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ABSTRACT

A new method of predicting automobile occupant posture is presented. The Cascade Prediction Model approach combines multiple independent predictions of key postural degrees of freedom with inverse kinematics guided by data-based heuristics. The new model, based on posture data collected in laboratory mockups and validated using data from actual vehicles, produces accurate posture predictions for a wide range of passenger car interior geometries. Inputs to the model include vehicle package dimensions, seat characteristics, and occupant anthropometry. The Cascade Prediction Model was developed to provide accurate posture prediction for use with any human CAD model, and is applicable to many vehicle design and safety assessment applications.

INTRODUCTION

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 (1).[1] 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 is hampered by the lack of valid methods to posture the models in the simulated vehicle interior.

In the mid-1950s, Dempster (2) 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 (3). 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). See Roe (4) for a thorough review of the use of these tools in contemporary occupant packaging.

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 SAE 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 values.

As computer technology has developed, CAD models have been created to simulate the two- and three-dimensional physical manikins, supplemented by more complete three-dimensional human representations. Porter et al. (1) briefly reviewed the features of 13 human-modeling systems in use prior to 1993 with potential application to vehicle design. Software development moves rapidly, however, and some of the systems that are commercially available as of this writing, including Genicom SafeWork, TecMath RAMSIS, and Transom Jack, are not included in the Porter et al. review. Most of the commercially available human models include substantial anthropometric scaling capability, allowing the model to be configured to represent geometrically the exterior dimensions of a wide range of potential vehicle occupants, but only RAMSIS is known to include any significant prediction capability for vehicle occupant postures (5). 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 pos-

1. Numbers in parentheses denote references at the end of the paper.

ture prediction, CAD human models are valuable primarily for visualization rather than for assessment.

There are few published studies applicable to posture prediction for vehicle occupants. In many early studies, data are presented only in the aggregate or in terms of a population distribution, so the findings are not applicable to human-model posture (6-8). Seidl (5) presented the most complete approach to whole-body driving-posture prediction to date. Using posture data collected in a laboratory vehicle mockup, he developed an optimization-based approach that is now used with the RAMSIS human model. The Seidl approach selects a posture consisting of the set of joint angles that is empirically most likely within the specified kinematic constraints. This technique uses posture data collected from three vehicle configurations, and can be interpreted as representing an analog of the driver's inherent posture-selection process, but there are several important limitations. The data on which the predictions are based are proprietary, and hence cannot be independently assessed except through the use of the RAMSIS software, and cannot without considerable effort be applied to a human model having a different linkage. More importantly, the posture-prediction method itself, while an innovative approach for predicting postures in novel situations, may be more difficult to use as accurately as other methods in well-studied situations, such as normal driving postures.

The research presented in this paper was conducted in conjunction with the ASPECT program, an industry-funded effort to develop new automobile and seat design and measurement tools (9). The primary objective of the ASPECT program was the development of a replacement for the SAE J826 H-point machine (3). The new ASPECT manikin is a measurement tool, however, and is not intended to represent humans for design purposes. Computerized human models are available to represent humans of different sizes for design purposes, but a review of the currently available human modeling software demonstrated that a comprehensive, accurate system of positioning human models was necessary to realize their potential for vehicle and seat design.

A new method of posture prediction was developed that is focussed specifically on vehicle occupant postures. By sacrificing the generality provided by some other posture prediction approaches (5), greater accuracy is obtained in the prediction of key degrees of freedom. The new modeling approach is termed the Cascade Prediction Model (CPM), because the whole-body posture is predicted using a series of submodels, each of which takes as input the result of the previous submodel. The CPM emphasizes accurate prediction of hip and eye locations, the postural degrees of freedom that are most important for vehicle interior design. This paper presents an overview of the CPM, with an emphasis on the structure of the model. Although a preliminary formulation of the model has been validated using driver posture data from five vehicles, the model remains under development as additional capabilities are added.

METHODS

DATA SOURCES – The posture-prediction model was developed using data from a laboratory study of driving posture that has been presented in detail elsewhere (10, 11). An anthropometrically diverse group of 68 men and women selected their preferred driving postures in a vehicle mockup that was configured to represent a wide range of vehicle interior conditions. The study was conducted in three phases, each of which used different subjects and test conditions. Table 1 summarizes the subject stature range and Table 2 lists the test conditions by test phase. External body landmark data recorded with a sonic digitizer were used to calculate joint locations defining a three-dimensional kinematic-linkage representation of the body (12). The resulting lengths, positions, and orientations of the linkage segments were used in the development of the posture prediction models.

Table 1. Subject Pool for Laboratory Study by Phase

Subject Group	Stature Range (mm)	Gender	Phase 1 n	Phase 2 n	Phase 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 2. Test Conditions for Initial Laboratory Study by Phase

Configuration Number	N	Phase 1	Phase 2	Phase 3	Seat Cushion Angle (L27) (degrees)	Seat Height (H30) (mm)	SWBOFX† (L6) (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
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 included a modification to the seat. The data are excluded from this analysis.
†Horizontal distance from the steering wheel center to the Ball of Foot reference point.

GENERAL MODEL FORMULATION

Vehicle Geometry Definitions and Model Inputs – Posture prediction is conducted in a vehicle package coordinate system, defined by several commonly used vehicle reference points. Complete definitions of these points can be found in Society of Automotive Engineers Recommended Practice J1100 and associated practices (3). The X axis in the package coordinate system runs positive rearward, the Y axis positive to the driver's right, and the Z axis positive up. The origin is defined by a different point on each axis. The origin X coordinate is defined by the Ball of Foot (BOF) reference point, while the origin Z coordinate is defined by the Accelerator Heel Point (AHP). In general terms, vertical dimensions are measured from the floor and fore-aft dimensions are measured from a point on the accelerator pedal. For the current analysis, the origin Y coordinate is the centerline of the driver seat. Figure 1 illustrates these reference points on a sideview schematic of the driver's station.

A number of vehicle package dimensions are used as inputs to the posture prediction models. These parameters have been varied systematically in testing or are those whose specification is necessary to sufficiently characterize the locations of components. The weighted, contoured H-point manikin (SAE J826) measures a reference point on the seat known as the H-point (a hip-joint location estimate). When the seat is moved forward and rearward along its adjustment track, the orientation of the path of the H-point relative to the horizontal defines the seat track angle. The seating reference point (SgRP) is the H-point location that lies on the 95th-percentile selected seat position curve given by SAE J1517 (3). This curve is a second-order polynomial describing the horizontal position of the 95th-percentile of the seat position distribution as a function of seat height. Seat height is defined by the vertical distance between the SgRP and the AHP, and is termed H30, following the dimension definitions in SAE J1100.

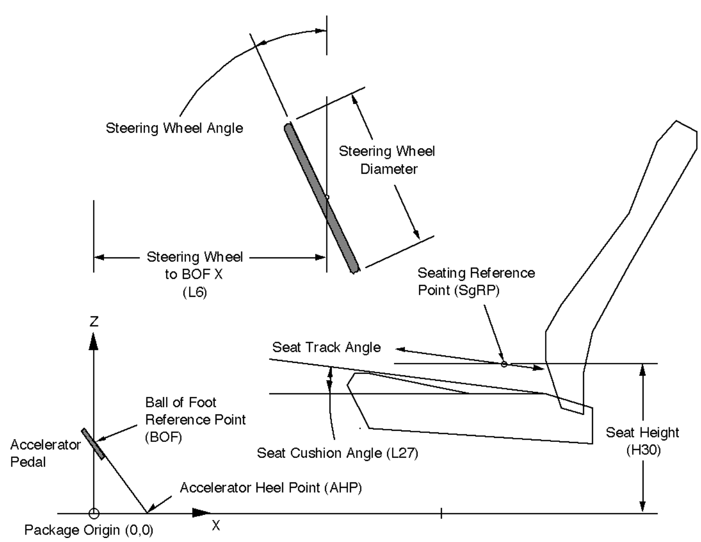

Figure 1. Vehicle package geometry. Expressions in parentheses are Society of Automotive Engineers nomenclature from SAE J1100 (3).

Seat cushion angle (L27) specifies the orientation of the lower part of the seat (seat pan) with respect to horizontal, and is measured using the H-point manikin with a procedure described in SAE J826. Seat cushion angle does not generally correspond to any measure of the unloaded centerline contour of the seat, but instead represents the cushion orientation experienced by a standardized sitter. The steering wheel is characterized by the coordinates of the center of the front surface of the wheel, the angle of the front surface of the wheel with respect to vertical, and the diameter of the wheel. The horizontal distance from the center of the steering wheel to BOF is a key package dimension and is denoted L6 in SAE J1100.

Table 3 lists vehicle geometry inputs to the posture prediction model in two categories: parameters that solely affect kinematic constraints imposed on the models, and those that are variables in the predictive equations. Only three variables are used in the posture prediction models: H30, L6, and L27. Notably, the vertical position of the steering wheel and the degree of forward vision restriction imposed by the instrument panel or vehicle cowl are not included. The vertical position of the steering wheel is highly constrained in vehicle design, because of the conflicting requirements of sufficient leg space beneath the wheel and sufficient vision above the wheel. The leg depth of large drivers and the eye height of small drivers tends to constrain the vertical steering wheel position to a small range relative to the SgRP location. Restrictions on forward vision, in the range that is reasonable for vehicle design, do not have important effects on posture (10).

Table 3. Vehicle Geometry Inputs

Prediction Variables	Kinematic Constraints
Seat Height (H30)	Seating Reference Point (X,Y,Z)
SWBOFX (L6)	Steering Wheel Center (X,Y,Z)
Cushion Angle (L27)	Steering Wheel Angle
	Steering Wheel Diameter
	Seat Track Angle
	Center of Accelerator Pedal Y Coordinate (with respect to seat centerline)

The driver's characteristics are represented in the models using four parameters: gender, stature, weight, and sitting height. Additional anthropometric data, such as arm or leg lengths, do not provide substantially better prediction. Because stature, weight, and sitting height are correlated in the data set, two transformations of the variables were used as regressors. The ratio of sitting height to stature (SH/S), a measure of body proportion, was used in lieu of sitting height, and the Body Mass Index (BMI), the ratio of mass (kg) to stature (m) squared, was used instead of mass. Each of these two ratio variables is only moderately correlated with stature in this dataset (*r* = –0.34 and 0.32 for SH/S and BMI, respectively). The predictive ability of regressions using these variables, assessed using the adjusted R2 value, was within 0.01 of the values obtained using sitting height and mass directly, while reducing the problems associated with correlated regressors.

<u>Kinematic Model</u> – Driving posture is represented using a kinematic linkage model of the human body. The linkage and its derivation from external body landmark data is described in detail elsewhere (12). Figure 2 shows the linkage and defines variables that are used in the posture prediction models.

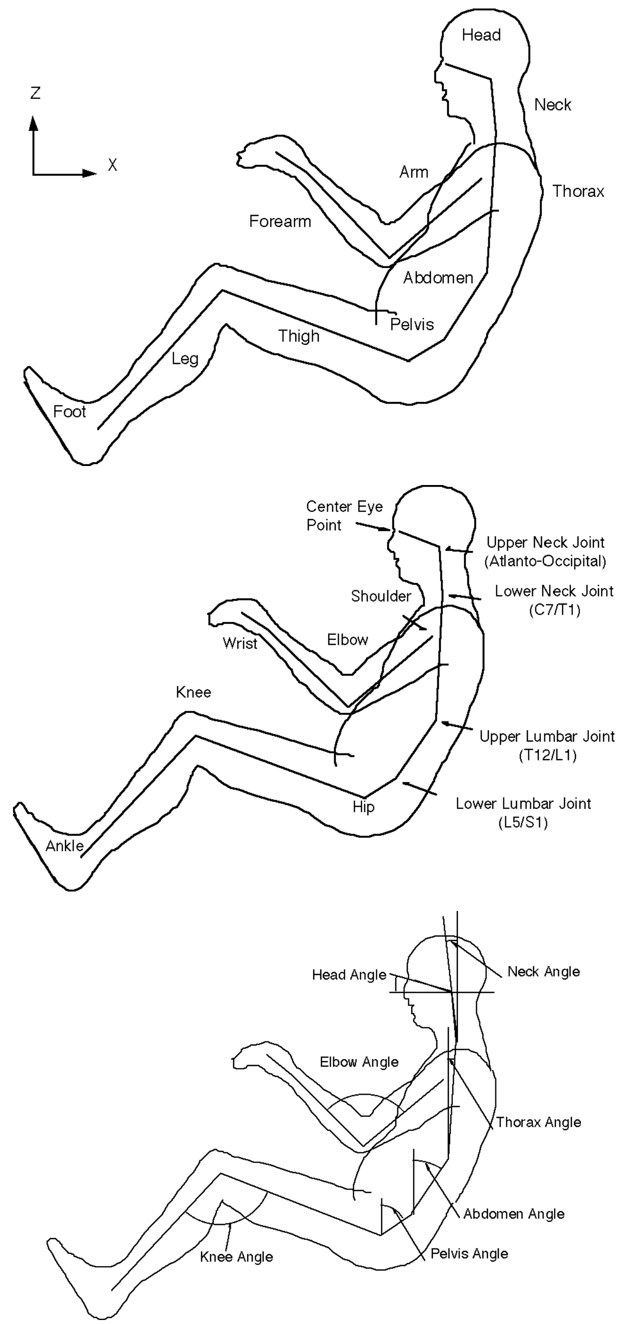

Figure 2. Definitions of kinematic linkage and posture measures (12). Angles referenced to horizontal or vertical are XZ (sagittal) plane angles. Angles between segments (elbow angle, knee angle, and ankle angle) are measured in the plane formed by the segments (included angles). Note: Neck angle is negative as shown. All other angles are positive as shown.

Model Simplifications and Restrictions – Several simplifying assumptions are made to reduce the model complexity. Normal driving posture is considered to be sagittally symmetric, with the posture of the left side of the body mirroring the right. In the data collection used to develop the models, subjects were asked to choose a "normal, comfortable driving posture" with their hands located at the 10-o'clock and 2-o'clock position on the steering wheel. By observation, the only important deviations from sagittal symmetry occurred when left lower-extremity postures did not match the right lower-extremity, which was constrained by the requirement of operating the accelerator pedal. Data from the right upper and lower extremities were used exclusively for developing the models, since the geometric task constraints imposed by the pedals operate solely through the right lower-extremity. The hand-position constraint in testing was imposed so that the elbow angle would be a reliable measure of the distance between the steering wheel and torso. The performance of the models in predicting postures measured in conditions with free hand placement suggests that this constraint provides useful upper-extremity posture data without otherwise affecting posture (see below). To simplify limb kinematics calculations, the hands are assumed continuous with the forearms. Foot posture is neglected in favor of direct prediction of ankle joint location. Prediction of foot position in is based on data in Schneider et al. (13).

Regression Equations – In the CPM, a number of degrees of freedom are predicted using regression equations developed from the laboratory study data. These equations were created by a stepwise process after a thorough analysis of the study data (10). The original analysis concluded that seat height, steering wheel position, and seat cushion angle have important, independent effects on posture. There were also small differences in posture between the two seats tested, but these are neglected in the development of the posture-prediction models because appropriate tools to characterize seat differences beyond seat cushion angle remain under development.

Data from all subjects and conditions were pooled (68 subjects in a total of 916 trials) to create the prediction models. A stepwise-regression technique was applied with potential regressors stature, weight, sitting height, sitting height divided by stature, seat height, steering-wheel-to-BOF distance, and seat cushion angle. An automated algorithm selected a model using $p<0.25$ to enter and $p>0.10$ to leave, after which manual selections were made to obtain parsimonious models that maintain an adjusted R2 value within 0.02 of the maximum values obtained by the automated procedure.

SPECIFIC MODEL FORMULATION – The Cascade Prediction Model (CPM) is termed "cascade" because the predictions are obtained using a series of submodels, each based on the results of the previous model. The motivation for this approach is to provide the best possible prediction accuracy for the hip and eye locations, the posture characteristics that are most important for ergonomic assessments of the driver's station. Hip location is closely related to seat position and lower-extremity posture, while eye location is critical for vision analyses.

Figures 3 and 4 depict the CPM algorithm schematically. The fore-aft hip location is predicted, using a regression equation, as a function of stature, SH/S, H30, L6, and L27 (Figure 4A). The hip-to-H-point offset vector is calculated using another set of regression equations, yielding a hip travel path in the XZ plane corresponding to fore-aft seat position adjustment. The point along this line with X value equal to the predicted fore-aft hip location is the predicted hip location in the XZ plane. The Y coordinate of the hip joint is set so that each hip joint lies equidistant from the seat centerline, placing the torso segments in the XZ plane of the seat centerline.

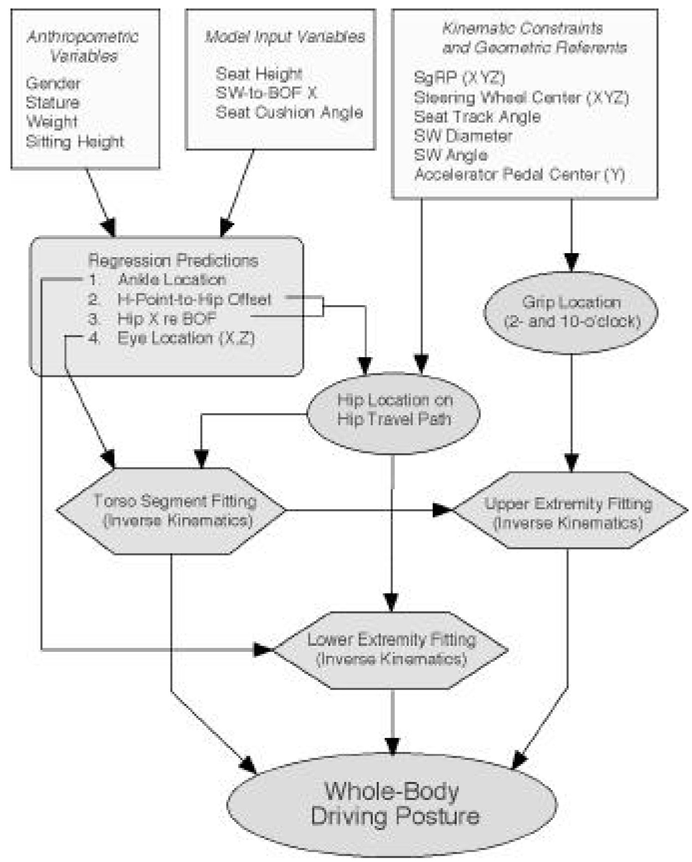

Figure 3. Schematic of Cascade Prediction Model (CPM).

Eye location with respect to the hip is then calculated using the regression equations. With respect to the original dataset, predicting the eye location relative to the hip location and relative to AHP/BOF give essentially identical results. However, the indirect procedure avoids potential errors associated with seat track angles different from the angle used in testing. The predicted eye location is the center-eye point, a point on the midline of the body that has a Z coordinate equal to the corner-of-eye landmark and an X coordinate equal to the infraorbitale landmark. This allows all torso segment calculations to be conducted in a plane.

An inverse-kinematics submodel is used to fit the kinematic-linkage representation of the torso to the predicted hip and eye locations (Figure 4B). In the torso, analyses of these data found statistically significant but small effects of vehicle and seat geometry on torso segment orientations (10). In particular, changes in steering wheel position tend to create small changes in overall torso recline, which are accompanied by flexion or extension motions at various levels of the spine. Reflecting these motion patterns in the fitting procedure for the torso segments will allow the resulting models to be used for realistic assessment of the effects of changing vehicle and seat parameters on spine flexion.

Once the torso segment orientations have been calculated using the inverse-kinematics procedure, the right shoulder (glenohumeral) joint location is calculated. Shoulder joint location with respect to the thorax segment did not vary significantly with the vehicle or seat variables studied, so the shoulder location on the thorax segment is calculated with respect to anthropometric variables only.

Given the right shoulder and right hand-grip locations, the forearm-hand and arm segments are fit using inverse kinematics (Figure 4C). Arm splay angle is calculated as a function of elbow angle. Arm splay angle is the angle around the shoulder-to-grip vector that the elbow location would have to be rotated to lie in a vertical plane with the grip and shoulder points.

An analogous process is used to fit the thigh and leg segments to the predicted hip and ankle locations. Leg splay is taken as a constant, average value, since leg splay was not significantly affected by the test variables. Leg splay is the angle around the hip-to-ankle vector that the knee location would have to be rotated to lie in a vertical plane with the ankle and hip joints. The limb postures are reflected to the left side of the body to complete the posture prediction.

MODEL ASSESSMENT – The accuracy and precision of the CPM was assessed both by comparing model predictions to both the original data set and to a new set of driver posture data obtained in actual vehicles. There are many potential metrics for assessing posture prediction performance, ranging from assessments of accuracy on individual degrees of freedom to combinations of many degrees of freedom. For simplicity, the evaluations presented here address only eye location prediction, which is arguably the most important postural variable for driver station design. Assessments with other metrics have led to similar conclusions. Table 4 shows the average errors in eye location predictions for the CPM across the total range of test conditions in the original data set (Table 2). As expected, the mean prediction is excellent, with average errors of less than 1 mm.

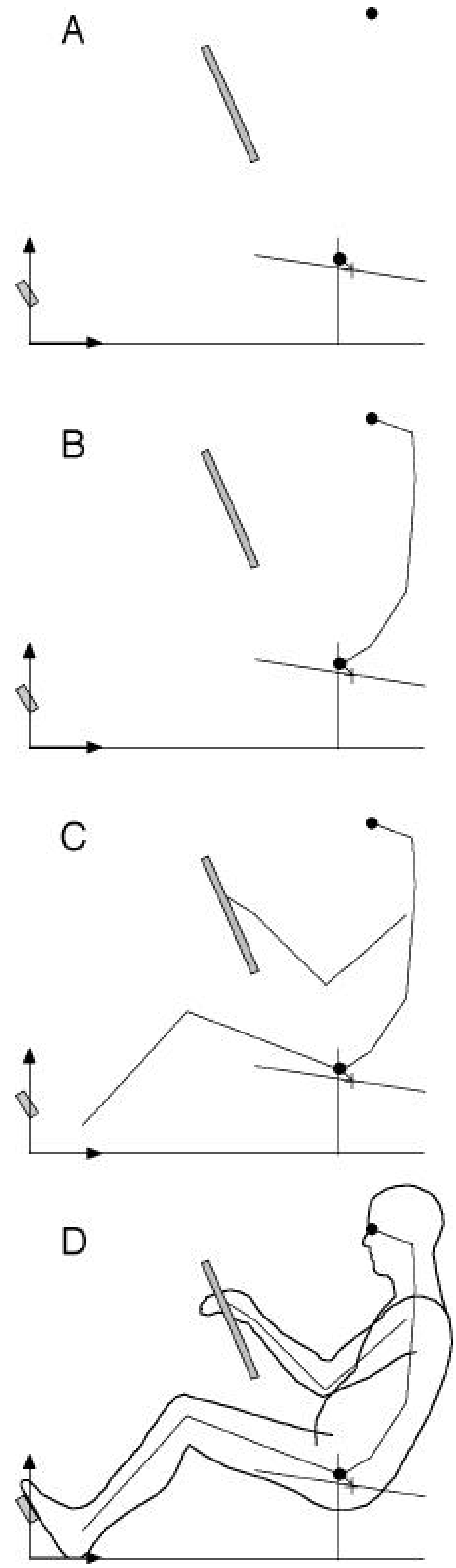

Figure 4. Step-by-step illustration of Cascade Prediction Model approach to predicting driver posture. A: Predict hip and eye locations; B: Fit torso segments by inverse kinematics using data-based motion distribution; C: Fit limb segments by inverse kinematics using splay data; D: Fit full 3-D model to kinematic linkage.

Table 4. Comparison of Model Predictions vs. Observed Eye Locations in Original Data

Value	Eye X (mm)	Eye Z (mm)
Mean (Obs-Pred)	0.9	-0.4
Standard Deviation (Obs-Pred)	50.5	19.9

The standard deviation of the errors, a measure of the residual posture variance not accounted for by the model predictions, is about 51 mm for the X coordinate and about 20 mm for the Z coordinate. Figure 5 shows the deviations between the observed and predicted eye locations in the original data set along with a 95 percent density ellipse. The Z-axis errors are approximately normally distributed (Shapiro-Wilk W-test), but the X-axis errors have a broader-than-normal distribution. Nonetheless, the normal distributions overlying the marginal distribution plots in Figure 5 illustrate that the XZ-plane prediction error distribution can reasonably be approximated as bivariate normal.

The correlation among the errors is due to the effects of the principal ways in which the posture-selection behavior can deviate from the prediction. People can select a different seat position than predicted, or can choose a different recline angle. Both of these deviations tend to cause a movement of the eye along an inclined sideview path. Seat position prediction errors result in discrepancies along a path having the same slope as the seat track, and recline angle errors result in errors along a slightly more inclined path.

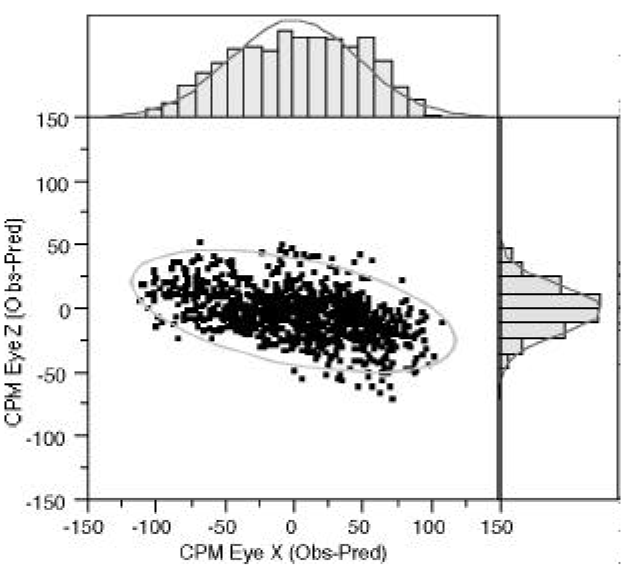

Figure 5. Observed-predicted eye locations for the CPM, showing marginal histograms and a 95 percent bivariate normal density ellipse. A normal distribution with equivalent variance is depicted overlying each histogram.

One important question concerning the prediction errors is whether the prediction precision varies substantially with the input variables. Is the prediction precision approximately the same for small people and large people, or for different seat heights? To address this issue, the subjects were divided into five stature groups using 100-mm bins from 1550 to 1850 mm (three groups), and creating two groups from those with statures above 1850 and below 1550 mm. The number of subjects in each group ranged from 9 to 26. Table 5 lists the group definitions and the within-group error standard deviations. The error variance from the CPM was compared among the groups using Levene's test for homogeneity of variance. Levene's test is an ANOVA on the absolute differences between each observation and the group mean. No significant differences in variance were found among groups for X-coordinate errors, but there were small but significant differences in the distribution of Z-coordinate errors. However, the standard deviations in Table 5 indicate that there is not a consistent trend with body size, and the differences are small enough to be of minimal practical importance. Similar trends are observed for other variables (seat height, etc.). These findings suggest that the precision of the model predictions can reasonably be approximated as constant throughout the range of the input data.

Table 5. Prediction Error Standard Deviations by Stature Group for CPM

Group	Stature Range (mm)	Subjects in Group	Eye X Std. Dev. (Obs-Pred) (mm)	Eye Z Std. Dev. (Obs-Pred) (mm)
1	<1550	11	48.9	16.0
2	1550 – 1650	13	47.2	18.5
3	1650 – 1750	26	50.5	22.4
4	1750 – 1850	9	55.9	16.2
5	>1850	9	47.7	21.2

A more important measure of the model performance than the fit to the original data is the correspondence between the model predictions and the postures of drivers in actual vehicles. In a separate study, 120 men and women ranging in stature from 1441 to 1952 mm drove five vehicles over a 15-minute road route, adjusting the seat track position and seatback angle to obtain a comfortable driving posture (14). Each car was equipped with an automatic transmission and was tested with the seat track adjustment restricted to two-way (fore-aft) travel. After returning from the road route, the driver's preferred posture was recorded using a FARO coordinate measurement arm and procedures similar to those used in the laboratory (12). Table 6 lists some of the characteristics of the vehicles. The vehicles were selected to represent a substantial part of the range of the interior geometry available in current passenger cars.

Table 6. Vehicle Characteristics

Vehicle	Seat Height (H30) (mm)	SWBOFX (L6) (mm)	Seat Cushion Angle (L27) (deg)
Plymouth Voyager	326	504	14.0
Chrysler LHS	250	597	17.7
Dodge Avenger	189	577	16.6
Jeep Grand Cherokee	298	607	11.3
Plymouth Laser	194	550	11.3

Table 7. Comparison of Model Predictions vs. Observed Eye Locations in Vehicle Data: Mean Observed minus Predicted (s.d.)

Vehicle	EyeX (Obs - Pred) (mm)	Eye Z (Obs - Pred) (mm)
Voyager	0.7 (52.2)	-4.8 (20.6)
LHS	0.0 (46.5)	-6.5 (18.1)
Avenger	2.5 (47.5)	-7.4 (18.8)
Jeep Grand Cherokee	5.9 (49.6)	-13.6 (18.9)
Laser	8.7 (46.2)	-2.2 (17.3)
Overall Mean	3.6 (48.4)	-6.9 (18.7)
Dynamic Z Correction*	--	2.1
Overall Range	8.7	11.4

*Eye Z predicted location lowered by 9 mm (see text).

The CPM was exercised using the vehicle configurations and subject anthropometry. The resulting eye position predictions were compared with the observed eye positions to assess the model accuracy. Table 7 lists the means and standard deviations of the prediction errors by vehicle for each posture model.

The CPM predicts the mean eye location for the five vehicles with considerable accuracy. The predicted horizontal coordinate was within 10 mm in all cases, with an average error of 3.6 mm. On the vertical coordinate, the predicted mean eye locations were higher than observed in all cases. Pilot testing in three vehicles demonstrated that eye locations after the 15-minute drive were on average 9 mm lower than those measured immediately prior to the drive. The cause appears to be settling into the seat, rather than additional slumping, as the distance between the anterior-superior iliac spine landmarks and the eye landmarks remained unchanged. Since the prediction models were generated from static, vehicle-mockup data, a 9-mm dynamic correction was made to the Z-coordinate predictions. With the correction, the average vertical error across vehicles is 2.1 mm. The range of prediction errors, a measure of the consistency of the models across vehicles, was under 10 mm for the X coordinate and about 10 mm for the Z coordinate. The standard deviations of the errors, a measure of the individual prediction accuracy, were essentially identical to the standard deviations computed with the original vehicle mockup data, suggesting that the error distribution for the vehicle data is similar to that observed in the laboratory.

DISCUSSION

A good predictive model of driving posture will have a number of useful characteristics for any degree of freedom of interest. Taking the prediction of eye location as an example, the model will:

1. Be accurate and precise, on average, across vehicles, meaning that the mean predicted eye location will deviate only a small amount from the mean observed eye locations across vehicles. This implies both that the error in mean eye location prediction for each vehicle will be small, and also that the errors will offset so that, across vehicles, the average error is small.
2. Have the accuracy characteristics described in (1) for any population composition, e.g., for a group of small females or large males.
3. Have minimal error variance for individual predictions, meaning that the absolute deviations of individuals from the predictions for people with matching anthropometry on the key variables is small.

The CPM performs well, based on criteria 1 and 2, but the error variance for individual predictions is fairly large (criterion 3). Individual prediction performance is constrained by the consistency of driving postures chosen by different people with similar anthropometry. In effect, the only opportunity for improving the model's ability to predict individuals' postures is to add anthropometric descriptors as input to the models. However, such additions are not likely to be useful for general vehicle design, because the intended user population is anthropometrically diverse, and hence cannot usefully be described by more than a few variables. For example, a vehicle that is to be driven by people from the 3rd to 97th percentiles of the U.S. population by stature will cover a similarly large range of other anthropometric variables of interest. Furthermore, efforts to use additional measures, such as arm or leg length, have not yielded substantial improvements in prediction precision.

The observed error variance may be a measure of the variance in subject preference that cannot be attributed to useful subject descriptors and therefore must be accounted for in predicting any individual's posture. The variance is large enough that the driving posture of an individual cannot effectively be predicted from a general model except within a large window. For vehicle design, this does not pose any particular problems, provided the mean postures of population groups of interest are accurately predicted, and the prediction error variance is kept always in mind. However, this finding indicates that a

CAD representation of a person sitting in a vehicle will be only one of a wide range of postures that a person with the specified dimensions might choose. The accommodation of people with diverse anthropometry will not be assessed accurately by using a family of various manikin sizes, even if they are postured in ways that accurately represent the average postures of the corresponding anthropometric group.

This finding has important implications for the use of CAD human models in vehicle design. Currently available human models, while varying widely in surface appearance, all have sophisticated capabilities for specifying the model dimensions according to anthropometric variables. Anthropometric variability is one important factor affecting occupant accommodation, but postural variability is a second, largely independent factor that is not generally accommodated in current human model application methods. Methods for incorporating postural as well as anthropometric variability in human-model-based design procedures are needed.

ONGOING IMPROVEMENTS – The CPM has recently been improved in a number of areas. Data from a large-scale study at UMTRI of the effects of seat factors on driver and passenger posture were used to add seat factor effects to the posture prediction. Findings from several other studies (10, 13-15) have also been integrated into the CPM. In addition to seat cushion angle, the model takes as input the seatback angle (if fixed) and lumbar support prominence. Prior to the ASPECT program, no standardized measure of lumbar support prominence was available for use in posture prediction. The new ASPECT manikin provides a measure of seatback contour under a loading pattern similar to that produced by a midsize male (9). A revised version of the CPM is based on measures obtained with the new ASPECT manikin, including H-point location, seatback angle, cushion angle, and lumbar support prominence. The CPM can predict postures of drivers, front-seat passengers, and rear seat passengers, with fixed or adjustable seatback angles. The CPM is currently being modified to use the new package dimension definitions developed in conjunction with the ASPECT manikin (9).

LIMITATIONS – The model is currently limited to use with driver seats that have two-way (fore-aft) seat-track adjustment and seatback angle adjustment, but without any seat height or seatpan angle adjustment. While the majority of production passenger cars still fall within this restriction, an increasing number are manufactured with height- or angle-adjustable seats. Further research will be necessary to expand the models to predict postures for vehicles with these seats. However, testing in vehicles with height-adjustable seats has demonstrated that the eye locations are similar, on average, to those measured with a two-way seat track positioned at a height in the middle of the adjustment range (14), suggesting that the CPM can be readily adapted for use with height-adjustable seats.

The CPM also assumes that seat track position is not censored, meaning that drivers are free to choose a fore-aft seat position without constraint from track travel limitations. The effects of censoring are generally important only for very large and very small people, but it is likely that the additional kinematic constraint changes posture adaptation. The subjects whose postures were used to develop and validate the model ranged in age from 21 to 75 years, but their behavior may not be representative of certain population segments, such as the very old or those with visual or other impairments. The short-duration sitting sessions used to develop the models also restrict the application of the models to prediction of short-term postures, although Reed and Schneider (15) demonstrated that postures do not change substantially in long-term driving, relative to intersubject differences.

The vehicle mockup testing leading to the development of these models was conducted without the use of seatbelts, but the accuracy of the models in predicting in-vehicle postures, for which the drivers used the seatbelts, suggests that these restraints do not significantly affect posture. Observations of people selecting their driving postures in vehicles suggest that driving posture is generally selected before buckling the seatbelt.

The CPM does not currently include a number of additional factors that might affect driving posture. Restrictions to downward, forward vision have been demonstrated to have negligible affects, within the range applicable to production vehicles (10), but other vision restrictions could be important. For example, restrictions to lateral vision might cause posture changes. More research will be necessary to determine if these effects are important. In a separate study, headroom restriction has been found to affect driving posture for drivers whose head or hair would contact the roof in their normal driving posture (16). Although not currently included in the CPM, it appears that these effects can be simulated using a kinematic constraint.

APPLICATIONS – The CPM is applicable to any situation in which accurate prediction of normal vehicle occupant posture is required. The primary route of application is expected to be through human modeling software that represents human figures in CAD environments. Publishers of the RAMSIS, SafeWork, and Transom Jack human models are participating in the ASPECT program and have begun implementation of the CPM. Other potential applications include prediction of individual degrees of freedom for design assessments (e.g., average eye locations for specific occupant sizes), and crash dummy positioning.

CONCLUSIONS

A new approach to predicting whole-body vehicle occupant posture has been developed. The Cascade Prediction Model emphasizes accuracy on two of the most important characteristics of posture for vehicle design, namely eye and hip locations. Submodels using inverse kinematics with heuristics developed from vehicle occupant posture data produce accurate torso and limb posture predictions for normal riding and driving postures. The model prediction errors are largely independent of body size and vehicle geometry, allowing a straightforward interpretation of prediction precision. Vehicle design assessments using human models can proceed more accurately using posture prediction based on the CPM.

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