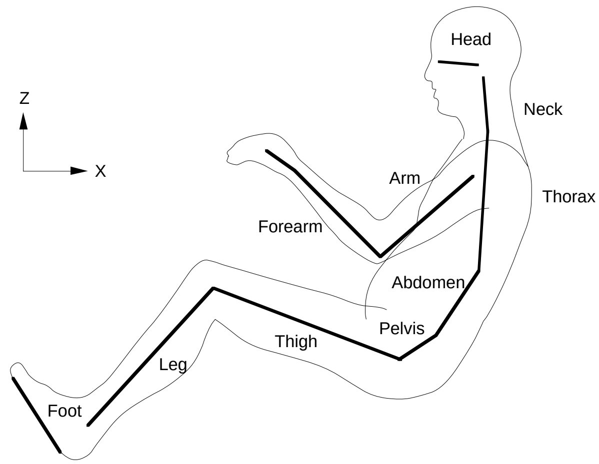

Figure 1. Kinematic model showing segments used to represent posture.

The joints in the model shown in Figure 2 correspond to approximate centers of rotation between adjacent bones and are located near the geometric center of particular anatomical joints.   Some additional clarification of the nature of these joint locations may reduce potential confusion about their usage. The selected anatomical reference points correspond to joints in the kinematic model of human posture, and are generally located near the estimated anatomical center of a joint between bones, but are not necessarily at the actual center of rotation of the adjacent bones. As has been noted by many researchers, the instantaneous center of rotation between adjacent bones (or helical axis for three-dimensional rotation) changes position relative to the bones as the adjoining body parts are moved through their ranges of motion.   This means that there is no single kinematic joint center at which all rotation between adjacent segments occurs.

However, for representation of normal vehicle occupant posture, the range of motion of interest at each joint is usually small; that is, the range of postures associated with different seats and packages is small relative to the range of possible human postures, so the potential for movement of the kinematic joint centers relative to the body segments is also small. Where posture changes can be large, such as at the knee and elbow, the adjoining segments are long relative to the potential discrepancies between the actual and estimated joint centers, so kinematic errors associated with joint location estimates will also be small.

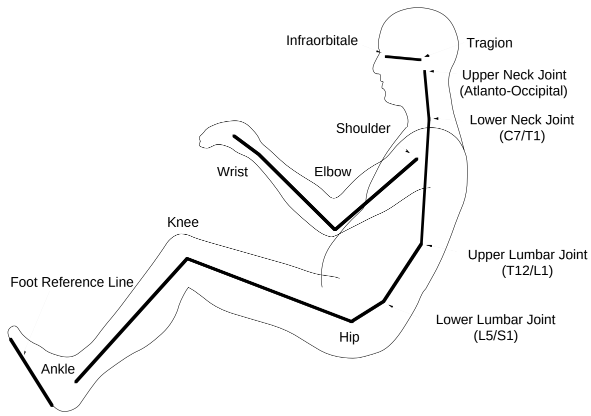

Figure 2. Joints in kinematic model used to represent vehicle occupant posture.

However, data represented using the techniques presented here may be applied to computer models that are used over much wider posture ranges, e.g., for reach assessments or ingress/egress studies. These models may rely on linkages that have joints located differently relative to the skeleton, or may have different linkages with more or fewer joints. Since the potential requirements of future models cannot be completely anticipated, the kinematic model joints in the current approach are anatomically defined, rather than kinematically defined. These joints are fixed in relation to skeletal landmarks and represent approximations of the center of rotation between adjacent bones. The relationships between these internal points (kinematic model joints) and external landmarks are thoroughly described in the following sections, so that the posture data reported using these techniques can be used in the future to estimate the location of any other bony reference point of interest, or to identify a joint location that is more suitable for a particular purpose. This approach is believed to provide a high level of generalizability for future modeling applications.

The orientation of the terminal segments (hands, feet, and head), are defined by vectors within the segments connecting landmarks of interest. Because the hands in normal driving and riding postures are, by definition, either on the steering wheel or resting on the thighs, the hand segment is assumed to be aligned with the forearm with whatever orientation (forearm pronation or supination) is appropriate to the task. For other occupant tasks, such as reaching, additional data on hand position and orientation could be collected.

An important distinction should be made between the use of this kinematic model for representing posture and for simulating posture changes. The model is used to represent posture when the posture is reported in terms of the lengths and orientations of the specified body segments. The corresponding posture can be reconstructed from this information and the model topology. Posture change for a particular subject can be represented by changes in orientation of model segments that were initially scaled to match the subject in a specific posture, or by a recalculation of each of the joint locations from new landmark data, resulting in different segment lengths and orientations. The latter approach has been used exclusively in this research for two reasons. The complexity of fitting a particular kinematic model to a new set of body landmark data is avoided, but, more importantly, the kinematic model has been found to be a sufficiently accurate representation of the human body linkage that the changes in apparent segment length between different sitting postures are small (18). Thus, the differences between the segment orientations obtained by fitting a single kinematic model to all of a particular subject's postures and those obtained by direct calculation of joint locations for each posture are also small.

For this approach to posture representation, the number of joint degrees of freedom are unimportant, because the lengths of segments are allowed to vary as needed. However, for simulations of posture changes using this model, the model segment lengths are fixed and articulated according to movement relationships developed from data. In simulations, the joint degrees of freedom are specified in the particular set of posture prediction functions that are used, which may vary depending on the application. Thus, for prediction of normal driving posture, the wrist may be assigned zero degrees of freedom, but for other tasks, two or more degrees-of-freedom may be simulated.

One substantial difference between the current kinematic model and other similar models is that the shoulder joint is not connected by a rigid link to the thorax. Instead, the position of the shoulder (glenohumeral) joint in a thorax-based coordinate system is reported. This allows the arm position resulting from complex motion of the clavicle and scapula to be described without reference to a mechanical linkage. This approach is believed to result in greater generality, particularly because the treatment of the shoulder complex varies widely among kinematic models of the body.

2.2 Experimental Method

A driver's posture is recorded by measuring the three-dimensional locations of body landmarks with respect to a vehicle coordinate system. The surface landmark locations are used to calculate the joint locations that define the kinematic model posture. These data may be obtained by many different techniques, including: photogrammetry of targets applied to the subject's skin or clothing, automated marker tracking systems, or by direct recording with three-dimensional coordinate measuring equipment, such as the FARO arm or SAC sonic digitizer. Each technique has advantages and disadvantages relating to accuracy, equipment cost, ease of use in vehicle and laboratory environments, and data processing requirements. In recent studies at UMTRI, landmark locations were measured using a Science Accessories Corporation GP8-3D sonic digitizer probe or a FARO Arm coordinate measurement device. Using both tools the experimenter first locates the landmark by direct palpation, then places the measuring probe at the landmark location to record the location. The pubic symphysis landmark is located by the subject. Each subject is trained to palpate down the midline of the abdomen until locating the symphysis. Assessments of the precision of pelvis landmark measurements using these techniques suggest that they are sufficiently reliable for characterizing pelvis location and orientation (19).

2.2.1 Body Landmarks

The experimenter palpated each landmark individually for each measurement to accurately locate the landmark and avoid the problems associated with movement of targets relative to the underlying bone. This technique also eliminated the need for target-to-landmark transformation calculations.

Table 1 and Figure 3 define and illustrate the body landmarks that are used to represent sitting posture with the kinematic model. These definitions are adapted from those in Schneider et al. (6), and are mostly identical or similar to those used in previous studies (15, 20). Note that some of these landmarks are not accessible when the subject is sitting in a vehicle seat. They can, however, be collected when the subject is standing or sitting in a specially designed laboratory seat.

One important difference between these definitions and the conventional definitions is for the acromion landmark. In McConville et al. (20), the acromion landmark is defined as "the most lateral point on the lateral edge of the acromial process of the scapula." The definition used in Schneider et al. (6) is identical to McConville et al. This landmark definition is somewhat ambiguous because, on most subjects, the lateral margin of the acromion process extends for 10 to 20 mm in a sagittal plane, making a precise identification of the landmark in that plane difficult. For the current work, the definition of the acromion landmark has been refined to be the most anterior corner of the lateral margin of the acromion process. This bony point can be identified precisely on most subjects, and provides a more stable reference for shoulder location.

Table 1
Definitions of Body Landmarks

Landmark	Definition
Glabella	Undepressed skin surface point obtained by palpating the most forward projection of the forehead in the midline at the level of the brow ridges.
Infraorbitale	Undepressed skin surface point obtained by palpating the most inferior margin of the eye orbit (eye socket).
Tragion	Undepressed skin surface point obtained by palpating the most anterior margin of the cartilaginous notch just superior to the tragus of the ear (located at the upper edge of the external auditory meatus).
Occiput	Undepressed skin surface point at the posterior inferior occipital prominence. Hair is lightly compressed.
Corner of Eye	Undepressed skin surface point at the lateral junction of the upper and lower eyelids.
C7, T8,* T12*	Depressed skin surface point at the most posterior aspect of the spinous process.
Suprasternale (manubrium)	Undepressed skin surface point at the superior margin of the jugular notch of the manubrium on the midline of the sternum.
Substernale (xyphoid process)	Undepressed skin surface point at the inferior margin of the sternum on the midline.
Anterior-Superior Iliac Spine (ASIS - right and left)	Depressed skin surface point at the anterior-superior iliac spine. Located by palpating proximally on the midline of the anterior thigh surface until the anterior prominence of the iliac spine is reached.
Posterior-Superior Iliac Spine* (PSIS - right and left)	Depressed skin surface point at the posterior-superior iliac spine. This landmark is located by palpating posteriorly along the margin of the iliac spine until the most posterior prominence is located, adjacent to the sacrum.
Pubic Symphysis	Depressed skin surface point at the anterior margin of pubic symphysis, located by the subject by palpating inferiorly on the midline of the abdomen until reaching the pubis. The subject is instructed to rock his or her fingers around the lower margin of the symphysis to locate the most anterior point.
Lateral Femoral Condyle	Undepressed skin surface point at the most lateral aspect of the lateral femoral condyle. Measured on the skin surface or through thin clothing.
Wrist	Undepressed skin surface point on the dorsal surface of the wrist midway between the radial and ulnar styloid processes.
Acromion	Undepressed skin surface point obtained by palpating the most anterior portion of the lateral margin of the acromial process of the scapula.
Lateral Humeral Condyle	Undepressed skin surface point at the most lateral aspect of the humeral condyle.
Lateral Malleolus	Undepressed skin surface point at the most lateral aspect of the malleolus of the fibula.
Medial Shoe Point	Point on the medial aspect of the right shoe medial to the first metatarsal-phalangeal joint (approximately the ball of the foot).
Shoe Heel Contact Point	Point on the floor at the center of the right shoe heel contact area with the foot in normal driving position contacting the accelerator pedal.

*These points are not accessible when the subject is sitting in a conventional vehicle seat, but are recorded in other sitting and standing experimental situations to characterize the subject's torso geometry. See text for details.

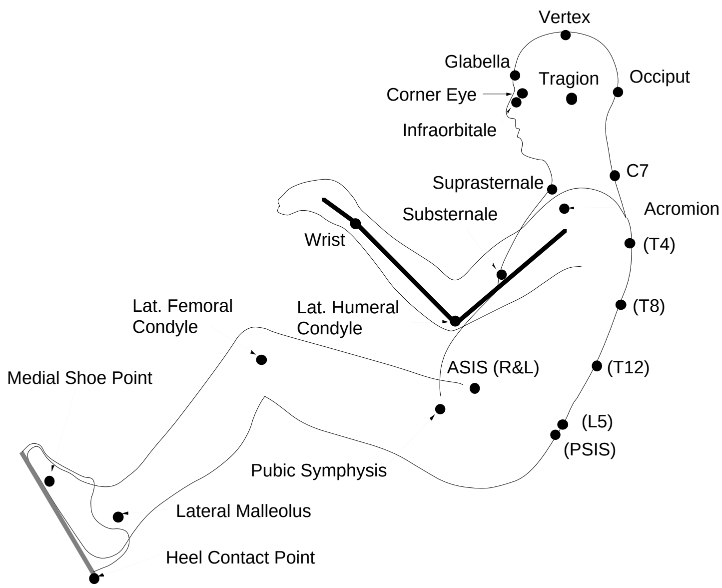

Figure 3. Body landmarks used to calculate internal joint locations and segment orientations.

The landmark set is sparse with regard to limb landmarks, reflecting the practical constraints of measuring vehicle occupant postures. Medial landmarks on the limbs are often difficult to reach with the measurement probes or to view with automated marker tracking systems, and the need to measure each subject in a large number of vehicle and seat conditions (in a typical study design) provides incentive to reduce the number of landmarks to shorten test times. However, because vehicle driving and riding postures are highly constrained, sufficient information to describe the posture is available with a sparse landmark set.

2.2.2 Calculation of Joint Locations

The kinematic model used to describe posture has joints that correspond to anatomical locations inside of the body. Calculation methods are needed to translate the exterior landmark locations to interior joint locations. This problem is common to any attempt to represent the body by a kinematic linkage, but is complicated because joint locations can be measured directly only with cadavers or through the use of x-rays or other internal imaging technology. Dempster (1) conducted the first large-scale effort to address this problem. He performed dissections of cadavers and made systematic measurements for the specific purpose of developing scalable linkage models of the human body for use in human factors analysis. Snyder et al. (15), in another important study, used radiography of male volunteers to study the locations and movements of the joints for a wide variety of seated and standing postures. Their specific emphasis was to determine the relationship between the motions of skin-mounted surface targets and the underlying joints.

Many researchers are currently performing biomechanical analysis of human activity using linkage models, and there are almost as many techniques for estimating internal joint locations from external, measurable locations of body landmarks to internal joints.

In each case, the type of transformation chosen is dependent on the needs of the research. This section presents the calculation methods that have been selected based on the requirements of posture representation for automotive interior design using three-dimensional CAD manikins.

Data Sources — The landmark-to-joint transformation methods described here are based largely on the data and analysis presented by Schneider et al. (6) and Robbins (13, 14). This three-volume publication describes a detailed study of passenger-car drivers conducted to develop anthropometric specifications for crash-dummy design. Body landmark locations in a driving posture were recorded for 25 subjects in each of three size/gender groups: small females (approximately 5th-percentile U.S. by stature and weight), midsize males (approximately 50th-percentile U.S. by stature and weight), and large males (approximately 95th-percentile U.S. by stature and weight). The seated landmark data were supplemented by a large number of standard anthropometric measures and some developed specifically for automotive postures.

Robbins used the external landmark data to estimate internal joint locations, using skeleton geometry data from several sources. Table 2 shows the references for each of the model joints. In the current work, the original reference materials have been consulted to verify that the methods and estimates in Robbins (13) are valid. In the case of the upper lumbar and lower neck joints (T12/L1 and C7/T1), the data presented by Snyder et al. (15), on which Robbins relied, support a number of different location estimates, both because there is considerable variability in the data and because the data are presented in a number of different ways. A reexamination of the Snyder data indicated that the Robbins estimates were among the reasonable interpretations, so the location methods for these joints were selected to be consistent with Robbins. The only area in which the current methods differ substantially from Robbins is in the calculation of the hip and lower lumbar (L5/S1) joints. Robbins' analysis contains some discrepancies in regard to pelvis location that have been resolved by an analysis of data from several sources, including data from recent studies that were not available to Robbins.

Hip Joint Calculations — The location of the pelvis in the Robbins analysis has been criticized because of the large apparent flesh margin under the ischial tuberosities. Recent data from Reynolds (16) suggest that a typical flesh margin at the ischial tuberosities for a midsize-male cadaver on a rigid seat is about 16 mm, compared with about 42 mm in the Robbins analysis. The discrepancy appears to relate to the interpretation of the anterior-superior iliac spine (ASIS) landmarks relative to the ilia, which Robbins may have located too low on his pelvis reconstruction. Further, Robbins did not apparently include any flesh margin in the relationship between the measured ASIS location and the bone, which may have contributed to the discrepancy.

Because of these concerns about Robbins' estimates of the pelvis joint locations, the hip and lower lumbar joint (L5/S1) locations are estimated using pelvis landmark data with scaling methods developed from several other sources. Reynolds et al. (22) presented data on the positions of a large number of landmarks on pelves from a skeleton collection. Data were summarized for large male, midsize male, and small female pelves, categories selected so that the data would be applicable to the design of crash dummies of those sizes. Bell et al. (23) suggest using the distance between the anterior-superior iliac spine landmarks as a scaling dimension. A similar method was used by Manary et al. (24) in a study of driver hip joint locations. Recently, Seidel et al. (25) demonstrated that the use of other pelvis dimensions in addition to inter-ASIS breadth would improve the estimate of the hip joint center location. Data from each of these sources have been examined to determine the best method for calculating the hip joint locations.

Table 2
Data Sources Used by Robbins (13) to Estimate Joint Locations

Joint	Reference	Type of Data
Upper Neck (atlanto-occipital)	Ewing and Thomas (21)	Kinematic analysis of head/neck motion
Lower Neck (C7/T1)	Snyder et al. (15)	Radiographic study of torso movement
Upper Lumbar (T12/L1)	Snyder et al. (15)	Radiographic study of torso movement
Wrist	Dempster (1)	Cadaver dissection
Elbow	Dempster (1)	Cadaver dissection
Knee	Dempster (1)	Cadaver dissection
Ankle	Dempster (1)	Cadaver dissection
Shoulder (glenohumeral)	Snyder et al. (15)	Radiographic study of torso movement

Seidel et al. (25) define three pelvis dimensions, illustrated in Figure 4: pelvis width (PW), which is the inter-ASIS distance; pelvis height (PH), which is the length of a line perpendicular to the inter-ASIS line to the pubic symphysis; and pelvis depth (PD), which is the distance from the ASIS to the posterior-superior iliac spine on the same side of the pelvis. They present the mean hip joint coordinates for 65 pelves relative to these dimensions. Table 3 compares the Seidel et al. scaling with that proposed by Bell et al. (23) from radiographic measurements, and that obtained from the Reynolds et al. (22) data. Figure 5 illustrates the X and Z coordinates. The Y coordinate is measured perpendicular to the midsagittal plane.

The scaling relative to pelvis width (inter-ASIS breadth) is very similar in the three studies, varying most in the X coordinate. There are larger discrepancies in the scaling based on pelvis height and pelvis depth. The four-percent difference between Seidel and Robbins in Hip-Z/PH produces a difference in estimated hip joint location of about 3 mm for a midsize-male pelvis. The two-percent difference in Hip-X/PD also amounts to a difference of about 3 mm.

Seidel et al. found no statistically significant relationship between pelvis width and Hip-Z, suggesting that if pelvis width is the only available dimension, a constant value for

Hip-Z, rather than the scaled value, could be used for all subjects. In contrast, Seidel et al. showed a significant relationship between Hip-Z and pelvis height, indicating that pelvis height would be a suitable scaling dimension for that coordinate. The improved performance of the pelvis-height scaling was demonstrated by a smaller mean estimation error (3.5 mm vs. 7.5 mm). Similarly, scaling Hip-X by pelvis depth produced a smaller mean error compared with scaling by pelvis width (3.0 mm vs. 4.9 mm).   Notably, Seidel et al. also found no important differences between male and female pelves in these scaling relationships.

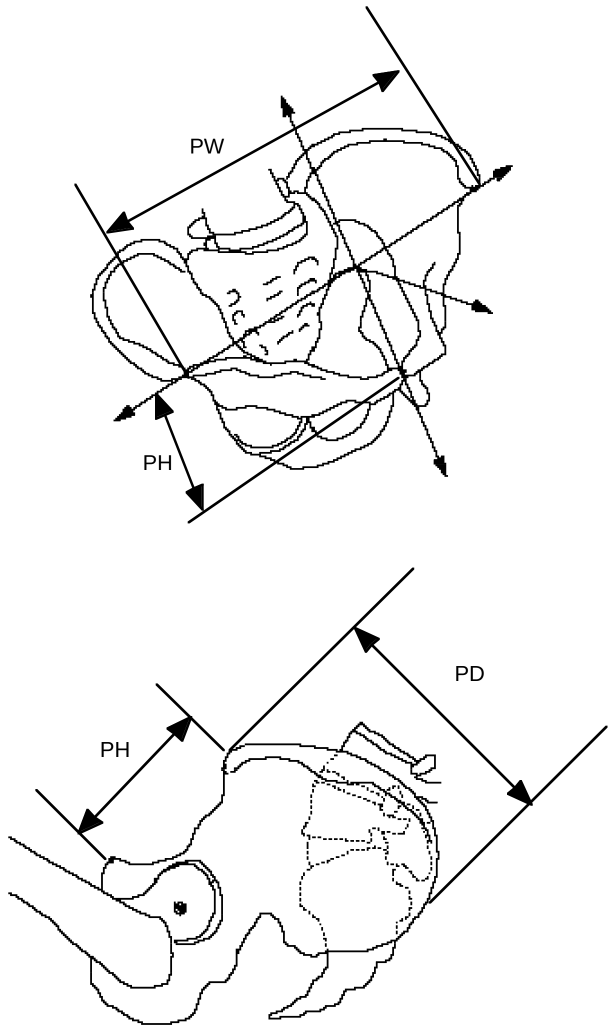

Figure 4. Illustration of pelvis scaling dimensions:
pelvis width (PW), pelvis height (PH), and pelvis depth (PD).

Table 3
Comparison of Hip Joint Location Methods:
Mean Scaling Relationships

Measure*	Seidel et al. (24)	Bell et al. (23)	Reynolds et al. (22)†	Location Error Estimates** (mm)
Hip-X/PW	24%	22%	22%	4.9 (3.4)
Hip-Y/PW	36%	36%	37%	5.8 (4.2)
Hip-Z/PW	30%	30%	29%	7.5 (5.6)
Hip-X/PD	34%	--	32%	3.0 (2.3)
Hip-Z/PH	79%	--	83%	3.5 (2.8)

*The ratio of the coordinate value to the scaling dimension.
†Data from Reynolds et al. (22) are the averages of values for small-female, midsize-male, and large-male pelves.
** Mean (standard deviation) of prediction error from Seidel et al. (25), N = 65 except N = 35 for Hip-X/PD.

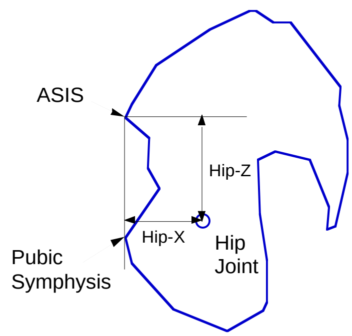

Figure 5. Location of the hip joint in the sagittal plane relative to the ASIS and pubic symphysis landmarks, showing the X and Z dimensions listed in Table 3.

The foregoing analysis led to the conclusion that the scaling relationships proposed by Seidel et al. should be used when the necessary data are available and reliable, meaning the locations of both ASIS, the pubic symphysis, and both PSIS landmarks. However, the Seidel et al. analysis demonstrated that the difference in error magnitudes for the alternative scaling techniques is small, so any of the techniques should give similar results.

Lower Lumbar Joint (L5/S1) Calculations — The joint between the fifth lumbar vertebra and first sacral vertebra can be considered to be a joint on the bony pelvis if motions within the sacral vertebrae and at the sacroiliac joints are assumed to be negligible. For analysis of seated postures, this is a reasonable assumption (26).

Reynolds et al. (22) include two data points on the top edge of the first sacral vertebra (S1) in the midsagittal plane. An offset vector of 10 mm, constructed perpendicular to the center of the line segment connecting the two S1 data points, was used to estimate the joint location, as shown in Figure 6.

The findings of Seidel et al. with respect to the superior scaling performance of pelvis height and pelvis depth for hip joint location suggest using those measures for estimating lower lumbar joint location as well. Table 4 shows scaling percentages from Reynolds et al. for L5/S1 location estimated as described in Figure 6. Although there are differences between the small-female, midsize-male, and large-male pelves, they do not appear to be systematically related to body size. Given the lack of important gender differences in the Seidel et al. analysis, the mean scaling values from Robbins were selected.

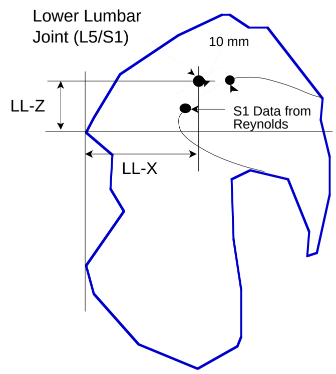

Figure 6. Method used to estimate lower lumbar joint (L5/S1) location from the data in Reynolds et al. (22). Not to scale.

Table 4
Scaling Relationships for L5/S1 from Reynolds et al. (22)

Measure	Small Female	Midsize Male	Large Male	Mean*
LL-X/PW	28.9%	26.4%	27.0%	27.4%
LL-Z/PW	17.2%	12.6%	15.1%	15.0%
LL-X/PD	42.5%	37.7%	39.4%	39.9%
LL-Z/PH	45.2%	39.9%	44.5%	43.2%

*Mean of small-female, midsize-male, and large-male values.

Flesh Margins — The preceding analyses of data relating to hip and lower lumbar joint location are based on landmarks on the pelvis bones. In live subjects, however, the landmark measurements are made through a thickness of compressed tissue. These flesh margin thicknesses are important to consider in calculating these joint locations. In previous analyses, Manary et al. (24) and others at UMTRI have used estimates of compressed flesh margin thickness of 5 mm at the ASIS and 15 mm at the pubic symphysis. Recently, a small-scale, unpublished study was conducted in which the flesh margins at these landmarks were measured directly in 30 male and female cadavers, using a probe configuration similar to that used to record body landmark data. Flesh margins of 10 mm at the ASIS and 15 mm at the pubic symphysis were found to be good estimates for all subjects. Accounting for clothing and differences between subject palpation and the cadaver experiments, flesh margins of 10 mm at the ASIS and 25 mm at the pubic symphysis are used.

Landmark Selection and Scaling for Other Joints— As with the pelvis joints, the locations of other joints relative to the surface landmarks are calculated using simple linear scaling relationships. Since Robbins presents a large set of surface landmark locations along with the joint location estimates, it is possible to identify a number of different relationships among surface landmarks and joints that could be used to perform the transformations with new surface landmark data. The landmarks were selected to be as close as possible to those that were referenced in the original source materials listed in Table 2.

Since each joint lies some distance from the nearest measured landmark, a method must be developed to scale the vector relating the two, to account for differences in body size. In the current work, these joint location vectors are scaled by comparing the distance between two measured landmarks with the corresponding data for midsize males given by Robbins. This is analogous to the procedure used with pelvis landmarks. While the particular dimensions chosen may not be the ideal dimensions for scaling, they have been selected such that they are likely to be fairly well correlated with the vector magnitudes of interest. (In general, data on skeletal geometry necessary to test these assumptions are not available.) The scaling approach for all subjects uses the Robbins midsize-male data as the reference geometry because the underlying data on which the landmark-to-joint transformations are based (sources in Table 2) relied exclusively on male subjects. Table 5 lists the landmarks that define the location vectors and scaling measurements for each joint.

Table 5
Landmarks Used To Define and Scale Joint Location Vectors

Joint	Landmarks
Upper Neck (atlanto-occipital)	Infraorbitale, Tragion
Lower Neck (C7/T1)	C7, Suprasternale
Upper Lumbar (T12/L1)	T8, T12, C7, Suprasternale
Lower Lumbar (L5/S1)	ASIS, PS, PSIS
Hip	ASIS, PS, PSIS
Shoulder	Acromion, C7, Suprasternale
Knee	Lateral Femoral Condyle (plus Hip Joint and Lateral Malleolus)
Elbow	Lateral Humeral Condyle (plus Shoulder Joint and Wrist landmark)
Wrist	Wrist
Ankle	Lateral Malleolus (plus Lateral Femoral Condyle and Hip Joint)

Shoulder Joint — The shoulder joint of the kinematic model approximates the anatomical glenohumeral joint, the articulation of the humerus with the glenoid fossa of the scapula. As noted above, the acromion landmark definition used here is slightly different than that used in other studies, resulting in a measurement point that is anterior to that measured using the more conventional definition. As a consequence, the acromion-to-shoulder-joint relationship in Robbins' data is different from the relationship in data measured using the current methods.

Robbins estimated the glenohumeral joint location by orienting a midsize-male humerus according to the measured humeral landmarks (greater tubercle, lateral epicondyle, and medial epicondyle). This procedure was used because the Dempster definition referred to an arm position dissimilar to a normal driving posture. Snyder et al. (15) report that the average sagittal-plane vector from the humeral head (approximately the glenohumeral joint center) to the acromion landmark is 52 mm long and oriented 42 degrees rearward from vertical, although there is considerable variability in both measurements. Starting from the glenohumeral joint location calculated by Robbins and applying the vector from Snyder et al. results in an estimated acromion location about 10 mm forward and 16 mm above the landmark location reported by Robbins. Alternatively, starting at the acromion location given by Robbins, the Snyder et al. vector predicts a humeral head location 16 mm below and 10 mm forward of that reported by Robbins. It should be noted that these discrepancies are within the range of the vector length data and vector angle data reported by Snyder et al.

The potential effects of the revised acromion definition were assessed by comparing the relative sagittal plane locations of suprasternale, C7, and acromion landmarks in data collected using the current definition and those reported by Robbins. Figure 7 shows mean values for 12 midsize males in one typical vehicle package from a recent UMTRI study, using the revised acromion definition, and those from Robbins for midsize males, aligned at C7 and rotated so that the C7-to-suprasternale vectors are at the same angle. The mean distance from C7 to suprasternale is 130 mm for the recent subjects and 138 mm for the Robbins subjects, indicating that the overall thorax size is similar. The acromion location reported by Robbins is considerably rearward and lower than the acromion location recorded using the revised landmark definition. The differences in the definitions may account for the more forward position, but no explanation is apparent for the vertical difference.

Since Robbins generated the glenohumeral joint location by using a humerus aligned with data from humeral landmarks, i.e., without relying on potentially lower-precision transformations from points on sternum or scapula, Robbins' joint location is assumed to be reasonably accurate. A transformation was developed to relate the revised acromion landmark to Robbins' glenohumeral joint location relative to C7 and suprasternale. Figure 7 shows that the glenohumeral joint location in the sagittal plane can be estimated by constructing a vector 58 mm long at an angle of 67 degrees with respect to the C7-to-suprasternale vector. The Snyder et al. data are difficult to interpret with regard to the necessity of scaling the acromion-to-humeral-head vector, because the data are not expressed in those terms. However, because it is reasonable to believe that the length of this vector will, on average, vary with body size, the length of the vector is scaled as a fraction of the C7-to-suprasternale vector, using the reference dimensions of 58 mm for acromion-to-glenohumeral-joint and 138 mm for C7-to-suprasternale, where the latter value is obtained from Robbins' midsize-male landmark data.

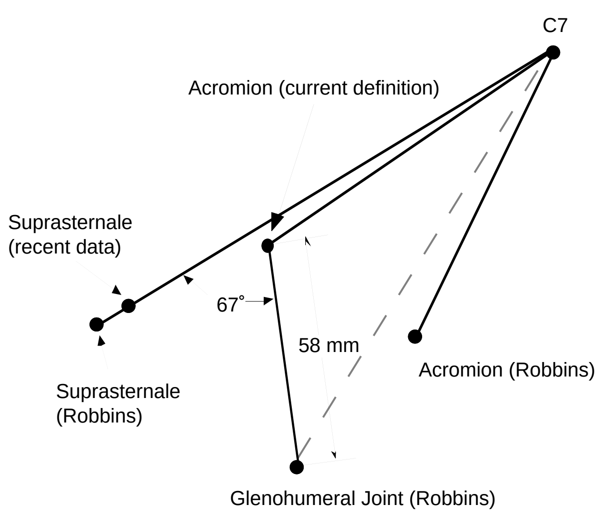

Figure 7. Acromion location comparison between current definition (N = 12 midsize males) and Robbins (N = 25 midsize males). Side-view data from Robbins have been aligned with the recent UMTRI data at C7 and rotated to align the C7-to-suprasternale vectors.

According to Snyder et al., the average angle from the center of the humeral head to the acromion landmark in the coronal (YZ) plane is only 2 degrees from vertical. Since the differences between the current and Snyder et al. acromion landmark definitions are believed to affect primarily the sagittal plane coordinates, the medial-lateral (Y-axis) coordinate of the shoulder (glenohumeral) joint will be taken to be the same as that of the acromion landmark.

This method for estimating the shoulder joint location for the kinematic model is based on fewer and less precise data than the methods for the hips and other extremity joints. However, the methods are likely to be sufficient for the intended applications.

Special Considerations for the Upper Lumbar Joint— The upper lumbar joint, which corresponds to the joint between the twelfth thoracic vertebra (T12) and the first lumbar vertebra (L1), is normally estimated, as indicated in Table 5, using the data from the T8 and T12 surface landmarks. However, these landmarks are not accessible when a subject is sitting in a normal automobile seat. Consequently, a method was developed to estimate the location of this joint from landmarks that are accessible in normal driving and riding postures.

Prior to posture measurement in the vehicle seat, the subject sits in a special laboratory seat that has approximately the same seatpan and seatback orientation as a normal vehicle seat, but has a 50-mm-wide slit in the center of the seatback that allows access to the spine. This seat is constructed with flat, rigid surfaces and is referred to as the “reference hardseat.” With the subject sitting in the hardseat, the locations of suprasternale, C7, T8, and T12 are recorded. The data from T8 and T12 are used to calculate the location of the upper lumbar joint using the scaling techniques described below. The data from C7 and suprasternale are also used to calculate the lower neck joint location (C7/T1). These two joints define the thorax segment for the subject. The length of the thorax segment (distance between the upper lumbar and lower neck joints) and the orientation of the vector between these joints relative to the C7-to-suprasternale vector is recorded for each subject. When analyzing subsequent test data from the subject in which T8 and T12 are not available, the location of the upper lumbar joint is calculated using the thorax geometry previously measured in the hardseat.

2.2.3 Joint Location Diagrams

The Appendix contains complete information on the methods for calculating each joint in the kinematic model from the surface landmarks.

3.0 SUMMARY AND DISCUSSION

These procedures provide a means of representing a vehicle occupant’s posture as a kinematic linkage, using joint locations calculated from a sparse set of external body landmarks. The joint location calculation procedures are based on a review of the literature, with particular emphasis on a recent study of driver anthropometry used to formulate anthropometric specifications for a new family of crash dummies. In all cases, the joint calculations are believed to be sufficiently accurate for representing normal vehicle occupant postures. Using these techniques, the effects of vehicle and seat design parameter as well as anthropometric factors on posture can be quantified and expressed in terms useful to the developers of ergonomic software.

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Appendix

Calculation Diagrams for All Joints

This section contains detailed descriptions of the calculation procedures for each joint, along with figures depicting the scaling methods. As noted above, torso postures are restricted to being sagittally symmetric. Consequently, torso joint locations are calculated in the midsagittal XZ plane only, which is assumed to be parallel to the vehicle or seat XZ (side-view) plane. Extremity joints are located in three dimensions.

These landmark-to-joint transformations are presented in terms of rotated and scaled vectors. They could instead be presented in terms of segment-specific coordinate systems, but the current, equivalent procedure was judged to be simpler to present and closer to the manner in which such transformations would be implemented in computer software.

Upper Neck Joint — The upper neck joint corresponds anatomically to the atlanto-occipital joint. Figure 8 shows the technique for calculating the location of the upper neck joint from the infraorbitale and tragion landmarks, measured on the same side of the body. In the XZ plane, the upper neck joint center is located by rotating a vector from tragion to infraorbitale downward through 117 degrees. The vector length is 31 percent of the measured sagittal plane distance from tragion to infraorbitale. If a Y coordinate for the upper neck joint is required, it can be estimated by using the Y-coordinate of the mid-tragion or mid-infraorbitale point, i.e., centerline of head.

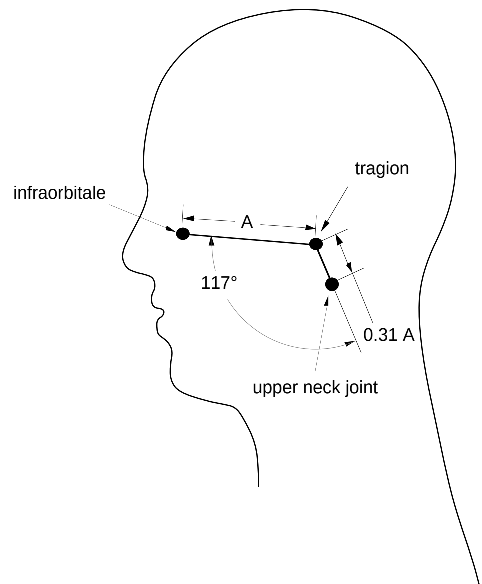

Figure 8. Calculation techniques for upper neck joint.

Lower Neck Joint — The lower neck joint corresponds anatomically to the C7/T1 joint. The location of this joint is calculated using the C7 and suprasternale surface landmarks, as shown in Figure 9. The vector from C7 to suprasternale is rotated upward 8 degrees and scaled to have a length equal to 55 percent of the measured sagittal-plane distance from C7 to suprasternale.

Upper Lumbar Joint — The upper lumbar joint corresponds anatomically to the T12/L1 joint. With the subject sitting in the reference hardseat, the locations of suprasternale, C7, T8, and T12 are recorded. The data from T8 and T12 are used to calculate the location of the upper lumbar joint, as shown in Figure 9.

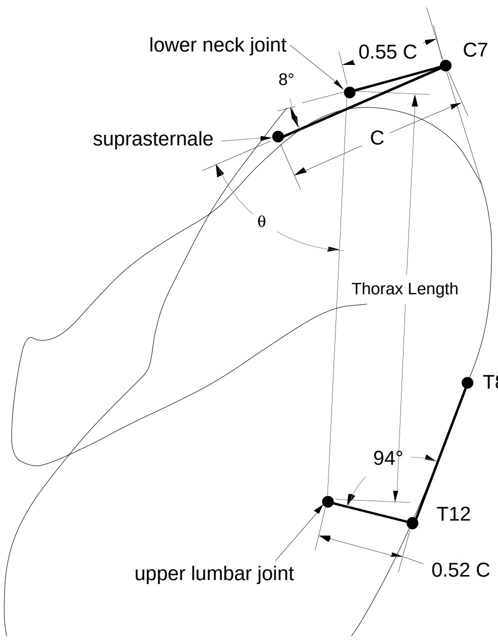

Figure 9. Calculation method for lower neck joint and upper lumbar joint.

Suprasternale and C7 data are used to calculate the lower neck joint location as described above. The thorax length (the distance from the lower neck joint to the upper lumbar joint) and the angle θ (formed by the thorax segment and the C7-to-suprasternale vectors) are recorded for the subject using data collected in the reference hardseat (see above). These two values comprise the subject's thorax geometry for subsequent posture calculations.

When the subject's posture is measured in experimental vehicle conditions, the locations of suprasternale and C7 are used to calculate the lower neck joint location as described above. A thorax segment vector is then constructed and oriented relative to the C7-to-suprasternale vector based on the subject's thorax geometry obtained in the hardseat.

Shoulder Joint— The shoulder joint calculation in the sagittal plane is shown in Figure 10. The sagittal-plane distance from the shoulder joint to acromion landmark is 42 percent of the distance from C7 to suprasternale on a vector forming an angle of 67 degrees with the C7 to suprasternale vector. The Y-axis (medial-lateral) position of the shoulder joint is taken to be the same as the Y coordinate of the acromion landmark. Since the postures are restricted to sagittal symmetry, the contra-lateral shoulder joint has the same X and Z coordinate, and lies the same distance lateral from the C7 landmark.

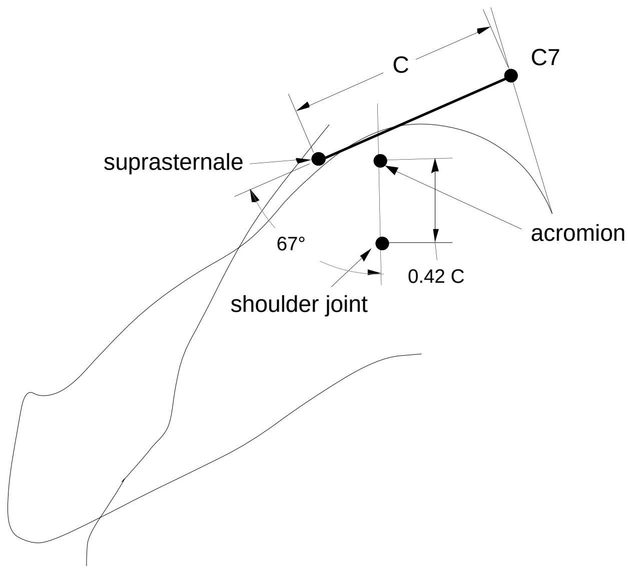

Figure 10. Calculation method for the shoulder joint.

Lower Lumbar Joint and Hip Joints— The hip joint and lower lumbar joint locations are calculated using the anterior-superior iliac spine (ASIS) landmarks (right and left), the pubic symphysis (PS) landmark, and the posterior-superior iliac spine landmark (PSIS). Calculations are conducted in three dimensions to obtain good estimates of both the left and right hip joint center locations for subsequent calculation of lower extremity posture. Although the measured postures are nominally sagittally symmetric and aligned with the package axes, a test subject's pelvis is sometimes tilted laterally or twisted relative to the package coordinate system. Consequently, the hip joint locations are calculated individually, then averaged in the XZ plane to obtain a mean hip joint location for use in calculating pelvis segment orientation (pelvis angle).

The lower lumbar and hip joint locations are calculated in a pelvis-centered coordinate system, which is then transformed to the desired global coordinate system. The pelvis coordinate system is shown in Figure 11. The Y axis is defined by the vector connecting the left and right ASIS. The Z axis is perpendicular to this line and passes through the pubic symphysis (PS). The X axis is mutually perpendicular to the Y and Z axes. Note that the coordinate system shown in Figure 11 is based on points on the bone, rather than surface landmarks. The flesh margins at the ASIS and PS landmarks are taken into account in the calculations.

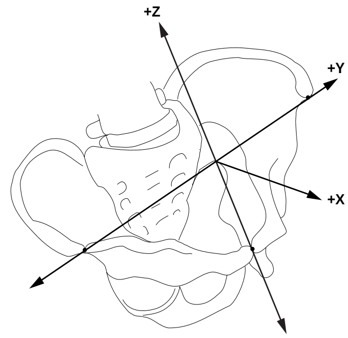

Figure 11. Pelvis coordinate system, adapted from Reynolds et al. (22).

The first step in the calculation of pelvis joints is to account for flesh margins at the landmarks. Using the rationale described above, margins of 10 mm at the ASIS and 25 mm at the pubic symphysis are used. A landmark-to-bone margin of 10 mm at the PSIS is used. As shown in Figure 12, a preliminary surface pelvis coordinate system {Xs, Ys, Zs} is established using the definition in Figure 11 with the ASIS and PS surface landmarks. The landmark points are then translated according to the flesh margins to obtain estimates of the underlying bony landmark location. The bone points are then used to define a pelvis bone coordinate system {Xb, Yb, Zb} identical to that shown in Figure 11. Table 6 shows the flesh margin correction vectors in the surface pelvis coordinate system.

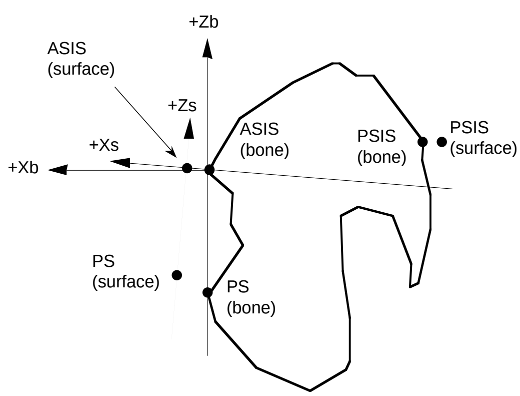

Figure 12. A sagittal view of surface and bone pelvis coordinate systems based on measured landmark locations (not to scale).

Table 6
Flesh Margin Correction Vectors
in the Surface Pelvis Coordinate System {Xs, Ys, Zs}
(mm)

Landmark	X	Y	Z
ASIS (right and left)	-10	0	0
PS	-17.7	0	-17.7
PSIS	5	0	0

The locations of the hip and lower lumbar (L5/S1) joints are calculated in the bone coordinate system {Xb, Yb, Zb} using vectors scaled with reference to pelvis dimensions defined by the bone landmark locations. The reference dimensions, all measured in three dimensions, are as follows:

Pelvis Width (PW): Distance between right ASIS (bone) and left ASIS (bone).

Pelvis Height (PH): Distance between PS (bone) and the midpoint of the line connecting left ASIS (bone) and right ASIS (bone).

Pelvis Depth (PD): Distance between right ASIS (bone) and right PSIS (bone) or the distance between left ASIS (bone) and left PSIS (bone); if all four landmarks are available, use average of values from left and right sides.

Figure 13 shows the X and Z coordinates of the hip and lower lumbar joints. Tables 7 and 8 give the scaling relationships to be used. Note that the X and Z coordinates may be scaled using PW or PD and PH, respectively. The latter should be used when the required landmark data are available. The Y coordinate of the lower lumbar joint in the bone coordinate system is zero, i.e., equal to the Y coordinate of the midpoint of the line connecting right ASIS (bone) and left ASIS (bone). The Y coordinate of the hip joints are found by moving laterally right or left from the mid-ASIS point according to the scaling in Table 7.

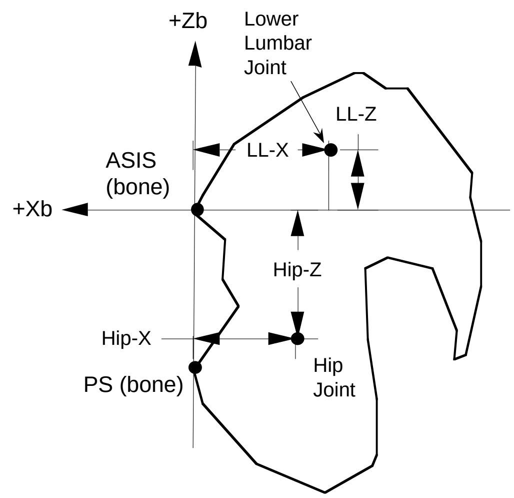

Figure 13. Location of hip and lower lumbar joints in XZ plane relative to bone coordinate system (not to scale). See Tables 7 and 8 for dimension scaling.

Table 7
Mean Hip Joint Scaling Relationships from Seidel et al. (25)

Measure*	Scale Factor
Hip-X/PW	24%
Hip-Y/PW	36%*
Hip-Z/PW	30%
Hip-X/PD	34%
Hip-Z/PH	79%

*Y coordinate measured laterally from the mid-ASIS point.

Table 8
Mean Lower Lumbar Joint Scaling Relationships
Using Data from Reynolds et al. (22)

Measure*	Scale Factor
LL-X/PW	27.4%
LL-Z/PW	15.0%
LL-X/PD	39.9%
LL-Z/PH	43.2%

Lower Extremity — The knee and ankle joint locations are calculated using simplifications of the techniques described by Dempster (1) and adapted by Robbins (13). Both the Dempster and Robbins procedures locate these joints on vectors connecting landmarks on opposite sides of the limb. Because it is often difficult to measure the locations of medial landmarks with vehicle-seated occupants, the simplified procedures use data from only the lateral side of the limb to obtain reasonably similar results. The procedure is to project a vector a scaled distance perpendicular to the plane formed by two measured and one calculated landmark. The scaling was developed from data on limb breadth at the joints in Schneider et al. (6). Figure 14 shows the procedure schematically.

To calculate the knee joint location, a plane is formed by the measured lateral malleolus and lateral femoral condyle locations, along with the calculated hip joint location on the same side of the body. A vector is constructed perpendicular to this plane, passing through the lateral femoral condyle landmark. The knee joint is located on this vector medial to the lateral femoral condyle landmark by a distance equal to 11.8 percent of the measured distance between the lateral malleolus and the lateral femoral condyle landmarks.

The ankle joint location is calculated similarly. A vector is constructed perpendicular to the plane described above, and passing through the lateral malleolus landmark. The ankle joint is located medial to the lateral malleolus landmark by a distance equal to 8.5 percent of the distance between the lateral malleolus and the lateral femoral condyle landmarks.

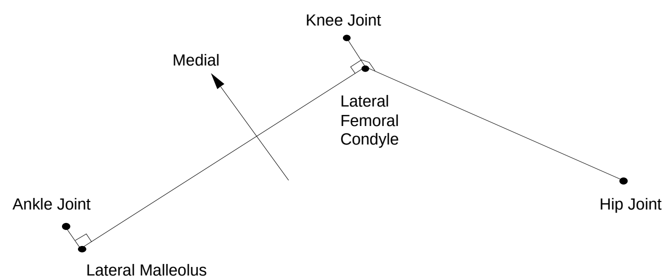

Figure 14. Calculation procedure for knee and ankle joints. Vectors from knee joint to lateral femoral condyle, and from ankle joint to lateral malleolus, are perpendicular to the plane formed by the hip joint, lateral femoral condyle, and lateral malleolus. See text for scaling length of vector from lateral femoral condyle to knee joint.

Upper Extremity — Calculations of upper extremity joint locations are similar to those for the lower extremity. Because of pronation and supination of the forearm, more than one wrist landmark would be necessary to use a method similar to the ankle technique to locate the wrist joint. However, a single point on the dorsal surface of the wrist is a sufficiently accurate estimate of the joint location for representing normal riding and driving postures. The measured wrist point is a skin surface point midway between the palpated radial and ulnar styloid processes.

The elbow location is calculated in a manner analogous to the knee, as shown in Figure 15. A plane is constructed that passes through the wrist landmark, lateral humeral condyle landmark, and the shoulder joint location on the same side of the body. A vector is constructed perpendicular to this plane, passing through the lateral humeral condyle landmark. The elbow joint is located medial to the lateral humeral condyle landmark a distance equal to 15.5 percent of the distance between the lateral humeral condyle and wrist landmarks. This scaling was determined from data on elbow width as a percentage of forearm length in Schneider et al. (6).

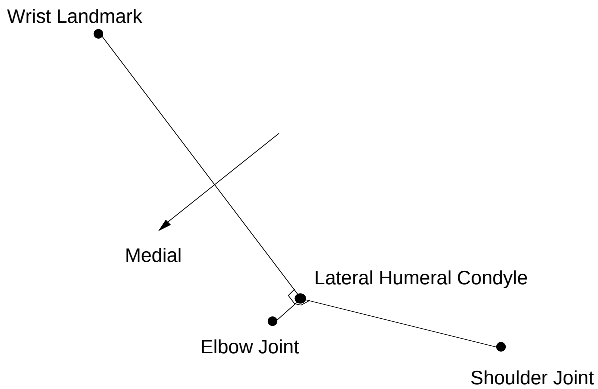

Figure 15. Calculation procedure for elbow joint. Vector from lateral humeral epicondyle to elbow joint is perpendicular to plane formed by the shoulder joint, lateral humeral epicondyle, and wrist landmark.

CHAPTER 7

ASPECT VEHICLE OCCUPANT POSTURE PREDICTION MODELS†

1.0 INTRODUCTION

1.1 Background

The design of passenger car interiors is increasingly assisted by the use of three-dimensional human representations that can be manipulated in a computer environment (Porter et al. 1993). These computer-aided-design (CAD) human models have increased in sophistication in recent years with advances in computer hardware and software, but their effective use has been hampered by the lack of valid methods to posture the models in the simulated vehicle interior.

In the mid-1950s, Dempster (1955) introduced an approach to ergonomic assessment for seated vehicle occupants using an articulated, two-dimensional template. A similar template design and a weighted three-dimensional manikin for measurements in actual vehicles were standardized in the mid-1960s for passenger car interior design by the Society of Automotive Engineers in Recommended Practice J826 (SAE 1997). These two tools, the two-dimensional template and the three-dimensional H-point machine, are still widely used for designing vehicle interiors, but are supplemented by statistically based tools that predict the distributions of particular posture characteristics for the U.S. population. These task-oriented percentile models, based on posture data from a number of different studies, are available for driver-selected seat position (SAE J1517), eye position (J941), reach (J287), and head location (J1052). Recently, the ASPECT program has developed a new H-point manikin and computerized design tool that are intended to replace the current SAE H-point machine and 2D template (Schneider et al. 1999). Further, improved seat position and eye position models have been developed at UMTRI over the past few years (Flannagan et al. 1996, 1998; Manary et al. 1998).

Although the existing task-oriented percentile models are very useful for vehicle design, they are not directly applicable to the posturing of human models because they address the population distribution of particular posture characteristics, rather than predicting the posture for any particular anthropometric category. For example, the eyellipse provides a prediction of the mean and distribution of driver eye locations, but does not predict the eye location for women 1550 mm tall or men 1800 mm tall. This more detailed information is necessary to establish an accurate posture for a particular instance of a CAD human model, which necessarily represents a single set of anthropometric variable

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† Portions of this chapter were previously published in SAE Technical Paper 1999-01-0966.

values. Yet, the CAD manikins must be used in concert with the task-oriented percentile models. The vehicle occupant posture prediction models described in this report were developed allow the two different types of design tools to be used together without conflict.

In recent years, rapid advances in computer hardware have made feasible interactive design evaluations using CAD manikins that were impractical or impossible a decade ago. Software advances have kept pace with the hardware improvements, so that the available modeling tools are markedly improved from those available at the start of the decade. Porter et al. (1993) briefly reviewed the features of 13 human-modeling systems in use prior to 1993 with potential application to vehicle design. As an indication of the rapid progress in the field of human modeling, none of the three commercial human modeling groups participating in the ASPECT program (Genicom SafeWork, TecMath RAMSIS, and EAI Jack), which together now represent nearly all auto-industry human model installations, were included in the Porter et al. review.

Most of the commercially available human models include substantial anthropometric scaling capability, allowing the manikin to be configured to represent geometrically the exterior dimensions of a wide range of potential vehicle occupants, but only RAMSIS included any significant prediction capability for vehicle occupant postures prior to the ASPECT program (Seidl 1994). Without posture-prediction capability built into the model or available through other external data or statistical models, many of the most useful applications of the CAD human models are unreliable. For example, vision and reach assessments require an accurate starting posture for the particular manikin dimensions being used. In the absence of accurate posture prediction, CAD human models are valuable primarily for visualization rather than for assessment.

The ASPECT program was conducted to develop new tools for vehicle design (Schneider et al. 1999). The primary objective was the development of a new H-point manikin (Reed et al. 1999a), but the increasing use of CAD manikins pointed to the need for methods to generalize the information obtained from a single-size H-point manikin to posture predictions for any size occupant. Consequently, the ASPECT program was begun with the secondary objective of developing a large, comprehensive occupant posture database that could be used as a reference for posturing CAD manikins. It soon became clear, however, that posture data alone, even from a large range of vehicle and seat configurations, would be difficult to apply to posture prediction in specific vehicle design cases. Statistical models based on the data were needed to express the large posture database in a readily implemented format.

This report presents a set of vehicle occupant posture prediction models developed by statistical analysis of posture data from hundreds of subjects in a large number of vehicle package and seat configurations created in laboratory vehicle mockups. The models were tuned and validated by comparison to a large UMTRI database of actual driver and passenger posture obtained in on-road testing. The ASPECT human-posture studies are described in detail in Manary et al. (1999). A preliminary posture-prediction model based on a subset of the ASPECT data was presented by Reed et al. (1999b). The models presented here have been extensively revised and expanded, and have been integrated with the latest task-oriented percentile models available for vehicle interior design.

Most of the references in this report are to SAE papers concerning the ASPECT program presented at the 1999 SAE Congress. These papers include extensive descriptions of the ASPECT program, the data collection and analysis methods, and the preliminary development of posture prediction models. Rather than duplicate that information here, the details are included by reference.

1.2 Modeling Objectives

The ASPECT human posture studies were undertaken to determine the effects of a range of vehicle and seat design factors, as well as occupant anthropometry, on driver and passenger posture. In these experiments, men and women selected to span a wide range of stature and weight chose their preferred driver or passenger postures in a set of test conditions produced by varying factors such as seat height, steering wheel position, lumbar support prominence, and seatback angle (Manary et al. 1999). Body landmark locations were recorded in three-dimensions, and the landmark data were used to estimate internal skeletal joint locations. The resulting body segment orientations create a kinematic linkage representation of the body that provides a quantitative description of posture (Reed et al. 1999c).

The postures of individual subjects in various vehicle and seat conditions are, by themselves, of substantially limited use for vehicle design, because it is unlikely that either the subjects or the test conditions exactly match the conditions of interest for a particular design. The primary objective of the statistical modeling effort is to create concise equations that represent the effects of the test conditions (vehicle and seat factors) on the occupant posture. In effect, this process condenses the information in the large posture database into a short list of equations.

Another objective in the development of the ASPECT methods was that the resulting models should be applicable to any CAD manikin. Prior to the ASPECT program, the RAMSIS software included some posture prediction capability, but the method was inherently linked to the kinematic structure and software algorithms of RAMSIS, and hence could not be used or evaluated outside of RAMSIS. Since the ASPECT program was supported by companies who use a number of different models, an approach restricted in application to one software tool was unacceptable. Further, a general model would be in keeping with the overall ASPECT goal of creating tools for industry-wide use.

Creating posture prediction that can be applied with any CAD manikin imposes important constraints on the model development. First, the modeling methods must be independent of any particular kinematic representation of the human body. Second, the methods must not require any particular processing capability that might be lacking in some models, such as an optimization routine. Clear and concise description of the models would be aided if they could be presented in closed form, using simply defined input and output variables. Ideally, the models should be presented in such a way that they can be used for some purposes without a CAD manikin. Lastly, the modeling method should produce predictions that are as accurate and precise as possible for the intended applications.

The modeling approach developed to meet these objectives is termed the Cascade Model, because the whole-body posture prediction results from a sequential series (cascade) of submodels. The Cascade Model emphasizes accurate prediction of the vehicle occupant hip and eye locations, since these two characteristics are the most important posture and position parameters for most vehicle interior assessments. Further, once hip and eye locations are specified accurately, acceptable accuracy can readily be achieved in other postural degrees of freedom using a variety of alternative approaches.

1.3 The Cascade Model

1.3.1 Overview

Figure 1 shows a schematic overview of the Cascade Model. Package, seat, and anthropometric variables are used to predict fore-aft seat position (for drivers and front-seat passengers), referenced to the H-point location on the seat. Hip location is then predicted relative to H-point, followed by prediction of eye location with respect to the hips. This sequence forms the core of the Cascade Model. The prediction of torso segment and limb postures can then be achieved using inverse kinematics, guided by behavioral observations from the ASPECT posture studies. The precise implementation of the torso and limb segment fitting may vary among models because of differences in kinematic linkages, but the H-point, hip, and eye predictions can be implemented uniformly across models, regardless of the underlying kinematic structure.

Figure 2 illustrates the prediction sequence for drivers. Beginning with the side-view package layout, the fore-aft seat position (H-point location) is predicted from the vehicle and seat variables and driver stature. The driver hip location is then calculated relative to H-point. The angle of the side-view line from hips to eyes is then computed, along with the distance between these points. The torso segments are then fit between the eyes and hips using inverse kinematics. The limbs are positioned similarly, using the hip and shoulder locations along with hand and foot positions. Individual degrees of freedom are predicted using linear equations derived from regression analyses of posture data. The development of these equations is described in detail in Section 3 of this report.

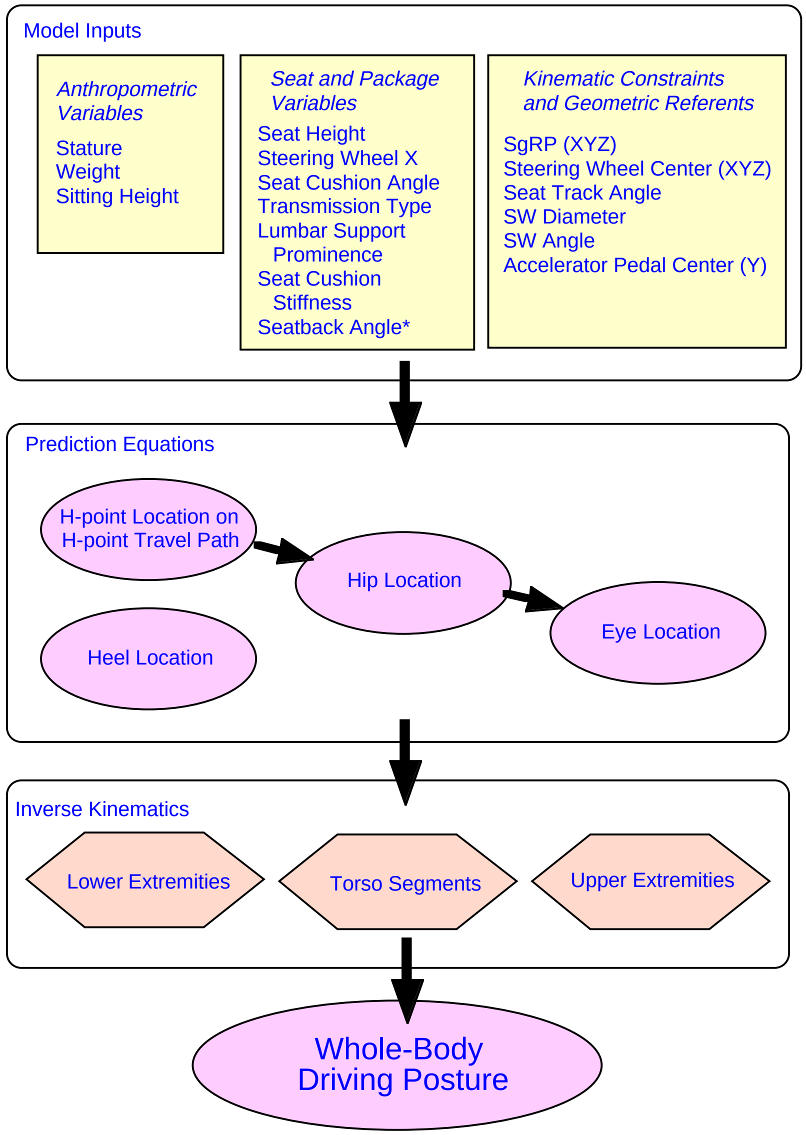

Figure 1. Cascade Model schematic.

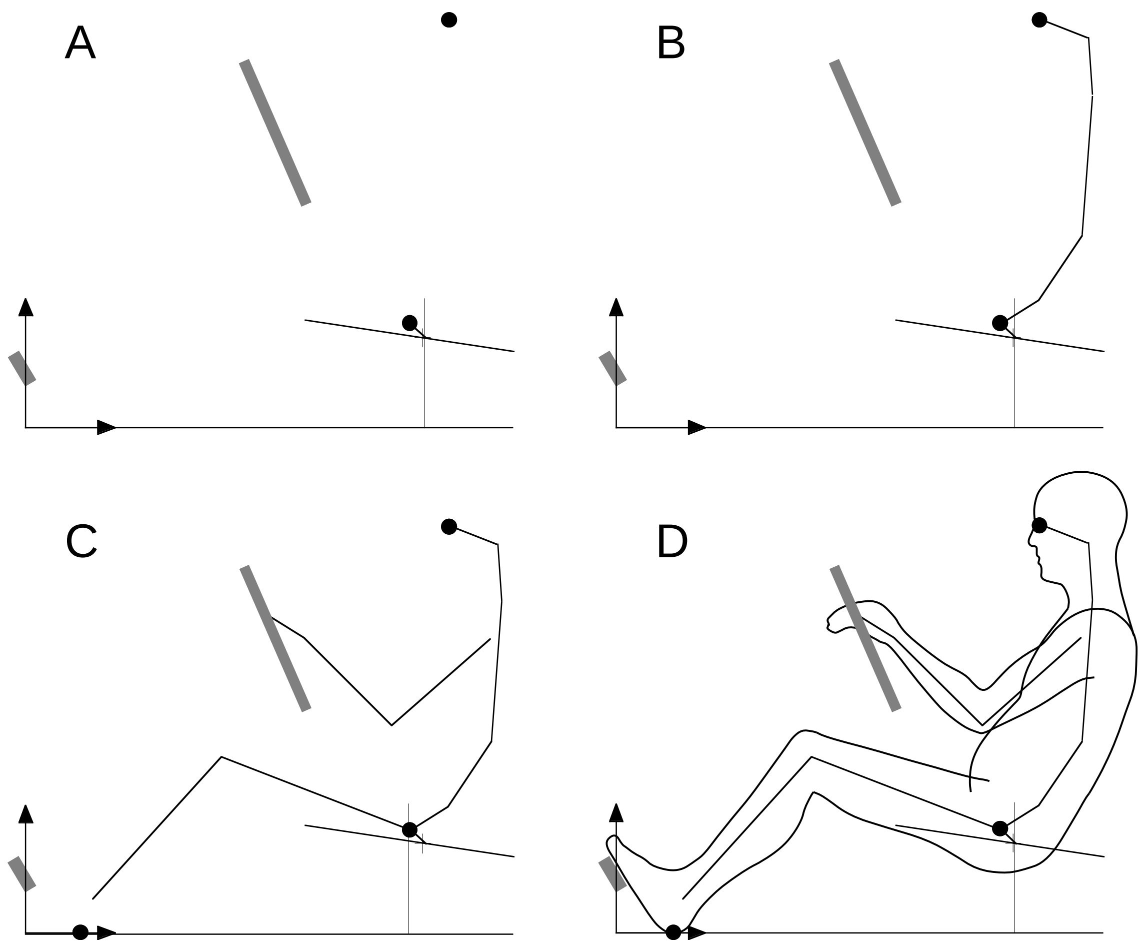

Figure 2. Cascade Model prediction sequence for drivers. A: Predict fore-aft H-point location, H-point-to-hip offset, eye location with respect to hip. B: Use inverse kinematics to fit torso segments. C: Predict heel location, use inverse kinematics to fit upper and lower extremities. D: Fit rest of human figure model.

Although the Cascade Model was developed for application to any CAD manikin, the ASPECT posture analysis used a specific kinematic representation of the human body. A brief summary of these methods is provided here. For complete details, see Reed et al. (1999c). Figure 3 shows the body segmentation created by kinematic joints at anatomical joint locations. A number of body segment angles are defined for use as dependent measures in posture analyses. Figure 4 shows the primary posture variables used in the Cascade Model. These describe the fore-aft position of the seat H-point, the hip offset from the H-point in side view, and the angle with respect to vertical formed by the side-view line from hip to eye.

The eye point used in these analyses is a composite landmark intended to represent the approximate midpoint between the centers of the orbits. The center eye point is computed using the Z (vertical) coordinate of the corner eye landmark, the X (fore-aft) coordinate of the infraorbitale landmark, and the Y (lateral) coordinate of the glabella landmark (see Reed et al. 1999c for detailed definitions of these body landmarks). For these analyses, only the X and Z coordinates are important. This eye point is intended to represent, in side-view, the approximate pivot center of the eyeball and hence a single point through which sight lines attained without head movement pass.

The Cascade Model predicts normal driving or riding posture, which is defined by the subject responses to the instruction “sit as you would to comfortably drive/ride in this vehicle” or “sit as you would to comfortably drive/ride in a vehicle like this” for laboratory studies. Based on observations that such postures are largely sagittally symmetric, the torso postures predicted by the model are exclusively sagittally symmetric, and all torso posture predictions are accomplished in the XZ (side-view) plane. Driver right leg postures are predicted, but left leg postures are not. Only the average driver arm splay angle (assumed to be symmetric) is predicted for the upper extremities.

There are obviously a range of driving and riding postures available to any individual, but extensive testing prior to and during the ASPECT program has reinforced the idea that individuals have a clear concept of a “normal” driving or riding posture and that the overall character of such postures is consistent across individuals. Thus, the predictions produced by the Cascade Model likely represent the vast majority of vehicle occupant postures, both in incidence and prevalence, but do not attempt to represent the extreme or unusual postures that individuals may adopt on occasion. There is no attempt in these models to represent extreme reclined postures (e.g., sleeping passengers), or postures produced by tasks other than normal, straight-ahead driving (such as adjusting the radio).

The version of the Cascade Model in this report differs in a few respects from previously published versions (Reed et al. 1999b). Notably, the sequence of predictions has been changed. In the earlier model versions, the fore-aft position of the drivers’ hips was predicted first, followed by the H-point location. In the current version, the fore-aft driver-selected H-point location (seat position) is predicted first, followed by hip location relative to H-point. The latter sequence allows predictions to be made using an equation from the Seating Accommodation Model (SAM), a model developed at UMTRI to describe the distribution of driver-selected seat positions (Flannagan et al. 1996, 1998). This change in modeling procedure integrates the seat position modeling in SAM with the whole-body occupant posture prediction given by the Cascade Model. UMTRI has also developed a new eyellipse model (Manary et al. 1998), which, in its latest version, is also integrated with SAM. The new ASPECT posture prediction models, together with the other UMTRI models, provide consistent predictions of seat position distributions, driver eye location distributions, and individual posture predictions for use with human models. In the future, head location models based on the eyellipse, and hence integrated with the other models, are anticipated.

One additional change in the model formulation is that eye location with respect to hip position is predicted using the angle of the hip-to-eye vector and the side-view distance between the two points. In previous versions, the X and Z offsets between the eye and hip were predicted. The new formulation is believed to provide a better demonstration of the effects of the relevant vehicle, seat, and anthropometric variables on torso recline by capturing more directly the underlying kinematics.

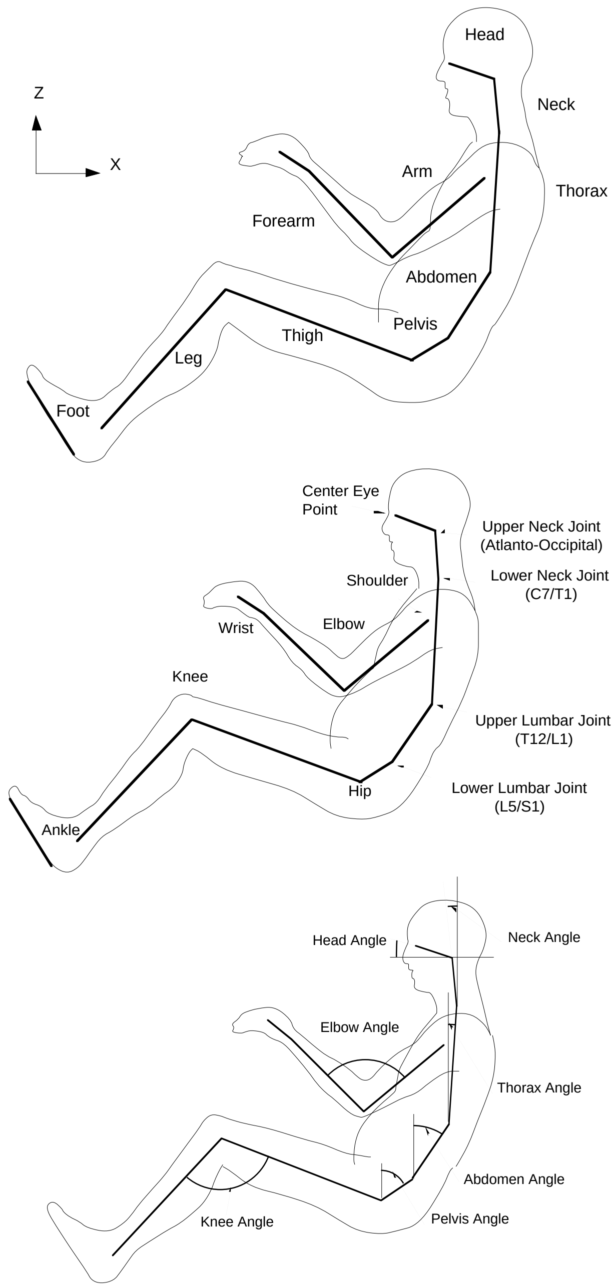

Figure 3. Definitions of kinematic linkage and posture measures. Angles referenced to horizontal or vertical are XZ (sagittal) plane angles. Angles between segments (elbow angle, knee angle, and ankle) are measured in the plane of the segments.

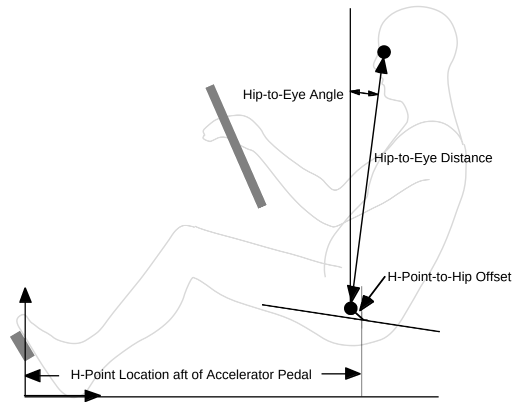

Figure 4. Primary dependent measures predicted by the Cascade Model.

The ASPECT posture prediction models are produced at a time when all vehicle design is done using the currently available SAE H-point manikin and other tools, but plans are underway to adopt the new ASPECT manikin as a replacement for the current machine. To facilitate both immediate and long-term use, the ASPECT posture prediction models have been developed for consistent application using either the current SAE or the new ASPECT manikin and associated dimensions (see Reed et al. 1999d for a review of the new measurement and design concepts). The ASPECT manikin adds one additional important measurement of seat geometry: lumbar support prominence (LSP). LSP has a minor effect on occupant posture, but also influences the offset between the ASPECT and J826 manikin H-points. In general, the ASPECT manikin H-point lies further rearward on a seat relative to the J826 H-point as LSP increases (Reed et al. 1999a). When LSP is zero, the J826 and ASPECT H-points are approximately coincident. LSP must therefore be taken into account in the posture prediction, particularly with respect to H-point-to-hip offset.

1.3.2 Model Variables

The ASPECT driver and passenger posture studies explored a wide range of vehicle package and seat design factors that were known or anticipated to affect occupant posture. Detailed analyses of the data led to the selection of the most important factors for inclusion in the posture prediction models. The model inputs are defined in Tables 1 and 2 and illustrated in Figure 5. The reference points for several of the dimensions are different under the ASPECT system (Pedal Reference Point replaces Ball of Foot, for example), but the actual values of the analogous dimensions are assumed to be unchanged. As noted above, the ASPECT manikin measures Lumbar Support Prominence, which is an input to several model equations. Occupant anthropometry is represented using stature (standing height), erect sitting height, and body weight (all without shoes). These dimensions are used to construct two anthropometric predictors that are less correlated with stature and therefore provide more robust predictive ability. The ratio of sitting height to stature represents the relative “limbiness” of an individual, and Body Mass Index (BMI) represents weight-for-stature. A person with a high BMI is heavier for their stature than a person with a lower BMI.

Table 1
Vehicle and Seat Variables for Posture Prediction

Current J826/J1100 Inputs	ASPECT Inputs	Definition	Symbol
Seat Height		Vertical distance between the seating reference point (SgRP) and the heel surface (accelerator heel point) when the SgRP is located at the intersection between the mid-height H-point travel path and the SAE J1517 95^{th}-percentile accommodation curve.	H
	Seat Height	Vertical distance between the seating reference point (SgRP) and the heel surface (accelerator heel point) when the SgRP is located at the mid-height intersection between the SgRP locator line defined in Reed et al. (1999d) and the H-point travel path. See Figure 4.	H
Steering Wheel Fore-aft Position		Horizontal distance in the side-view plane between the Ball of Foot and the intersection between the steering column axis and the front plane of the steering wheel rim (SAE L6)	SWX
	Steering Wheel Fore-aft Position	Horizontal distance in the side-view plane between the Pedal Reference Point and the intersection between the steering column axis and the front plane of the steering wheel rim. Pedal Reference Point is defined in Reed et al. (1999d).	SWX
Seat Cushion Angle		Angle of depressed seat cushion measured using legless manikin procedure in SAE J826 (L23). If adjustable, use the middle value of adjustment range that is available with the seat at SgRP.	CA
	Seat Cushion Angle	Angle of depressed seat cushion measured using the ASPECT manikin and procedures described in Roe et al. (1999).	CA
Back Angle		Angle of seatback (torso angle) obtained using J826 manikin (L40). This variable is an input to the posture prediction models only for seats with fixed seatback angles.	BA
	Back Angle	Angle of seatback obtained using ASPECT manikin and procedures described in Roe et al. (1999).	BA
	Lumbar Support Prominence	Lumbar Support Prominence measure obtained using ASPECT manikin and procedures described in Roe et al. (1999). Measure is made at 23-degree back angle for	LSP

		seats with adjustable seatback angle.	
Transmission Type	Transmission Type	This binary variable is used to account for the effect of manual transmissions (presence of a clutch) on driver-selected seat position. The variable assumes the value of 1 for manual transmissions, 0 for automatic transmissions (no clutch).	T
	Cushion Stiffness	Categorical measure of the seat cushion foam stiffness; can assume values of “soft”, “firm”, or “typical”, coded numerically as –1, 1, and 0, respectively.	CS
Accelerator Pedal Position		Lateral offset from the driver seat centerline to the lateral center of the accelerator pedal at the height of the Ball of Foot reference point.	PRPY
	Accelerator Pedal Position	Lateral offset from the driver seat centerline to the lateral center of the accelerator pedal at the height of the Pedal Reference Point.	PRPY

Table 2
Anthropometric Variables for Posture Prediction

Variable (Abbreviation)	Definition (units)
Stature (S)	Erect standing height without shoes (mm)
Sitting Height (SH)	Erect sitting height, measured from rigid horizontal sitting surface to top of head (mm)
Weight or Mass	Body mass with clothing, without shoes (kg)
Body Mass Index (BMI)	Derived quantity obtained by dividing body mass in kg by stature in meters squared (kg/m^2). Used as a measure of weight-for-stature.

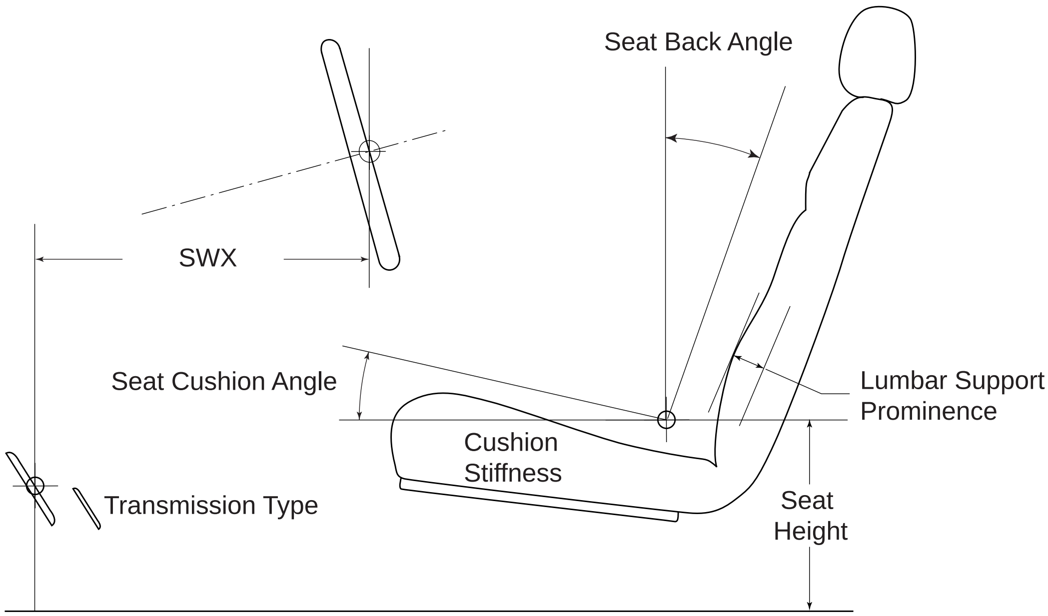

Figure 5. Illustration of seat and package input variables.

2.0 METHODS

2.1 Data Sources

The data used to develop the ASPECT posture prediction models were obtained from seven ASPECT posture studies and two previous UMTRI studies. Table 3 lists the studies, number of subjects, and major test factors. The data collection methods for the ASPECT studies are described in Manary et al. 1999. Procedures for the other two UMTRI studies were similar, and resulted in data that could be analyzed in the same ways. All of the studies included male and female subject with a wide range of anthropometry, except that the ASPECT Laboratory Passenger Posture study included only midsize males and the Manikin Validation study used only men with a wide range of stature.

Table 3
Data Sources

Study	Number of Subjects	Primary Test Factors
ASPECT Driver Posture	68	Seat Height, Steering Wheel Position, Seat Cushion Angle, Seat Type
ASPECT Seat Factors I	24	Lumbar Support Prominence, Lumbar Support Height
ASPECT Seat Factors III	48	Lumbar Support Prominence, Lumbar Support Height, Seat Cushion Angle, Seat Cushion Length, Seat Cushion Stiffness
ASPECT Laboratory Passenger Posture	15	Seat Type, Seatback Angle
ASPECT In-vehicle Passenger Posture	24	Vehicle, Front/Rear Passenger
ASPECT Manikin Validation	30	Seat Type (12 production seats)
UMTRI/AAMA H-Point Study	40	Seat Type, Seatback Angle
UMTRI/AAMA Driver Posture Study	120	Five vehicles spanning a wide range of seat height, steering wheel position, and other factors

2.2 Analysis Methods

The basic data from these studies are three-dimensional body landmark locations relative to the seat and package. The body landmark locations are used to estimate anatomical joint center locations, which define a kinematic-linkage representation of the body. Details of the calculation methods are presented in Reed et al. 1999c. A number of posture variables are defined from the landmarks, joint locations, and body segment orientations, as described in Figures 3 and 4.

The effects of the independent variables, such as seat height and lumbar support prominence, on the subjects' postures are determined using standard Analysis of Variance (ANOVA) and linear regression techniques. The analysis proceeded in two phases. In the first phase, a within-subjects analysis was conducted using ANOVA to examine the factor effects and potential interactions with as much sensitivity as possible. In general, the studies with 20 or more subjects provide sufficient statistical power to detect significant within-subject effects that are considerably smaller than those having meaning for vehicle design (on the order of 1 mm or 0.1 degree).

The within-subjects ANOVA gains its statistical strength by correcting for each subject's average response. This approach provides a good estimate of, for example, the average effect of lumbar support prominence on lumbar spine flexion across subjects, but does not provide an understanding of why particular subjects' average postures differ. In the regression analysis (general linear model), subjects are characterized by selected anthropometric descriptors, and the effects of these variables on the posture are considered along with the seat and package variables. Previous analyses have demonstrated that most of variance in anthropometric measures associated with vehicle accommodation can be captured using only gender, stature, weight, and erect sitting height, or combinations of these variables (Manary et al. 1999). It might seem that the inclusion of additional anthropometric variables would improve the prediction, but repeated investigations in ASPECT and other studies have shown that additional variables beyond those listed above rarely add substantially to a posture analysis. Further, it is impractical to specify a design population on more than a few anthropometric variables, so the utility of including additional variables is negligible.

The design of the ASPECT and other experiments is such that the possibility of interactions between various within- and between-subjects effects can be investigated. For example, the Seat Factors III study examined whether lumbar support prominence produced different postural affects at different seat cushion angles. In all of the studies with anthropometrically diverse subject pools, potential interactions between test factors and anthropometric variables can also be assessed. In general, however, few interactions have been found to be statistically significant, and none have been found to be important for posture prediction. In the extensive data analyses conducted for the ASPECT program, no true interactions have been found in which a factor has an opposite effect at two levels of another factor. Instead, the statistically significant interactions are matters of degree. For example, the effect of lumbar support prominence on hip-to-H-point offset in the Seat Factors III study differs slightly within subjects at different cushion angles. These interactions are never significant, however, when a between-subjects analysis is conducted, using anthropometric variables to characterize the subjects. Consequently, the prediction models presented in this report contain no interaction terms; all factor effects are additive.

The prediction models are also exclusively linear, with no higher-order terms. There have been few opportunities to investigate nonlinearities in seat and package factor effects, because of the need to have data from more than two factor levels. However, the two most important package factors, seat height and steering wheel position, have been investigated at three to five levels, and no nonlinearities have been observed. The large range of anthropometric variables also allows assessment of potential nonlinearities in the effect of, for example, erect sitting height on torso recline. However, no anthropometrically related nonlinearities have been observed.

The ASPECT posture prediction models were generated by a “meta-analysis” procedure, which combines findings from a number of studies to obtain a model accounting for as many factor effects as possible. This procedure is necessary because the research was conducted as a number of discrete studies, each having different combinations of factors and levels. In most cases, a basic model was generated from one study and amended slightly using results from other studies. In a few cases, where factor effects were estimated in more than one study, an average factor effect was used in the final prediction model.

In all cases, factors included in the final model were significant in the original ANOVA and regression analyses with $p < 0.01$. However, some effects that are significant at that level but account for only a small amount of postural variance were excluded. The principle of parsimony was employed routinely in an attempt to create prediction models as simple as possible but nonetheless capturing the important research findings. This process is necessarily somewhat subjective, but guided by the statistical findings. Because the meta-analysis combines results from several different statistical analyses, R^2 values and residual variance estimates are not available for the complete models (although they could be generated from selected datasets). However, for each predicted variable (e.g., driver hip-to-eye angle), the summary statistics are supplied for the core regression model that includes the most important factor effects. The true model fit can be expected to be only slightly better than that reported for the core model. The best assessments of model performance, however, are the comparisons between the model predictions and actual vehicle occupant postures, which are presented in Section 3.7.

The selection of predictors was also guided to some extent by the desire to have a uniform set of input variables. For example, anthropometry inputs are stature, Body Mass Index, and the ratio of erect sitting height to stature. In some cases, a regression analysis could attain a slightly higher R^2 value using weight or sitting height directly. However, a combination of stature and the sitting-height-to-stature ratio was used to preserve consistency with the other models. In no case is the predictive ability of the models substantially degraded by this approach.

One of the most important observations from the analyses is that considerable postural variance remains unpredicted by seat, package, and anthropometric effects. The best of the prediction models have R^2 values in the range of 0.75, leaving approximately 25% of the variance unaccounted for. This residual variance means that there is considerable uncertainty in the prediction of posture for any individual. The posture models predict the mean values of posture variables expected under the input conditions, which can be interpreted as the average or mostly likely posture. However, the user should be aware that the predicted posture is only one of a large range of postures that can be expected, even from an anthropometrically homogeneous population. The implications of the residual posture variance for vehicle design are considered in the Discussion.

2.3 In-Vehicle Comparison Data

Most of the data in the ASPECT studies were collected in laboratory vehicle mockups. Such experiments provide an opportunity to vary seat and vehicle parameters independently over a wide range, but the lack of an actual driving task and the rest of the dynamic vehicle environment may result in small differences between laboratory postures and actual vehicle occupant postures. To account for this possibility, data from a previous UMTRI/AAMA study of in-vehicle driving postures were used to adjust and validate the findings from the laboratory studies.

In that study, body landmark locations were recorded from 120 drivers in each of five vehicles. The sixty men and sixty women spanned a wide range of stature, from less than 5^{th}-percentile female to more than 95^{th}-percentile male for the U.S. adult population.

Each subject drove the vehicles over a road route, after which their preferred driving posture was recorded. Although these vehicles were equipped with six-way power seats, the data used in this analysis were obtained with the seats restricted to two-way (fore-aft) seat track travel.

These data were used in two ways. First, similar analyses were conducted with the laboratory and in-vehicle data to determine ways in which the laboratory postures differed from actual driving postures. These analyses typically resulted in the calculation of a small correction factor to be applied to the models developed in the laboratory. Second, the in-vehicle data were used to obtain estimates of the overall accuracy and precision of the posture-prediction models for drivers.

3.0 RESULTS

3.1 Overview

The Cascade Model is comprised of a series of individual models, most of which are linear equations relating input variables to posture variables. Separate models are available for use with current SAE dimensions and with the new ASPECT manikin and dimensions. These two sets of models are designed to give essentially the same results for a particular vehicle condition.

Driver posture is predicted in a stepwise (cascade) process, as follows:

1. Predict fore-aft seat H-point location.
2. Predict hip joint location with respect to H-point.
3. Predict eye location with respect to the hip joints.
4. Fit the torso segments using heuristically guided inverse kinematics (IK).
5. Fit limb postures using data-based heuristics and IK.

The first three steps form the core of the Cascade Model, because they are independent of any particular kinematic representation of the body and can be applied to any CAD manikin. The remaining two steps, fitting torso and limb segments, are described as they are applied using the ASPECT kinematic linkage. Some modification to these methods will be necessary to use them with other human models, but the results should be substantially equivalent if the core of the Cascade Model is applied first. The following sections describe the derivation of each of the submodels. Appendix A includes a concise listing of the equations, and Appendix B presents some usage examples. Note that all input and output variables in these models are reported in units of millimeters or degrees.

3.2 Occupant-Selected Seat Position

3.2.1 Drivers

Driver-selected seat position is predicted using the extensively validated Seating Accommodation Model (SAM) developed previously at UMTRI (Flannagan et al. 1996, 1998). SAM can be used to predict the most likely fore-aft seat position of drivers as a function of vehicle interior geometry and stature. SAM was developed using SAE-defined measurements of the vehicle interior. However, using conversion relationships developed in the ASPECT program, the model can be readily adapted for use with ASPECT measurements. The following assumptions are made:

- The Ball of Foot reference point used in SAM is equivalent in fore-aft position to the Pedal Reference Point used for ASPECT dimensions.
- The seat height variable in SAM is equivalent to the seat height dimension defined for ASPECT (see Table 1).
- The fore-aft position of the SAE J826-manikin H-point relative to the seat can be related to the ASPECT manikin location using a regression relationship with lumbar support prominence presented in Reed et al. (1999a).

Using the current SAE measurements, the fore-aft driver-selected H-point location is given by (Flannagan et al. 1998):

$$\text{HPtXJ826} = 16.8 + 0.433\ S - 0.24\ H - 2.19\ CA + 0.41\ SWX - 18.2\ T \qquad [1]$$

where

HPtXJ826 is the position of the seat J826 H-point aft of the Ball of Foot reference point,
S is the driver stature (mm),
H is the seat height (mm),
CA is the seat cushion angle (degrees),
SWX is the fore-aft steering wheel position (mm), and
T is the transmission type (0 = automatic, 1 = manual).

To use the ASPECT measurements, the relationship given by Reed et al. (1999a) is used to obtain the fore-aft offset of the ASPECT H-point from the J826 H-point as a function of lumbar support prominence:

$$\text{ASPECT H-Pt (X)} - \text{J826 H-Pt (X)} = 1.14\ LSP - 4.3 \qquad [2]$$

where LSP is the seat lumbar support prominence measured with the ASPECT manikin with the seat back (manikin torso) angle set to 23 degrees. This equation indicates that the ASPECT H-point lies increasingly rearward of the J826 manikin H-point as the lumbar support prominence increases. Accordingly, the value given by the H-point offset equation is added to SAM to predict ASPECT manikin H-point locations selected by drivers:

$$\text{HPtXASPECT} = 12.5 + 0.433\ S - 0.24\ H - 2.19\ CA + 0.41\ SWX - 18.2\ T + 1.14\ LSP \qquad [3]$$

Note that these two relationships are intended to predict the same physical seat position, but the H-point locations relative to the seat frame are different unless the lumbar support prominence is near zero.

If the seat has vertical adjustment, the H-point height (J826 or ASPECT) is set at the middle of the range available at the fore-aft H-point location calculated above. If the seat cushion angle is adjustable, it is set to the middle of the travel range available and that value is used as input for the rest of the posture prediction.

3.2.2 Front-Seat Passengers

An in-vehicle study was conducted to compare front-seat passenger seat positions with driver seat positions. A set of 24 men and women who had previously been tested as drivers in a set of vehicles were recruited to ride as passengers over a short road route (Manary et al. 1999). The initial passenger seat position was set to the same position near the middle of the track as was initially set for driver testing.

On average, subjects selected seat positions as front seat passengers that were closer to the middle of the track than they did as drivers. A regression function gives the average offset between driver and passenger seat position as a function of stature:

$$\text{DriverPassengerHPtOffset} = -0.243\ S + 430,\ R^2 = 0.22 \qquad [4]$$

To predict front-seat passenger seat position, add the DriverPassengerHPtOffset to the predicted driver seat position. This procedure will result in passenger seat position moving with, e.g., changes in steering wheel position, which is unrealistic. Yet, the method provides consistency between driver and passenger predictions. In general, the in-vehicle testing suggests that passengers can tolerate a much larger range of seat positions than can drivers, because they have few physical restrictions on hand and foot locations. More research will be necessary to develop an independent model of passenger-selected seat position.

3.3 Hip-to-H-Point Offset

The locations of vehicle occupants' hips (approximate hip joint centers) with respect to the H-point locations given by the J826 H-point machine and the new ASPECT manikin are of critical importance in interpreting the manikin measures for seat and vehicle design. In general, human hip locations are forward and above the measured H-point locations, and there is considerable variability among people. An UMTRI study prior to the ASPECT program found that hip locations were, on average, about 8 mm above and 13 forward of the J826 H-point location (Manary et al. 1994). These data were collected from 40 men and women in three driver seats at a 14.5-degree seat cushion angle and three fixed seatback angles of 19, 23, and 27 degrees.

The ASPECT studies show considerably larger fore-aft offsets, with both driver and passenger hip locations averaging about 45 mm forward of the H-point. A considerable amount of analysis of this observation has been conducted to determine if the measurements are accurate and if they are reasonable predictions for actual in-vehicle postures. The conclusion of these analyses is that the experimental measurements accurately represent the test subjects' postures, and, with small corrections, the resulting predictive models are applicable to in-vehicle postures. Recognizing both the importance and unexpected character of these findings, an overview of some of the hip location analyses is presented here.

3.3.1 Reanalysis of UMTRI/AAMA H-point Study Data

The data from the original UMTRI/AAMA H-point study data (Manary et al. 1994) were reanalyzed, using the ASPECT hip-joint calculation routines (Reed et al. 1999c). Table 4 shows the mean hip location with respect to J826 H-point for midsize males, comparing the original calculations with the new calculations. The ASPECT methods estimate the human hip locations to be about 10 mm above and about 12 mm forward of the original calculations. The differences may be due to the different flesh margins assumed in the ASPECT algorithms and slightly different pelvis geometry assumptions (see Reed et al. 1999c).

Table 4
Hip-to-J826-H-Point Offsets Calculated for Midsize Males in UMTRI/AAMA H-Point Study Data (mm)

Method	HipX-HPt (s.d.)	HipZ-HPt (s.d.)
Original Calculations	-14.4 (18.7)	6.5 (10.0)
ASPECT	-26.2 (17.7)	16.2 (10.1)

3.3.2 Hip-to-H-Point Offsets in Other Studies

Table 5 shows the hip-to-J826-H-point offsets from several UMTRI studies (midsize males only). The values are averaged across test conditions, so the effects of factors such as seat cushion angle are averaged out, but with a likely increase in variance.

Table 5
Hip-to-J826-H-Point Offsets Calculated for Midsize Males in Several Studies (mm)

Study (Number of Subjects)	HipX-HPt (s.d.)	HipZ-HPt (s.d.)
UMTRI H-Point (ASPECT Method)	-26.2 (17.7)	16.2 (10.1)
ASPECT Driver Posture	-48.3 (32.8)	9.1 (15.3)
ASPECT Seat Factors III	-56.0 (33.6)	7.8 (18.3)
ASPECT Laboratory Passenger	-39.6 (31.3)	16.8 (15.2)
ASPECT Manikin Validation	-51.0 (30.4)	6.2 (10.8)

All of the subsequent studies put the average midsize-male hip location further forward than the original UMTRI/AAMA study (using the same calculation algorithm). The vertical positions are more similar. The most similar location was observed in the

Laboratory Passenger study, which used fixed (imposed) seatback angles and the same seats as were used in the original H-point study. Note that the standard deviation of the fore-aft position is about twice as great in the ASPECT studies.

The trends toward more forward hip locations and increased variability are linked. The most rearward hip location on a seat available to a sitter is constrained by the geometry of the sitter's buttocks and pelvis and the location and shape of the seatback. The most rearward possible hip location will be obtained when the sitter chooses a maximally upright pelvis posture and slides maximally rearward on the seat. Reed et al. (1995) demonstrated that the average most-rearward hip location can be as much as 29 mm rearward of a average preferred hip location, depending on the seat contour. Although the most rearward possible hip location is constrained by the seat, forward hip movements are largely unconstrained. A sitter may readily and comfortably sit with his or her hips 50 to 100 mm forward of the most rearward position obtainable. Thus, the hip location data relative to H-point generally show a skewed distribution, with a much longer tail toward the front of the seat. Figure 6 shows the distribution of hip locations relative to J826 H-point from the ASPECT manikin validation study (30 men in 11 passenger car and light truck seats). The long forward tail pulls the mean offset forward of the median offset (-37 vs. -33 mm in Figure 6).

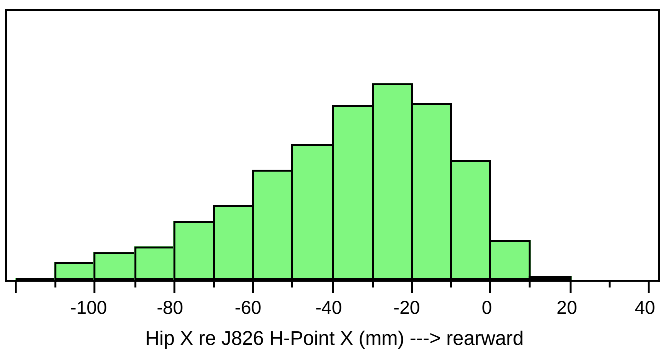

Figure 6. Distribution of fore-aft hip-to-J826-H-point offsets from the ASPECT Manikin Validation study (11 auto seats – one heavy truck seat excluded).

3.3.3 Thigh Segment Length

One possibility that could account for the large apparent hip-to-H-point offsets is that the ASPECT hip location calculation procedures are in error, and that the true hip joint location lies further rearward on the seat, closer to the H-point. One way to assess the accuracy of the hip location calculations is to examine the resulting thigh segment (hip-to-knee-joint) length. The knee joint location is estimated on a projection from the lateral femoral condyle landmark (see Reed et al. 1999c) for details). If the hip location was systematically estimated to be forward of its true location, the resulting thigh segment length would be shorter than expected.

Table 6 shows calculated thigh lengths (knee joint to hip joint) for three ASPECT studies. Where regressions on stature were significant, a solution for the ASPECT reference midsize male stature (1753 mm) was used, rather than the arithmetic mean. Table 6 also shows three comparison values obtained from a military anthropometric survey (Gordon et al. 1989), SAE J826, and a standard anthropometric reference (Webb Associates 1978). A typical estimate of the thigh segment length for a midsize U.S. male is 432 mm, which is very similar to the ASPECT studies. There does not appear to be a 30- or 40-mm discrepancy that would suggest a systematic error in the hip joint location calculations relative to the external landmarks.

Table 6
Calculated and Reference Midsize Male Thigh Segment Lengths

Study	Thigh Segment Length (mm)
Seat Factors III	429.0 (17.3)
Laboratory Passenger	433.6 (17.3)
Manikin Validation	430.2 (23.4)
ANSUR (Trochanterion height minus LFC height standing, regression on stature) (Gordon et al. 1989)	426
J826 (50th percentile)	432
Webb Associates (50th percentile male)	432

3.3.4 Comparison with In-Vehicle Data

The ASPECT data suggest that, in these laboratory studies, people sit with their hip joints forward of the H-point, indicating pelvis positions that are forward of those that would be required to place the hips at the H-point. The anterior-superior iliac spine (ASIS) landmarks on each side of the pelvis provide a useful measure of pelvis location that is independent of the calculation technique used to estimate hip joint locations. Comparing the fore-aft location of the mean (left-right) ASIS location with the J826 H-point gives a good comparison of pelvis position across studies.

Table 7 shows the fore-aft distance between the mean of the ASIS landmarks and the translated H-point for four ASPECT studies, the earlier UMTRI/AAMA H-point study, and five vehicles. In the original H-point study, the measured ASIS position was 7 mm rearward of the H-point on average, while in the ASPECT studies and in the vehicles, the average ASIS position was always forward of the J826 H-point. This suggests that the subjects in the original H-point study sat in a slightly atypical posture for driving, possibly because the seatback angle was fixed rather than adjustable. The ASIS-to-H-point offset in the vehicles is very consistent, with the ASIS an average of 6 mm forward of the H-point with a standard deviation of about 25 mm. The ASPECT manikin validation study, in which subjects sat in 12 different seats with a single driving package typical of a midsize sedan, produced comparable results (average –7.4 mm offset). In the other ASPECT studies, the ASIS locations are further forward, on average. This likely resulted from the fact that the test conditions were altered extensively, inducing different postures on the same seat. As noted above, posture changes will tend to bias the hip location average forward. This analysis indicates that the hip location offsets from the manikin validation study are likely to be most similar to those of actual drivers in vehicles. Referring to Table 5, the average fore-aft hip-to-J826-H-point offset in the manikin validation auto seats is -30.4 mm in driver postures (-43.1 mm in passenger postures). Since this analysis suggests that these are reasonable average values for in-vehicle conditions, the prediction models are constructed to produce these values for typical vehicle, seat, and anthropometric conditions. Seat, package, and anthropometric factors affecting the hip-to-H-point offset are then applied to these target averages.

Table 7
ASIS Landmark Locations in Several Posture Studies (Driver Postures Only)
(all subjects and conditions)

Study	ASISX-HPtX*	ASISZ-HPtZ
UMTRI/AAMA H-Point	7.0 (15.8)	87.7 (9.9)
ASPECT Driver Posture	-25.5 (32.0)	88.1 (15.6)
ASPECT Seat Factors	-32.2 (21.0)	98.9 (12.0)
ASPECT Manikin Validation	-7.4 (17.8)	101.5 (13.0)
Avenger	-8.8 (23.6)	94.1 (17.9)
Laser	-5.2 (26.1)	93.3 (18.1
LHS	-2.4 (25.5)	95.9 (17.2)
Grand Cherokee	-6.9 (25.4)	90.1 (16.2)
Voyager	-5.0 (24.6)	100.8 (15.6)
In-Vehicle Average	-5.7 (25.4)	94.8 (17.0)

*Positive values indicate ASIS is rearward of H-point. Standard deviations in parentheses.

The vertical ASIS-to-H-point values are similar across the laboratory and vehicle data. Table 7 shows that the vehicle average of 94.8 mm is near the middle of the range observed in the vehicle studies. A regression model created from the Driver Posture Study data using BMI and SWX as predictors predicts an average value of 92.3 mm for the in-vehicle conditions, very close to the observed average of 94.8. Thus, the vertical pelvis positions observed in the laboratory appear to be representative of vertical positions observed in actual driving conditions. The regression models for vertical hip-to-H-point-offset obtained from the laboratory studies are therefore used without modification.

3.3.5 Prediction Models

The strongest anthropometric predictor of hip location with respect to H-point is Body Mass Index (BMI). Body Mass Index is a measure of weight-for-stature, and is calculated by dividing body mass in kilograms by the stature in meters squared. A typical BMI is about 25, with a very thin person having a BMI of about 20 and BMIs above 30 associated with obesity. Based on ASPECT data, a person with a high BMI, and typically a greater amount of body fat in the buttock region, tends to sit with his or her hips further forward on the seat, relative to the H-point.

The other important predictor of horizontal hip-to-H-point offset is the seat cushion angle. In the Driver Posture study, the coefficient of the effect is about 5.0 mm/degree, with the hips moving rearward on the seat with higher cushion angles. In Seat Factors Study III and the Manikin Validation Study, the effect is smaller, estimated at about 1.1 mm/degree and 2.5 mm/degree, respectively. Because only two seats were used in the Driver Posture study, and no other modifications to the seat geometry were made, the Driver Posture estimate is probably near a maximum value of the effect. However, across seats in which a variety of other factors also differ, a more moderate value is probably appropriate.
For drivers, the steering-wheel fore-aft position is an important predictor of vertical hip position with respect to H-point. The coefficient is positive, meaning that larger steering-wheel-to-pedal distances result in the hips lying higher on the seat relative to the H-point. Considered in conjunction with the torso recline-angle prediction models (below), this result indicates that a more forward steering wheel position tends to pull drivers more upright, causing them to sink slightly further into the seat cushion. Note that the steering wheel position effect may to some extent reflect a seat height effect, since seat height is correlated with steering wheel position across vehicles. This does not reduce the effectiveness of the model, but rather reflects the dominant role of steering wheel position in determining driver posture.

Following the rationale described above, the typical fore-aft hip-to-J826 offset for drivers is -30.4 mm. This is assumed to apply to a person with a BMI of 24.6 (the mean of the subjects in the ASPECT Driver Posture Study) and for a seat cushion angle of 14.5 degrees (the mean of 11 and 18 degrees, the two angles used most commonly in these studies). The anthropometric, vehicle, and seat factor effects are used to adjust the typical value to apply to a specific case. To determine appropriate values for the effect coefficients, regression models were constructed from each of three ASPECT studies, shown in Table 8. As expected, the coefficients vary across the studies. Although there are a range of possible ways to compute an average effect across the studies (e.g., weighting by subjects, number of conditions, etc.), the simple arithmetic mean was chosen.

For driver postures, the resulting models are:

$$\text{HiptoJ826HPtX(Driver)} = -30.4 - 3.5*(\text{BMI}-24.6) + 3.0*(\text{CA}-14.5)$$

$$= 12.2 - 3.5\ \text{BMI} + 3.0\ \text{CA} \qquad [5]$$

$$\text{HiptoJ826HPtZ(Driver)} = 7.1\ (\text{mean of driver posture study}) + 1.2\ (\text{BMI}-24.6) + 0.1068\ (\text{SWX}-550) + 1.1\ (\text{CA}-14.5)$$

$$= -97.1 + 1.2\ \text{BMI} + 0.1068\ \text{SWX} + 1.1\ \text{CA} \qquad [6]$$

For adjustable-seat passenger postures, the fore-aft position is adjusted by subtracting 8.8 mm (increased forward offset of the hip from the H-point), and the vertical hip position is lowered by 3 mm.

HiptoJ826HPtX(Passenger) = -30.4 – 3.5*(BMI-24.6) + 3.0*(CA-14.5) – 8.8

= 3.4 – 3.5 BMI + 3.0 CA [7]

HiptoJ826HPtZ(Passenger) = 7.1 (mean of driver posture study) + 1.2 (BMI-24.6) + 1.1 (CA-14.5) – 3

= -41.4 + 1.2 BMI + 1.1 CA [8]

Table 8
Regression Models and Average Coefficient Values for
Hip Location with Respect to J826 H-Point

Variable	Intercept	Body Mass Index (kg/m^2)	SWX (mm)	Cushion Angle (deg)	Driver-Passenger	R^2_{adj}	RMSE
Driver Posture							
HipXreHPt	-62.9	-2.17		5.0		0.31	28.1
HipZreHPt	-108.0	2.08	0.1068	0.37		0.40	13.0
Seat Factors III							
HipXreHPt	42.9	-4.91		1.7	5.0	0.33	24.9
HipZreHPt	-44.5	1.55		1.8	-3.24	0.25	13.4
Manikin Validation							
HipXreHPt	14.2	-3.41		2.4	12.6	0.28	22.7
HipZreHPt	-2.3	0.0*		1.05	-2.92	0.04	13.7
Mean Effects:							
HipXreHPt		-3.5		3.0	8.8		
HipZreHPt		1.2		1.1	-3.08		

When used with ASPECT manikin measures, the predicted hip locations are interpreted with respect to the seat, so that the expected offset between the ASPECT and J826 H-points is applied to the hip predictions in a consistent manner. From Reed et al. (1999a), the offset between the J826 and ASPECT H-points is:

ASPECTHPtX – J826HPtX = 1.14 LSP – 4.3 [9]

ASPECTHPtZ – J826HPtZ = –0.24 LSP + 0.7 [10]

With positive lumbar support prominence (LSP), the ASPECT H-point is lower and rearward of the J826 H-point. Applying these expressions to the prediction equations given above, the hip-to-ASPECT-H-point offsets are given by the following equations:

HiptoASPECTHPtX(Driver) = 16.5 – 3.5 BMI + 3.0 CA – 1.14 LSP [11]

HiptoASPECTHPtZ(Driver) = -96.4 + 1.2 BMI + 0.1068 SWX + 1.1 CA + 0.24 LSP [12]

HiptoASPECTHPtX(Passenger) = 7.7 – 3.5 BMI + 3.0 CA – 1.14 LSP [13]

HiptoASPECTHPtZ(Passenger) = -42.1 + 1.2 BMI + 1.1 CA + 0.24 LSP [14]

3.4 Hip-to-Eye Angle and Distance

Eye location is determined by computing the angle and length of a side-view line segment connecting the hip and eye (see Figure 4). The eye location could instead be represented by X and Z offsets from the hip, but the chosen method better conveys the concept of torso recline and better models the underlying kinematic linkage. For drivers, hip-to-eye angle and hip-to-eye distance are predicted using regression functions developed from the Driver Posture Study (Manary et al. 1999), with adjustments determined by comparison to in-vehicle driver data. Equations for passenger postures were developed from the Seat Factors III and Manikin Validation studies.

For front seat passengers, the regression models were developed using data from Seat Factors Study III (Manary et al. 1999). Front seat passengers are unaffected by steering wheel position, the primary vehicle dimension affecting driver torso posture. Body proportions still have an important effect, however.

3.4.1 Lumbar Support Prominence Effects

Increased lumbar support prominence creates small reduction in lumbar spine flexion that alters the hip to eye distance slightly. In Seat Factors Study II, lumbar support prominence was varied over a large range on a test seat with minimal seatback padding intended to maximize the effect of lumbar support prominence. Lumbar support prominence was set to prominences of 3 and 27 mm, as measured by the ASPECT manikin. The resulting within-subject average reduction in lumbar spine flexion of 5.4 degrees is similar to the 6-degree reduction in lumbar spine flexion observed in an earlier study with the same test conditions (Reed et al. 1996). The hip-to-eye angle did not change significantly with the increase in lumbar support prominence, but the distance from hip to eye increased by an average of 7.2 mm.

In Seat Factors Study III, the lumbar support prominence was set to levels of 20.5 and 30.3 mm, as measured by the ASPECT manikin. (These values are averaged across levels of the other factors; changes in seat cushion angle, for example, can alter the measured lumbar support prominence, even though the backrest geometry does not change.) In this study, a 10-mm increase in lumbar support prominence increased the average hip-to-eye distance by 2.4 mm, a slope of 0.24 mm/mm compared with a slope from Seat Factors II of 0.3 mm/mm. As in Seat Factors II, there was no significant effect of lumbar support on hip-to-eye angle. Based on these findings, a lumbar support prominence effect is included in the hip-to-eye distance prediction.

3.4.2 Cushion Stiffness

In Seat Factors Study III, two cushion stiffness levels were tested over a range of other test conditions. On average, the two stiffnesses produced only small differences in posture. The hip-to-eye angle averaged 1.2 degrees more upright with the soft cushion than with the firm cushion. The predictive equations above should be consider to apply to typical seat cushion stiffnesses. The hip-to-eye angle prediction may be increased by 0.6 degrees for a particularly firm seat, or decreased by 0.6 degrees for a particularly soft seat.

3.4.3 In-Vehicle Data Correction

Data from the five validation vehicles were used to determine if, as with the hip-to-H-point offset, some adjustment to the laboratory-based torso angle and length measures would be appropriate. The data from the Driver Posture study were used to create a regression model of the angle from ASIS to eye. This relationship was used to predict the ASIS-to-eye angle for each subject and vehicle. The average predicted angle was 7.8 degrees, while the average observed angle was 7.0 degrees, indicating that people the same size and in comparable package conditions sat an average of 0.8 degrees more upright after driving a vehicle than in the laboratory. A similar calculation for ASIS-to-eye distance indicated a mean of 536.1 mm for the in-vehicle data and an estimate of 551.3 mm for the in-vehicle subjects based on a regression model from the laboratory study. The difference, 15.2 mm, probably reflects additional slumping after driving the vehicles on the road, since the vertical ASIS to H-point distance is similar in vehicles and in the laboratory. Noting that the ASIS landmark lies approximately on the side-view line from hip to eye, corrections of –0.8 degrees and –15.2 mm were applied to the hip-to-eye angle and distance predictions, respectively, to match the in-vehicle data more accurately. These corrections are also applied to predict front-seat passenger posture (adjustable seatback angles), but are not applied to fixed-seatback angle conditions, for which equivalent dynamic data are not available.

3.4.4 Prediction Models

Because of the need to combine findings from several different studies, the prediction models for hip-to-eye angle and distance are constructed in a manner similar to that used for the hip-to-H-point offset. Regression models were generated from the driver posture study, to which additional predictors were added based on other study results.

For drivers, the hip-to-eye angle in side view with respect to vertical is given by

$$\text{HipToEyeAngle(Driver)} = -57.0 + 100.2\ \text{SH/S} + 0.0147\ \text{SWX} + 0.10\ \text{CA} + 0.136\ \text{BMI},\ R^2 = 0.19,\ \text{RMSE} = 3.9 \quad [15]$$

RMSE is the root-mean square error for the regression. Under the assumptions of linear regression the residual error is modeled as a normal distribution with zero mean and standard deviation equal to the root mean square error. Adding the vehicle-data and cushion-stiffness adjustments, the equation becomes:

$$\text{HipToEyeAngle(Driver)} = -56.2 + 100.2\ SH/S + 0.0147\ SWX + 0.10\ CA + 0.136\ BMI + 0.6\ CS \quad [16]$$

where CS takes on values of –1 for a soft seat, 0 for a typical seat, and 1 for a firm seat. See the Discussion for seat stiffness classification strategies. The equation is the same if ASPECT measures are used, since the inputs are unaffected by differences between current SAE and ASPECT measures.

From the Driver Posture study, hip-to-eye distance is given by

$$\text{HipToEyeDistance} = -403.3 + 0.3480\ S + 859.6\ SH/S,\ R^2 = 0.77,\ RMSE=20.9 \quad [17]$$

Adjusting to in-vehicle data, the equation becomes:

$$\text{HipToEyeDistance} = -418.5 + 0.3480\ S + 859.6\ SH/S \quad [18]$$

If the ASPECT manikin lumbar support prominence is available, the equation becomes

$$\text{HipToEyeDistance(ASPECT)} = -418.5 + 0.3480\ S + 859.6\ SH/S + 0.24\ (LSP - 19)$$

$$= -423.1 + 0.3480\ S + 859.6\ SH/S + 0.24\ LSP \quad [19]$$

where 0.24 is the slope of the lumbar support effect from Seat Factors Study III, and 19 is the average lumbar support prominence from the Driver Posture study.

For front seat passengers,

$$\text{HipToEyeAngle(Passenger)} = -34.0 + 82.2\ SH/S,\ R2 = 0.10,\ RMSE = 4.4 \quad [20]$$

Note that the low R^2 value indicates that this relationship is only slightly better than using the mean. For a typical SH/S ratio of 0.52, the passenger hip-to-eye angle is 8.7 degrees. The hip-to-eye distance for passengers is given by the same expression used for drivers.

3.4.5 Fixed Seatback Angles

For seats with fixed seatback angles, the manikin-measured back angle becomes an input to the posture prediction. Data to generate models for this condition were obtained from the Laboratory Passenger Posture Study (Manary et al. 1999) and the UMTRI/AAMA H-Point Study conducted prior to ASPECT (Manary et al. 1994). In the ASPECT study, the postures of 15 midsize men were measured at three different imposed seatback angles as they sat in passenger postures in three different seats. In the previous study, the same three seats and seatback angles were used to measure driving postures for 40 men and women ranging in stature from 1509 to 1846 mm.

The hip-to-eye angles of the midsize men in each study (15 in the passenger posture study, 12 in the driver study) were examined by seatback angle across seats. There is no statistically significant difference in the angle between studies, indicating that driver and passenger torso postures are similar when seatback angles are fixed. This observation supports the use of the UMTRI/AAMA H-Point Study data to develop a model of torso recline for fixed seatback angles, equally applicable to drivers and passengers, that includes anthropometric effects. (A similar model could not be generated from the ASPECT study because only midsize males were tested.)

The hip-to-eye angle for fixed seatback angles is given by

$$\text{HipToEyeAngleJ826} = -12.4 - 0.0135\ S + 62.1\ SH/S + 0.559\ BA,$$
$$R^2 = 0.54,\ RMSE = 2.41 \qquad [21]$$

The hip-to-eye distance for fixed seatback angles is given by

$$\text{HipToEyeDistJ826} = -208.7 + 0.3167\ S + 625.8\ SH/S - 1.21\ BA,$$
$$R^2 = 0.72,\ RMSE = 18.7 \qquad [22]$$

With the ASPECT manikin, seatback angle measurements are affected by the lumbar support prominence, so that the measured seatback angle is greater when the lumbar support prominence increases. From Reed et al. (1999a), the relationship between SAE J826 and ASPECT manikin seatback angles is approximately

$$\text{BA-J826} = \text{BA-ASPECT} + 0.209\ LSP \qquad [23]$$

Using this relationship, the hip-to-eye angle and distance for ASPECT applications with fixed seatbacks are given by:

$$\text{HipToEyeAngleASPECT} = -12.4 - 0.0135\ S + 62.1\ SH/S + 0.559\ (BA+0.209\ LSP)$$

$$= -12.4 - 0.0135\ S + 62.1\ SH/S + 0.559\ BA + 0.117\ LSP \qquad [24]$$

$$\text{HipToEyeDistASPECT} = -208.7 + 0.3167\ S + 625.8\ SH/S - 1.21\ (BA+0.209\ LSP)$$

$$= -208.7 + 0.3167\ S + 625.8\ SH/S - 1.21\ BA - 0.253\ LSP \qquad [25]$$

Comparison with a small set of rear-seat posture data from three vehicles with two different legroom restriction levels demonstrated that the hip-to-eye angle and distance given by these equations are reasonable predictions for rear seat occupants.

3.5 Torso Kinematics

The preceding sections give the essential predictions of the Cascade Model, i.e., H-point, hip, and eye locations. These variables are predicted first because they are the most important postural characteristics for vehicle interior design. Often, a design analysis can proceed using only this information, without determining the posture of the rest of the body. However, CAD manikin applications require specification of the large number of other postural degrees of freedom.

3.5.1 Cascade Model Kinematics

The Cascade Model uses inverse kinematics to fit the torso and limbs to the constraints defined by the task (steering wheel and pedal locations, for example) and the hip and eye locations given by the model. For the torso, the procedures use the observed relationships between overall torso recline and the orientation of individual segments. Using data from the Driver Posture Study, individual torso segment angles were regressed on hip-to-eye angle to determine how each segment moves as the torso reclines. Table 9 shows the regression slopes, giving the average change in segment angle as a function of overall recline. Table 10 lists the average angles over all conditions for use as a starting torso posture.

Table 9
Average Change in Segment Orientation with Change in Hip-to-Eye Angle

Segment	Slope Estimate*	Std. Error	Gamma Value
Head	-0.62†	0.62	0
Neck	0.477	0.082	0.399
Thorax	0.739	0.046	0.617
Abdomen	1.437	0.052	1.199
Pelvis	1.198	0.067	1

*Estimated change in segment orientation (degree/degree)
†Head orientation slope is not significantly different from zero ($p = 0.32$). All other slope estimates are significantly different from zero with $p<0.001$.

Table 10
Overall Average Torso Segment Angles

Segment	Angle Positive Rearward of Vertical (degrees)
Head	-68.5
Neck	2.0
Thorax	-3.6
Abdomen	32.9
Pelvis	63.4

The regression slopes can be used to reduce the problem of fitting the torso linkage to the predicted hip and eye locations to a two-degree-of-freedom problem that can be readily solved by gradient-based search techniques. One approach is described here, but others will give substantially similar results.

Since head orientation does not change significantly with torso recline in the range of interest, the location of the head-neck joint (upper neck joint) is first calculated using the scaled head segment length and the head angle from Table 10. The motion distribution given by the values of Table 9 can be expressed in terms of a segment motion distribution parameter vector γ, where γ is rate of change of the segment with respect to a change in pelvis orientation. The γ values are obtained by dividing each slope value in Table 5.7 by the pelvis slope value. Use of the γ distribution parameter reduces spine motion to a single degree of freedom, denoted by variable α. Adding a second variable β that describes rotation of the whole torso around the hip, the coordinates of the head/neck joint with respect to the hip are given by

$$HN(X) = \sum_{i=1}^{4} L_i Sin[\theta_i + \gamma_i \alpha + \beta] \quad [26]$$

$$HN(Z) = \sum_{i=1}^{4} L_i Cos[\theta_i + \gamma_i \alpha + \beta] \quad [27]$$

where the L_i are the lengths of the four segments between the hip and head/neck joint and the θ_i are the starting segment orientations from Table 10. In the UMTRI implementation, a fast gradient-based minimization procedure is used to determine the combination of α and β that fits the head-neck and hip locations to within 0.01 mm. Values of α and β are generally less than five degrees. The predicted torso segment angles are then given by
$\theta_i + \gamma_i \alpha + \beta$.

A variety of alternative methods for fitting the torso posture are possible. All will provide reasonably accurate torso segment orientations if the values from Table 10 are used as a starting point and the changes in segment orientation with overall torso recline (hip-to-eye angle) approximately follow the ratios given in Table 9. Some adaptation of the method described here will usually be necessary, since many models use a different torso linkage. Predicting the hip and eye locations using the methods described above prior to fitting the torso segments will ensure that different CAD manikins produce postures that are accurate in their most essential characteristics.

3.5.2 Body Segment Scaling

The success of the application of the values in Tables 9 and 10 to torso posture prediction is predicated in part on the scaling of the torso segments. Simply put, different relative dimensions among the torso segments will produce different postures when fitting to predicted eye and hip locations. Table 11 lists the scaling ratios used with the Cascade Model at UMTRI. Torso segments are scaled using erect sitting height and limb segments are scaled using stature, allowing people with different ratios of stature to sitting height to be simulated. If only stature is supplied, sitting height may be estimated for a typical North American population by multiplying by 0.52. Users of the Cascade Model are encouraged to investigate the effects of differences between their kinematic linkage scaling methods and the UMTRI methods to ensure that the results of their techniques are reasonably similar to the UMTRI findings.

Table 11
Segment Length Scaling Fractions

Segment	Stature Fraction	Sitting Height Fraction
Head		0.105
Neck		0.143
Thorax		0.300
Abdomen		0.224
Pelvis		0.105
Pelvis Width		0.168
Thigh	0.257	
Leg	0.237	
Arm	0.162	
Forearm	0.147	
Hand	0.046	

3.6 Limb Postures

Once hip and eye locations are predicted using the core Cascade Model equations, the limb postures can be fit using inverse-kinematics procedures guided by heuristics derived from ASPECT data.

3.6.1 Shoulder Locations

The ASPECT kinematic model of the vehicle occupant locates the shoulder (glenohumeral) joint using three translational degrees of freedom with respect to the thorax. That is, there is no rigid link connecting the shoulder joint and thorax. This simplification was made in recognition of the fact that shoulder model complexity varies widely depending on the range of intended applications. Analyses of data from the Driver Posture study show that, for drivers with their hands on the steering wheel, the shoulder joint lies on a vector angled an average of 15.4 degrees rearward of the vector from hip to eye (standard deviation 2.8 degrees). Seat, package, and anthropometric variables do not substantially affect this value. In Seat Factors Study III, this offset angle did not differ significantly between driver and passenger postures. Shoulder position can therefore be located to a reasonable level of accuracy by adjusting the model shoulder linkage to place the glenohumeral joint on a line 15.4 degrees rearward of the calculated hip-to-eye angle.

3.5.2 Leg and Arm Splay

For drivers, arm, forearm, and hand postures can be readily calculated using inverse kinematics. The shoulder location anchors one end of the kinematic chain, and the forearm and hand can be connected in a straight line (neutral posture) at the wrist. Hand location on the steering wheel varies widely within and between individuals and cannot be reliably predicted, so a range of hand postures are appropriate for ergonomic analyses (for example, for elbow clearance assessment). Arm splay is defined in ASPECT as the angle through which the forearm/hand and arm segments must be rotated about an axis passing through the shoulder joint and wrist joint locations to lie in a vertical plane, as shown in Figure 7. Based on the Driver Posture study, typical arms splay angles are well represented by the mean value of 8.6 degrees. However, there is considerable variance that is not accounted for by anthropometric or vehicle variables, so that the standard deviation is 10 degrees, and the 90th percentile is 18.6 degrees.

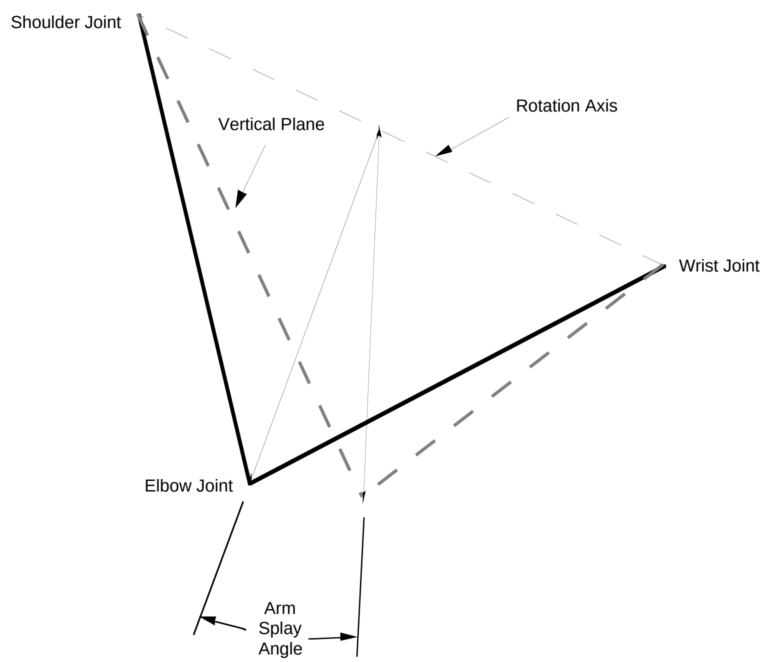

Figure 7. Definition of angle describing arm splay in three dimensions. Outward rotations (away from body centerline) are positive.

Leg splay angle is represented similarly, by calculating the angle that the leg and thigh must be rotated through around the hip-to-ankle axis to lie in a vertical plane, as shown in Figure 8. Some variables are significantly related to leg splay (stature, for example), but the maximum R^2 value attainable for a regression model in the Driver Posture study data is 0.09, indicating a very poor fit to the data. Consequently, the average value of 8.4 degrees is recommended. The standard deviation of 6.4 degrees and 90th-percentile value of 18.9 degrees may be used to assess the potential effects of intersubject variability on ergonomic analyses.

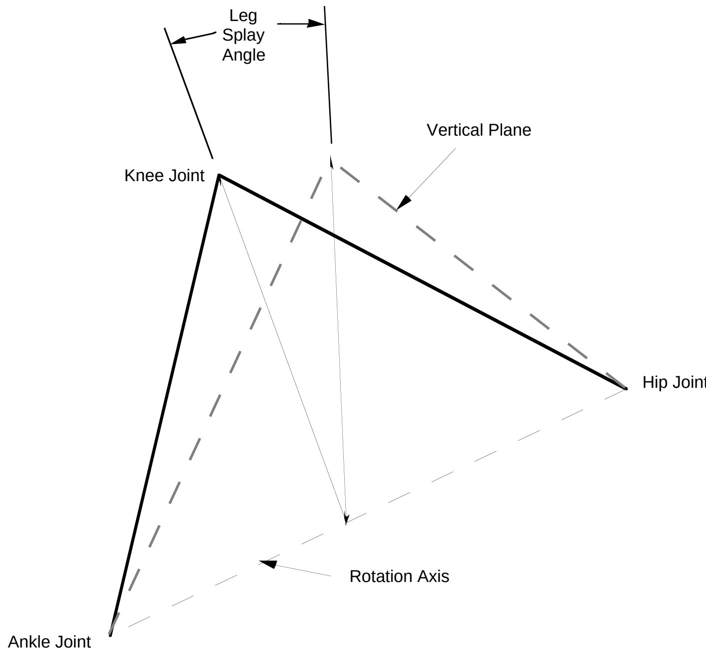

Figure 8. Definition of angle describing leg splay in three dimensions.

In a rear seat, the leg posture is dependent on the position of the front seat. Based on the rear-seat leg posture data gathered for ASPECT, a reasonable prediction for rear seat leg splay can be obtained by (1) placing the feet as far forward as possible under the front seat, and (2) splaying the legs outward at least the unrestricted (front passenger) value of 8.4 degrees or the minimum required to clear the front seatback.

3.6.3 Foot Posture

In general, drivers place their right heels to the left of the accelerator pedal centerline and angle their foot to the right to reach contact the pedal. The location of the heel contact with the floor is a useful measure by which to position a CAD manikin's right foot for driver simulations. Data from the five road-tested vehicles were used for this analysis. The location of the heel contact point aft of Ball of Foot or Pedal Reference Point is given by:

$$\text{HeelX} = -186.1 + 0.0425\ S + 357.3\ SH/S + 0.309\ H,\ R^2 = 0.27,\ \text{RMSE} = 28.8 \qquad [28]$$

The location of the heel contact to the left of the lateral center of the accelerator at the BOF/PRP is given by:

$$\text{HeelY} = 208.9 - 0.1441\ S - 0.297\ \text{PRPY},\ R^2 = 0.26,\ \text{RMSE} = 32.7 \qquad [29]$$

where PRPY is the lateral distance from the driver centerline to the lateral center of the pedal at the BOF or PRP. The heel is located more rearward with higher seat heights and taller drivers, or those with a greater ratio of sitting height to stature. Taller drivers also have their heels further to the left of the pedal, on average, and this offset increases as the accelerator pedal is moved further to the right of the driver centerline. The angle of the driver's foot can be set to a reasonable orientation by positioning the shoe to contact the bottom third of the accelerator pedal, the region typically contacted by drivers.

3.7 Head-Neck Joint Angle and Distance with Respect to H-Point for Head Contour Applications

A head contour has been developed for use with the ASPECT manikin, representing a side-view profile typical of a midsize male head. The ASPECT head contour is mounted on a tube that slides on the manikin torso rod and pivots around a joint corresponding to the human head-neck joint. The torso rod pivots at the hip, giving the head three degrees of freedom (XZ-plane position and orientation). A bubble level is provided to maintain the head orientation constant, leaving only the XZ position with respect to the H-point to determine.

For consistency with the other posture prediction equations, head position is predicted using a geometric transformation of the same predictions used for eye location. In the ASPECT data, the side-view distance from the head/neck joint to the eye point averages 0.105 times erect sitting height. From Table 10, the average head-neck-joint-to-eye angle is –68.5 degrees with respect to vertical for any seat and package condition.

The most accurate way of positioning the head contour is to use the posture prediction models to determine the hip and eye locations with respect to H-point (J826 or ASPECT), and then use the head length and angle to determine the head-neck joint location with respect to the predicted eye location. As an approximation, the H-point-to-head-neck-joint angle may be set to 4.7 degrees more reclined than the predicted hip-to-eye angle, and the H-point-to-head-neck-joint distance set to 97.3 percent of the predicted hip-to-eye distance.

When using these models to position the head contour, it is important to keep always in mind the large residual variance in eye/head location predictions. The following section comparing the model predictions to actual driver eye locations gives some concrete examples of the distribution of actual head positions relative to the predictions.

3.8 Driver-Selected Seatback Angle

The data from driver posture studies can be used to predict the seatback angle that will be selected by drivers with specified anthropometry in seat and package conditions of interest. The data from the Manikin Validation study are best for examining these trends, because eleven different passenger car and light truck seats were used. The seatback angles were measured using both the current SAE J826 manikin and the ASPECT manikin at the same physical seatback orientation. The subject-selected seatback angle was then calculated from the change in orientation of two reference points on the seatback, referenced to the manikin-measured angle.

The seatback angle is predicted as a rearward angular offset from the hip-to-eye angle (SBAHE). The best prediction of SBAHE for J826 manikin measured seatback angles is:

$$SBAHEJ826 = 83.1 = 131.0\ SH/S,\ R^2 = 0.29,\ RMSE = 3.2 \quad [30]$$

With the ASPECT manikin LSP measure, the prediction is improved:

$$SBAHEASPECT = 83.1 - 129.7\ SH/S - 0.267\ LSP,\ R^2 = 0.42,\ RMSE = 3.0 \quad [31]$$

In seats with more prominent lumbar supports, the difference between the ASPECT-manikin–measured driver-selected seatback angle and the sitter's hip-to-eye angle is reduced. With both manikins, however, there remains considerable variance due to subject torso posture preference. The residuals are approximately normally distributed with a standard deviation of about 3 degrees.

3.9 Model Comparison to In-Vehicle Data

The Cascade Model described above was exercised for the five vehicles used in on-road testing, inputting each individual subject's anthropometry into the model. The resulting predicted H-point and eye locations were compared to those observed, as shown in Table 12.

Table 12
Differences Between Model Predictions and Observed H-point and Eye Locations in Vehicles
Mean Observed Minus Predicted (Standard Deviation)

Vehicle	H-Point X (Obs-Pred)	Eye X (Obs-Pred)	Eye Z (Obs-Pred)
Avenger	-0.3(32.4)	-17.1 (48.3)	1.3 (18.5)
Laser	-10.9 (32.4)	-1.5 (43.5)	6.0 (16.9)
LHS	-0.4 (31.4)	-17.2 (48.5)	-0.9 (18.0)
Grand Cherokee	-1.2 (29.2)	4.0 (46.6)	-2.7 (18.7)
Voyager	-21.2 (37.4)	-8.1 (50.5)	19.3 (20.4)
Overall Mean	-6.8 (32.6)	-8.0 (47.5)	4.6 (18.5)
Overall Range	20.9	21.2	22

The H-point-X comparison is a measure of how well the Seating Accommodation Model (SAM) predicts the fore-aft driver-selected seat position. In general, the model works very well (see Flannagan et al. 1998 for a complete description and evaluation of SAM). The two larger average errors (Voyager, Laser) result from censoring at the rear of the seat track. When the taller third of subjects are excluded (those most likely to have insufficient rearward seat track travel), the mean error drops below 10 mm. Note that there is a fairly large residual variance, however. The implications for vehicle design of residual variance in the posture predictions are discussed below.

The mean eye location predictions are generally good, with most mean errors much smaller than one standard deviation. The only error large enough to have potential vehicle design implications is the vertical eye position in the Voyager, where the model predicts eye locations an average of 19.3 mm lower than observed. The problem with the model performance in this vehicle appears to be that the vertical hip-to-H-point offset predicted by the model is less than the actual offset. A forward steering wheel position reduces the vertical offset predicted by the model based on the laboratory analysis, but this trend is not observed in the vehicle data. However, since data from only five vehicles were analyzed, it is not possible to determine whether this is a deficiency in the model or merely one outlying vehicle.

The predictions from this version of the cascade model are slightly less accurate across vehicles than those of an earlier version (Reed et al. 1999b), because of the change in the prediction sequence. Specifically, the earlier model predicted eye location relative to hip location, with both prediction equations developed from the same source data. In contrast, the current version of the model uses SAM to predict seat position, then predicts hip location relative to H-point, followed by eye location relative to hip. This allows the hip-to-H-point predictions, which are least powerful predictive models, to influence the eye location predictions. The advantage of the current models, however, is that they can be integrated without conflict with SAM and the new UMTRI eyellipse model. Both SAM and the eyellipse have been developed and validated using much larger in-vehicle datasets, providing confidence that integration with them will ensure good prediction accuracy across a wide range of vehicles.

4.0 DISCUSSION

4.1 Model Application Ranges

The prediction models presented in this report draw on a large amount of previous work and represent an evolutionary advancement in the understanding of vehicle occupant posture. A considerable effort has been made to ensure that the postures resulting from these models are accurate representations of occupant postures in a wide range of vehicles. However, the models can be expected to be most accurate within the range of experimental test conditions on which they are based. Table 13 lists ranges of experimental parameters within which the models have been tested. In general, the models are expected to be valid for almost all Class A vehicles. Subject anthropometry spanned a range greater than 5^{th}-percentile female by stature to 95^{th}-percentile male, with ratios of sitting-height-to-stature from 0.48 to 0.56, and BMIs from 19 to 35. The models are expected to be valid within these anthropometric ranges.

Table 13
Application Ranges

Factor	Range
Seat Height	180 – 420 mm*
Steering Wheel to BOF (PRP) X	450 – 650 mm
Seat Cushion Angle	11 – 18 degrees
Lumbar Support Prominence	0 to 35 mm

* Testing in ASPECT included conditions up to only 360 mm seat height, but in-vehicle testing has demonstrated continuity throughout the Class-A seat height range (Flannagan et al. 1996, 1998; Manary et al. 1998).

There are a number of test factors whose effects on driver and passenger posture were either not significant or were judged to small enough to be negligible for posture-prediction purposes. Among these were lumbar support prominence height (120 to 180 mm above the H-point), seat cushion length (350 to 400 mm forward of the H-point along the cushion line), and lateral cushion bolsters (flat to highly prominent). Values of these parameters outside the tested range might effect postures in ways not captured by the prediction models.

These models are also based on data collected from people living in the Ann Arbor, Michigan area. Although the research was conducted at a university, the subject pool included few students, and spanned a large age range. This geographic area is ethnically diverse and includes people who were born in many different parts of the U.S., but the driving experiences of these subjects are typical of U.S. drivers and may not represent the experiences of those in other countries. One common hypothesis is that people from Europe or other areas with dense traffic and narrow roads will tend to adopt a more upright driving posture. While plausible, the data from studies at UMTRI suggests that this is likely to have a minor effect. In one study, the forward vision of drivers was restricted by masking off part of the windshield. In both a laboratory mockup and a vehicle with a two-way seat track adjuster, the drivers' postures were affected only slightly by this vision restriction (Reed 1998). Nonetheless, validation of these models using non-U.S. drivers would improve the confidence with which they can be applied internationally.

One additional caveat for these models is the assumption that the ASPECT manikin, as produced for use by industry, performs in a manner consistent with its specification. A recent prototype illustrates the potential problem: the seat cushion angle measurement from one prototype build was consistently 1.5 degrees higher than the target value. Calibration of the production manikins will be necessary to ensure that they provide data that are consistent with the inputs used in developing the posture prediction models.

One model input, seat stiffness, does not yet have a quantitative method for characterization. The ASPECT manikin has been designed with an incremental loading procedure that provides a means of measuring seat cushion stiffness using the manikin.

The seat cushion stiffness can be quantified by the amount the H-point location drops as the manikin buttock/thigh pan is loaded. The soft cushion level in the Seat Factors III experiment produces a deflection of 35 mm, while the firm cushion deflects 13 mm at the H-point. These values are the difference in vertical H-point position between the first installation step (no additional weights) and after all buttock/thigh weights are installed. If the ASPECT manikin is available, a similar value can be used to determine if a cushion stiffness adjustment should be used for posture prediction. Otherwise, a qualitative judgement should be made based on the relationship between the target cushion stiffness and the distribution of typical vehicle seat stiffnesses.

4.2 Residual Variance

One of the most important conclusions to be drawn from these posture analyses is that a substantial amount of posture variance is not predictable from vehicle, seat, and anthropometric variables. The fore-aft seat position, using equation adapted from the Seating Accommodation Model (SAM) is one of the best-predicted parameters (Flannagan et al. 1998). Yet, the residual variance is large, with the standard deviation of the normal error distribution about 30 mm. For one particular set of vehicle and seat, the fore-aft seat position window within which 95 percent of people with identical anthropometry would be expected to lie is about 120 mm (4 s.d.) wide. That is, we can regularly expect to find people with the same stature who choose seat positions 60 or 100 mm apart.

Seat position is strongly affected by some variables, particularly fore-aft steering wheel position, in spite of the large residual variance. Driver torso recline, however, is only moderately predictable. The R^2 for the primary regression used to predict driver hip-to-eye angle is only 0.19, meaning that about 80 percent of the variance in driver torso recline is not accounted for by any standard vehicle, seat, and anthropometric dimensions.

One might expect that adding more seat and vehicle variables would improve the prediction, but that is unlikely to be the case. This judgement is made by considering the variance between subjects within test conditions. For example, in the Manikin Validation study, 30 men were tested in 12 different vehicle seats. Additional seat-related variables would be expected to improve the prediction if there were large differences in posture between seats that could not be accounted for by the selected variables (seat cushion angle, lumbar support prominence, etc.). However, there were very few significant differences in posture between the seats, even with a powerful within-subjects analysis (except for the heavy truck seat, which differed dramatically from the other seats). These observations indicate that most of the unexplained posture variance is due to differences between subjects.

One might then conclude that the way to improve the precision of the posture prediction is to increase the number of parameters used to describe the occupant. However, this method is largely ineffective. First, the selected anthropometric variables (stature, SH/S, and BMI) account for a large amount of the variance in typically measured external body dimensions (about 75%). Consequently, any additional variables that might be added are likely to be highly correlated with those already used, contributing little additional predictive ability. The other limitation is practical: the vehicle occupant population is highly diverse, anthropometrically, and it is unproductive to attempt to specify a computer manikin on more than a few anthropometric variables, because to do so will exponentially increase the number of manikins that are required for an analysis. During data analyses on ASPECT and other UMTRI research programs, extensive efforts have been made to identify additional anthropometric descriptors that would improve posture prediction, but none have improved the prediction substantially. For example, functional leg length (estimated by stature minus sitting height) is not a substantially better predictor of driver-selected seat position than stature. Gender does not improve prediction of most degrees of freedom; seat position and torso recline are identical across genders once stature, weight, and sitting height are taken into account. Age also does not have predictive ability within these data sets. The older subjects, who include people in their 70s, do not sit significantly differently from younger subjects, once anthropometric factors are taken into account. Of course, this is a self-selected subject pool who may be more able than the older population as a whole. Nonetheless, the findings indicate that many common preconceptions about elderly and female postures are not supported by these data.

In summary, the analyses lead to the conclusion that most of the postural variance that is not accounted for by these models is essentially unpredictable. Substantial reductions in residual variance through more data collection and analysis are not expected. This finding has important implications for the use of CAD manikins for vehicle interior design and analysis.

A typical procedure for using human modeling software to analyze a vehicle interior involves selecting a family of manikins spanning a large anthropometric range and positioning those manikins in the seating position to be evaluated. The models presented in this report provide the means to posture these manikins very accurately, in the sense that the resulting postures, on several variables (seat position, eye location, etc.), lie within a narrow range of the most likely values for people matching the manikin's anthropometry. The postures are accurate "on average." However, the large residual variance means that many actual vehicle occupants will select postures that are more extreme on one or more variables than are the postures influenced by anthropometric variance alone. As a result, the needed seat adjustment range for accommodation, or the size of the occupant envelope or eye range, is larger than that described by the range of CAD manikin seat positions or eye locations. Models of the *distribution* of posture characteristics, such as seat position and eye location, are necessary to account for the posture variance that is unaccounted for by anthropometry and vehicle geometry. The Seating Accommodation Model (SAM) and the eyellipse are two models of this type.

4.3 Integration with SAM and the Eyellipse

SAM provides a means of predicting the distribution of driver-selected seat position for a wide range of driver stature distributions and gender mixes (Flannagan et al. 1998). One of the equations from SAM gives the mean seat position of a single-gender population of people with a particular mean stature. Since the model is linear, this is equivalent to giving the mean expected seat position of an individual of a particular stature. This equation is used in the ASPECT occupant posture prediction models to predict driver-selected seat position, thus providing a linkage between SAM and posture prediction for individuals.

The eyellipse (SAE J941) describes the distribution of driver eye locations. Recently, a completely undated version of the eyellipse was developed based on a large amount of new data collected in vehicles under driving conditions (Manary et al. 1998). As part of the preparation for implementing the new eyellipse in SAE J941, the calculation algorithm has been formulated to include the SAM seat position model as part of the prediction sequence. The effect of stature distribution on the eyellipse is now consistent with the effects on the seat position predictions from SAM. This integration among the models means that the tools can be used together without encountering conflicting results.

4.4 Further Work

The vehicle occupant posture research in the ASPECT program added considerably to the UMTRI vehicle occupant positioning database. In particular, a wide range of seat and package conditions were studied in laboratory mockups, providing a detailed picture of the relative contributions of seat geometry and package layout to driving posture. Detailed comparisons between driver and passenger posture were also made for the first time.

More data would be useful in a few areas, however. In particular, more study is needed on how drivers use highly-adjustable seats, such as those that include seat cushion angle and seat height adjustment. Data from previous UMTRI in-vehicle studies have shown that overall measures of driver posture, such as seat position and eye location, are largely unaffected by the presence of these adjustments. The mean driver-selected seat height is usually near the middle of the adjustment range, and the SAM predictions for fore-aft position are equally valid when used with height adjustable seats. However, as with the other package factors, laboratory research will be necessary to accurately differentiate between the effects of different types of adjustment and different adjustment range magnitudes. There is also a need for much more complete information on front-seat passenger posture, particularly the distribution of passenger seat positions. This information is important for safety applications, such as designing airbag systems.

There is also a tremendous amount of additional data analysis that could be conducted with the existing database. The posture prediction models in this report encompass the major seat, package, and anthropometric effects, but there are a wealth of more subtle postural effects that may have important implications for seat design. These effects could be documented with more complete analyses and comparisons between the studies.

Beyond experimentation and data analysis, considerably more validation of these prediction models is necessary. Some of this work can be done at UMTRI, using the extensive driver posture and position information from dozens of vehicles. If additional data collection is conducted, one goal should be to test non-North-American drivers to determine if these posture models, which characterize occupants solely using anthropometric dimensions, are adequate for international application.

4.5 Conclusions

The posture models presented in this report are the first vehicle occupant posture-prediction models to be published for use by the automotive industry. For the first time, there are data-based methods for predicting multiple degrees of freedom, such as seat position and eye location, simultaneously and consistently. The model formulation is explicit, allowing anyone to verify that a CAD manikin's performance is consistent with the models by means of a few simple calculations. The data on which the models are based have been provided to the ASPECT industry partners to provide the opportunity for verification or further statistical analysis.

In the past, the application of CAD manikins to vehicle design has been hampered by the lack of openly validated posture prediction. Most software packages provided some combination of optimization, inverse kinematics, and heuristics that would produce an occupant posture, but the postures produced by each model were different. There is now an independent source of information on how vehicle occupants sit and respond to changes in the interior geometry, encapsulated in a set of simple equations.

Further work on these models will be necessary to demonstrate the range of validity and to quantify the accuracy and precision of the predictions for a large number of in-vehicle conditions. Future refinements and adjustments are expected as more information becomes available. But now, at the conclusion of the ASPECT program, these models, based on a large, carefully developed vehicle occupant posture database, are available for use throughout the industry.

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APPENDIX A

SUMMARY OF POSTURE PREDICTION EQUATIONS

This appendix summarizes the prediction equations presented in the report text. The equations are presented in the typical application sequence. A complete set of equations is presented for simulations using the current SAE dimensions and H-point manikin and for simulations using the ASPECT manikin and proposed new vehicle and seat dimensions. The equations are further separated into driver, front-seat passenger, and rear-seat passenger applications. Tables A1 and A2 describe the input variables. For further information on the model outputs, see the report text.

Table A1
Anthropometric Variables for Posture Prediction

Variable (Abbreviation)	Definition (units)
Stature (S)	Erect standing height without shoes (mm)
Sitting Height (SH)	Erect sitting height, measured from rigid horizontal sitting surface to top of head (mm)
Weight or Mass	Body mass with clothing, without shoes (kg)
Body Mass Index (BMI)	Derived quantity obtained by dividing body mass in kg by stature in meters squared (kg/m^2). Used as a measure of weight-for-stature.

Table A2
Vehicle and Seat Variables for Posture Prediction

Current J826/J1100 Inputs	ASPECT Inputs	Definition	Symbol
Seat Height		Vertical distance between the seating reference point (SgRP) and the heel surface (accelerator heel point) when the SgRP is located at the intersection between the mid-height H-point travel path and the SAE J1517 95th-percentile accommodation curve.	H
	Seat Height	Vertical distance between the seating reference point (SgRP) and the heel surface (accelerator heel point) when the SgRP is located at the mid-height intersection between the SgRP locator line defined in Reed et al. (1999d) and the H-point travel path. See Figure 4.	H
Steering Wheel Fore-aft Position		Horizontal distance in the side-view plane between the Ball of Foot and the intersection between the steering column axis and the	SWX

		front plane of the steering wheel rim (SAE L6)	
	Steering Wheel Fore-aft Position	Horizontal distance in the side-view plane between the Pedal Reference Point and the intersection between the steering column axis and the front plane of the steering wheel rim. Pedal Reference Point is defined in Reed et al. (1999d).	SWX
Seat Cushion Angle		Angle of depressed seat cushion measured using legless manikin procedure in SAE J826 (L23). If adjustable, use the middle value of adjustment range that is available with the seat at SgRP.	CA
	Seat Cushion Angle	Angle of depressed seat cushion measured using the ASPECT manikin and procedures described in Roe et al. (1999).	CA
Back Angle		Angle of seatback (torso angle) obtained using J826 manikin (L40). This variable is an input to the posture prediction models only for seats with fixed seatback angles.	BA
	Back Angle	Angle of seatback obtained using ASPECT manikin and procedures described in Roe et al. (1999).	BA
	Lumbar Support Prominence	Lumbar Support Prominence measure obtained using ASPECT manikin and procedures described in Roe et al. (1999). Measure is made at 23-degree back angle for seats with adjustable seatback angle.	LSP
Transmission Type	Transmission Type	This binary variable is used to account for the effect of manual transmissions (presence of a clutch) on driver-selected seat position. The variable assumes the value of 1 for manual transmissions, 0 for automatic transmissions (no clutch).	T
	Cushion Stiffness	Categorical measure of the seat cushion foam stiffness; can assume values of “soft”, “firm”, or “typical”, coded numerically as –1, 1, and 0, respectively.	CS
Accelerator Pedal Position		Lateral offset from the driver seat centerline to the lateral center of the accelerator pedal at the height of the Ball of Foot reference point.	PRPY
	Accelerator Pedal Position	Lateral offset from the driver seat centerline to the lateral center of the accelerator pedal at the height of the Pedal Reference Point.	PRPY

PREDICTION EQUATIONS FOR USE WITH CURRENT SAE H-POINT MANIKIN AND DIMENSIONS

Driver Applications

1. Predict fore-aft driver-selected seat position.

   HPtXJ826 = 16.8 + 0.433 S – 0.24 H – 2.19 CA + 0.41 SWX – 18.2 T

   For seats with fore-aft adjustment only, predicted H-point location is the point on the travel path lying HPtXJ826 mm rearward of the Ball of Foot (BOF) reference point. For seats with vertical adjustment, the predicted seat position is the midpoint between the points lying at the upper and lower bounds of H-point travel path and HPtXJ826 mm rearward of BOF.

2. Predict fore-aft (X) and vertical (Z) H-point-to-hip offset (hip is forward and above H-point in most cases).

   HiptoJ826HPtX(Driver) = 12.2 – 3.5 BMI + 3.0 CA

   HiptoJ826HPtZ(Driver) = -97.1 + 1.2 BMI + 0.1068 SWX + 1.1 CA

3. Predict hip-to-eye angle in side view (positive rearward of vertical).

   HipToEyeAngle(Driver) = -56.2 + 100.2 SH/S + 0.0147 SWX + 0.10 CA + 0.136 BMI + 0.6 CS

4. Predict hip-to-eye distance in side view to complete eye location prediction.

   HipToEyeDistance = -418.5 + 0.3480 S + 859.6 SH/S

5. Predict driver-selected (H-point-manikin-referenced) seatback angle by adding an offset to the predicted hip-to-eye angle.

   SBAJ826 = HipToEyeAngle(Driver) + 83.1 = 131.0 SH/S

6. Predict driver right heel contact point relative to BOFX and APEDALY.

   HeelX = -186.1 + 0.0425 S + 357.3 SH/S + 0.309 H

   HeelY = 208.9 – 0.1441 S – 0.297 PRPY

7. Use constant recommendations for arm and leg splay.

   ArmSplayAngle = 8.6 degrees

   LegSplayAngle = 8.4 degrees

Front Seat Passenger Applications

1. Predict fore-aft seat position (H-point location) for drivers and add the passenger offset:

   HPtXJ826(Passenger) = 16.8 + 0.433 S – 0.24 H – 2.19 CA + 0.41 SWX
   – 18.2 T - 0.243 S + 430

2. Predict fore-aft (X) and vertical (Z) H-point-to-hip offset (hip is forward and above H-point in most cases).

   HiptoJ826HPtX(Passenger) = 3.4 – 3.5 BMI + 3.0 CA

   HiptoJ826HPtZ(Passenger) = -41.4 + 1.2 BMI + 1.1 CA

3. Predict hip-to-eye angle in side view (positive rearward of vertical).

   HipToEyeAngle(Passenger) = -34.0 + 82.2 SH/S

4. Predict hip-to-eye distance in side view to complete eye location prediction.

   HipToEyeDistance = -418.5 + 0.3480 S + 859.6 SH/S

Rear Seat Passenger Applications

These equations are for use with seats with fixed seatback angles. No data are available on torso postures selected in rear seats with adjustable seatback angles, although the user could consider applying the models for front passenger seats.

1. Predict fore-aft (X) and vertical (Z) H-point-to-hip offset (hip is forward and above H-point in most cases).

   HiptoJ826HPtX(Passenger) = 3.4 – 3.5 BMI + 3.0 CA

   HiptoJ826HPtZ(Passenger) = -41.4 + 1.2 BMI + 1.1 CA

2. Predict hip-to-eye angle (positive rearward of vertical).

   HipToEyeAngleJ826 = –12.4 – 0.0135 S + 62.1 SH/S + 0.559 BA

3. Predict hip-to-eye distance in side view to complete eye location prediction.

   HipToEyeDistJ826 = -208.7 + 0.3167 S + 625.8 SH/S – 1.21 BA

4. Set leg splay to 8.4 degrees or the minimum necessary to clear the front seat.

PREDICTION EQUATIONS FOR USE WITH ASPECT H-POINT MANIKIN AND PROPOSED DIMENSION REVISIONS

Driver Applications

1. Predict fore-aft driver-selected seat position.

   HPtXASPECT = 12.5 + 0.433 S – 0.24 H – 2.19 CA +
   0.41 SWX – 18.2 T + 1.14 LSP

   For seats with fore-aft adjustment only, predicted H-point location is the point on the travel path lying HPtXASPECT mm rearward of the Pedal Reference Point (PRP). For seats with vertical adjustment, the predicted seat position is the midpoint between the points lying at the upper and lower bounds of H-point travel path and HPtXASPECT mm rearward of PRP.

2. Predict fore-aft (X) and vertical (Z) H-point-to-hip offset (hip is forward and above H-point in most cases).

   HiptoASPECTHPtX(Driver) = 16.5 – 3.5 BMI + 3.0 CA – 1.14 LSP

   HiptoASPECTHPtZ(Driver) = -96.4 + 1.2 BMI + 0.1068 SWX + 1.1 CA
   + 0.24 LSP

3. Predict hip-to-eye angle in side view (positive rearward of vertical).

   HipToEyeAngle(Driver) = -56.2 + 100.2 SH/S + 0.0147 SWX + 0.10 CA + 0.136
   BMI + 0.6 CS

4. Predict hip-to-eye distance in side view to complete eye location prediction.

   HipToEyeDistance(ASPECT) = -423.1 + 0.3480 S + 859.6 SH/S + 0.24 LSP

5. Predict driver-selected (H-point-manikin-referenced) seatback angle by adding an offset to the predicted hip-to-eye angle.

   SBAASPECT = HipToEyeAngle(Driver) + 83.1 – 129.7 SH/S – 0.267 LSP

6. Predict driver right heel contact point relative to PRPX and APEDALY.

   HeelX = -186.1 + 0.0425 S + 357.3 SH/S + 0.309 H

   HeelY = 208.9 – 0.1441 S – 0.297 PRPY

7. Use constant recommendations for arm and leg splay.

   ArmSplayAngle = 8.6 degrees

   LegSplayAngle = 8.4 degrees

Front Seat Passenger Applications

1. Predict fore-aft seat position (H-point location) for drivers and add the passenger offset:

   HPtXASPECT(Passenger) = 12.5 + 0.433 S – 0.24 H – 2.19 CA +
   0.41 SWX – 18.2 T + 1.14 LSP – 0.243 S + 430

2. Predict fore-aft (X) and vertical (Z) H-point-to-hip offset (hip is forward and above H-point in most cases).

   HiptoASPECTHPtX(Passenger) = 7.7 – 3.5 BMI + 3.0 CA – 1.14 LSP

   HiptoASPECTHPtZ(Passenger) = -42.1 + 1.2 BMI + 1.1 CA + 0.24 LSP

3. Predict hip-to-eye angle in side view (positive rearward of vertical).

   HipToEyeAngle(Passenger) = -34.0 + 82.2 SH/S

4. Predict hip-to-eye distance in side view to complete eye location prediction.

   HipToEyeDistance(ASPECT) = -423.1 + 0.3480 S + 859.6 SH/S + 0.24 LSP

Rear Seat Passenger Applications

These equations are for use with seats with fixed seatback angles. No data are available on torso postures selected in rear seats with adjustable seatback angles, although the user could consider applying the models for front passenger seats.

1. Predict fore-aft (X) and vertical (Z) H-point-to-hip offset (hip is forward and above H-point in most cases).

   HiptoASPECTHPtX(Passenger) = 7.7 – 3.5 BMI + 3.0 CA – 1.14 LSP

   HiptoASPECTHPtZ(Passenger) = -42.1 + 1.2 BMI + 1.1 CA + 0.24 LSP

2. Predict hip-to-eye angle (positive rearward of vertical).

   HipToEyeAngleASPECT = –12.4 – 0.0135 S + 62.1 SH/S + 0.559 BA + 0.117 LSP

3. Predict hip-to-eye distance in side view to complete eye location prediction.

   HipToEyeDistASPECT = -208.7 + 0.3167 S + 625.8 SH/S – 1.21 BA – 0.253 LSP

4. Set leg splay to 8.4 degrees or the minimum necessary to clear the front seat.

APPENDIX B

APPLICATION EXAMPLES

Example 1. Predict driver posture for midsize U.S. male using ASPECT measures.

1. Assemble anthropometric descriptors:

   Stature: 1753 mm
   Erect Sitting Height: 913 mm
   Mass: 77.3 kg
   Sitting Height/Stature: 0.521
   Body Mass Index (Mass/Stature^2): 25.2 kg/m^2

2. Assemble vehicle and seat descriptors.

   Seat Height (H): 270 mm
   Steering Wheel X re PRP (SWX): 550 mm
   Seat Cushion Angle (CA): 14.5 degrees
   Cushion Stiffness (CS): Typical (CS = 0)
   Lumbar Support Prominence (LSP): 15 mm
   Transmission Type (T): Manual (T = 1)
   Seat Track Type: 2-way (fore-aft only)
   Seat Track Angle: 6 degrees above vertical
   SgRP with respect to PRP, AHP, and Driver Centerline (X, Y, Z): {932, 0, 270} mm
   Accelerator Pedal Center re Driver Centerline on Y Axis: 200 mm

3. Predict driver-selected H-point location aft of PRP:

   HPtX = 12.5 + 0.433 S – 0.24 H – 2.19 CA +
   0.41 SWX – 18.2 T + 1.14 LSP

   = 12.5 + 0.433*1753 – 0.24*270 – 2.19*14.5 + 0.41*550 –18.2*1 + 1.14*15 = 899 mm

4. Determine H-point Z location on H-point travel path. Since seat track has a six degree angle, H-point Z is equal to SgRP Z + (SgRPX-HpointX)*Sin(6˚) =

   HPtZ = 270 + (932-899) Sin(6˚) = 273 mm

5. Determine hip location with respect to H-point.

   HiptoHPtX = 16.5 – 3.5 BMI + 3.0 CA – 1.14 LSP

   = 16.5 – 3.5*25.2 + 3.0*14.5 – 1.14*15 = -45.3 mm

HiptoHPtZ = -96.4 + 1.2 BMI + 0.1068 SWX + 1.1 CA + 0.24 LSP

= -96.4 + 1.2*25.2 + 0.1068*550 + 1.1*14.5 + 0.24*15 = 12.1 mm

6. Add the offsets to the H-point location to determine hip location in package space.

   HipX = 899 – 45.3 = 853.7 mm

   HipZ = 273 + 12.1 = 285.1 mm

7. Calculate hip-to-eye angle and distance.

   HipToEyeAngle= -56.2 + 100.2 SH/S + 0.0147 SWX + 0.10 CA + 0.136 BMI + 0.6 CS

   = -56.2 + 100.2*0.521 + 0.0147*550 + 0.10*14.5 + 0.136*25.1 + 0.6*0

   = 9.0 degrees

   HipToEyeDistance = -423.1 + 0.3480 S + 859.6 SH/S + 0.24 LSP

   = -423.1 + 0.3480*1753 + 859.6*0.521 + 0.24*15

   = 638 mm

8. Calculate eye location in package space.

   EyeX = HipX + HiptoEyeDistance*Sin(HipToEyeAngle)

   = 853.7 + 638 Sin(9)

   = 953.5 mm

   EyeZ = HipZ + HiptoEyeDistance*Cos(HipToEyeAngle)

   = 285.1 + 638 Cos(9)

   = 915.2 mm

9. Predict heel contact point with respect to lateral center of accelerator pedal at PRP.

   HeelX = -186.1 + 0.0425 S + 357.3 SH/S + 0.309 H

   = -186.1+ 0.0425*1753 + 357.3*0.521 + 0.309*270

   =158 mm

   HeelY = 208.9 – 0.1441 S – 0.297 PRPY

= 208.9 – 0.1441*1753 – 0.297*200

= -103 mm

9. Fit torso and limb segments using inverse kinematics (see text for details).

Example 2. Small female rear seat passenger.

1. Assemble anthropometric descriptors:

   Stature: 1511 mm
   Erect Sitting Height: 771 mm
   Mass: 44 kg
   Sitting Height/Stature: 0.51
   Body Mass Index (Mass/Stature^2): 19.3 kg/m^2

2. Assemble vehicle and seat descriptors.

   Seat Cushion Angle (CA): 11 degrees
   Seat Back Angle (BA): 27.5 degrees
   Cushion Stiffness (CS): Typical (CS = 0)
   Lumbar Support Prominence (LSP): 10 mm
   SgRP: {0, 0, 0} mm

3. Calculate hip location with respect to H-point.

   HiptoASPECTHPtX(Passenger) = 7.7 – 3.5 BMI + 3.0 CA – 1.14 LSP

   = 7.7 – 3.5*19.3 + 3.0*11 – 1.14*10

   = -38.3 mm (forward of H-point)

   HiptoASPECTHPtZ(Passenger) = -42.1 + 1.2 BMI + 1.1 CA + 0.24 LSP

   = -42.1 + 1.2*19.3 + 1.1*11 + 0.24*10

   = -4.4 mm (below H-point)

4. Calculate hip-to-eye angle and distance.

   HipToEyeAngleASPECT = –12.4 – 0.0135 S + 62.1 SH/S + 0.559 BA + 0.117 LSP

   = -12.4 – 0.0135*1511 + 62.1*0.51 + 0.559*27.5

   = 14.2 degrees

HipToEyeDistASPECT = -208.7 + 0.3167 S + 625.8 SH/S – 1.21 BA – 0.253 LSP

= -208.7 + 0.3167*1511 + 625.8*0.51 – 1.21*27.5 – 0.253*10

= 553.2 mm

5. Calculate eye location in package space.

   EyeX = HipX + HiptoEyeDistance*Sin(HipToEyeAngle)

   = -38.3 + 553.2 Sin(14.2)

   = 97.4 mm

   EyeZ = HipZ + HiptoEyeDistance*Cos(HipToEyeAngle)

   = -4.4 + 553.2 Cos(14.2)

   = 531.9 mm

6. Place feet under front seat as far forward as possible. Set leg splay to 8.4 degrees or the minimum required to clear the front seat.

DISCUSSION AND CONCLUSIONS

This report documents a four-year effort to develop new automotive interior design tools, centered on a new manikin intended to replace the forty-year-old SAE H-point machine. The new manikin is designed to provide more information about vehicle seats than can be obtained with the old manikin, with superior ease of use and greater precision. The physical manikin is complemented by a set of CAD tools that tie the hardware into the software environments where modern vehicles are designed. A CAD version of the ASPECT manikin provides all of the manikin geometry in a 3D solid model, and three human body reference forms were developed to provide uniform whole-body contours for clearance analysis and visualization.

In addition to these hardware and software tools, a large posture database was created through extensive vehicle occupant posture measurement. This database has been distributed to the industry sponsors to serve as a basic source of reference for vehicle and seat design. In addition to posture data, the database includes pressure distributions, manikin performance data, and subjective evaluations obtained during testing.

The other major development of the ASPECT program is the Cascade Model, a new method of predicting vehicle occupant postures. Based on extensive analysis of the ASPECT posture database, together with other UMTRI databases, the Cascade Model provides a means of posturing CAD manikins with quantifiable accuracy. The effects of package, seat, and anthropometric variables on both driver and passenger postures are reflected in the prediction equations, allowing accurate depiction of expected postures in CAD mockups of vehicles.

The ASPECT program has been conducted together with an overarching occupant position research program at UMTRI aimed at restructuring and revising the core SAE Recommended Practices used for vehicle interior design. In ASPECT and associated UMTRI research programs, the foundations of SAE J1516, J1517, J941, J1052, J826, and sections of J1100 have been revised. Much work remains to be done, however, before these new developments are available to the industry as standardized practices. Although drafts of some of the practices have been developed (Annexes 1 and 2 of this report), considerable work will be required before they can be balloted and approved by the respective SAE committees.

Although the ASPECT program has addressed many of the key factors affecting driver and passenger posture and position, there is a need for further work in several areas.

- The ASPECT studies were conducted exclusively using two-way seat tracks (no seat height adjustment). Although other UMTRI data collected in vehicles with height-adjustable seats indicate that the ASPECT posture prediction models are reasonably accurate under those conditions, both laboratory and in-vehicle studies of driver and passenger behavior with highly adjustable seats are needed.

- Vehicles are now being manufactured with adjustable pedals and/or telescoping steering wheels to allow greater clearances to the steering wheel airbag. As with additional seat adjustments, detailed studies of these package configurations are needed to include them in the posture-prediction models.

- The factors influencing front passenger posture and position have been examined only at an initial level in ASPECT. Because of the importance of occupant position for proper airbag design, a more complete description of front passenger adjustment behavior is needed.

- The ASPECT program produced three-dimensional human body reference forms, but they do not currently include the articulations that are necessary to integrate them into vehicle design procedures. Additional work with the reference forms is needed to provide standard, industry-wide reference tools.

The implementation period for the ASPECT manikin and other outcomes can be expected to last several years, at the least, because the current tools are closely woven into the vehicle development process. To take one example, the current H-point machine is used in the positioning procedure for crash dummies. After the ASPECT manikin has been accepted in SAE J826, interaction with the SAE committee responsible for dummy position will be necessary to integrate the ASPECT manikin into the safety practices. These contacts have been established during the ASPECT program, but follow-through from both the researchers and industry representatives will be necessary.

The ASPECT program represents the first time that such a large group of companies have joined together to create a set of common tools for vehicle interior design. The success of this program provides a model for future efforts to advance the state of the art. Continued cooperation by the industry will ensure that the outcomes of the ASPECT program realize their potential to improve vehicle design practices.