Effects of Vehicle Interior Geometry and Anthropometric Variables on Automobile Driving Posture

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The effects of vehicle package, seat, and anthropometric variables on posture were studied in a laboratory vehicle mockup. Participants (68 men and women) selected their preferred driving postures in 18 combinations of seat height, fore-aft steering wheel position, and seat cushion angle. Two seats differing in stiffness and seat back contour were used in testing. Driving postures were recorded using a sonic digitizer to measure the 3D locations of body landmarks. All test variables had significant independent effects on driving posture. Drivers were found to adapt to changes in the vehicle geometry primarily by changes in limb posture, whereas torso posture remained relatively constant. Stature accounts for most of the anthropometrically related variability in driving posture, and gender differences appear to be explained by body size variation. Large intersubject differences in torso posture, which are fairly stable across different seat and package conditions, are not closely related to standard anthropometric measures. The findings can be used to predict the effects of changes in vehicle and seat design on driving postures for populations with a wide range of anthropometric characteristics.

INTRODUCTION

Accurate prediction of driving posture is essential for vehicle interior design. Optimal positioning of the controls, displays, and restraint systems depends on a detailed understanding of how and where drivers of widely varying sizes will sit. Early research into the problem of control and seat placement was concerned primarily with improving the comfort of designs rather than predicting how people would respond to particular vehicle and seat geometries (Lay & Fisher, 1940). Beginning in the late 1950s, designers began to use planar and three-dimensional (3D) manikins, based on the pioneering work of Dempster (1955), to assess leg room and control reach (Geoffrey, 1961; Kaptur & Myal, 1961).

Recently, advances in computer technology have led to the development of 3D software models of the entire human body that are increasingly used for vehicle design (Porter, Case, Freer, & Bonney, 1993). These human figure models provide a useful visualization of vehicle occupant size, shape, and position, but the success of design evaluations conducted with these models is strongly dependent on the accuracy of the model posture.

The current study investigates the effects on whole-body driving posture of three variables that are known to have important effects on seat position and eye location (Flannagan, Manary, Schneider, & Reed, 1998; Flannagan, Schnieder, & Manary, 1996; Manary, Flannagan, Reed, & Schneider, 1998). The analysis is intended to provide an understanding of the individual and interactive effects of seat height, steering wheel position, and seat cushion angle on all of the major posture characteristics of interest for vehicle interior design.

METHOD

Participants

This study was conducted in three phases,

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each of which used different participants and a different set of conditions. The participants were 68 licensed adult drivers who were selected in gender-stature groups spanning more than 95% of the stature range in the U.S. population (Abraham, Johnson, & Najjar, 1979). Table 1 summarizes the participants' stature distribution by phase.

Facilities

Testing was conducted in a reconfigurable vehicle mockup that allowed the seat height, fore-aft steering wheel position, and seat cushion angle to be varied over a wide range. The seat and control layout, termed the *vehicle package,* was specified and measured using standard reference points and dimension definitions documented in Society of Automotive Engineers (SAE) Recommended Practice J1100 and other related practices (described in SAE, 1997). Figure 1 illustrates these dimensions in a side view of a generic package. 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 vertically. 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, whereas the origin z coordinate is defined by the accelerator heel point (AHP).

The seating reference point (SgRP) is obtained using the weighted, contoured H-point manikin (SAE J826) to measure a reference point on the seat. The height of this point above the heel rest surface (AHP) defines the seat height and is termed H30, following the dimension definitions in SAE J1100. 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. 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 termed *SW-BOFX.*

Figure 2 illustrates the test mockup schematically. The seat was mounted on a motorized platform allowing unrestricted fore-aft travel along a path inclined 6° to the horizontal. Seat cushion angle was varied by pivoting the entire seat around a lateral axis. Seat height was set by adjusting the height of the heel surface relative to the seat. When the seat height was increased, the angle of the accelerator and brake pedals with respect to the horizontal was reduced, consistent with the pedal plane angle equation given in SAE J1516. In keeping with trends documented in vehicle fleet data (Flannagan et al. 1996, 1998), the steering wheel and instrument panel height were also lowered slightly with respect to the SgRP at higher seat heights (25 mm lower/90 mm of seat height

TABLE 1: Participant Pool

Participant Group	Stature Range (mm)	Gender (*n*)	Phase 1 (*n*)	Phase 2 (*n*)	Phase 3 (*n*)	All (*n*)
0	<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	>1869	Male		3	3	6
Total			20	24	24	68

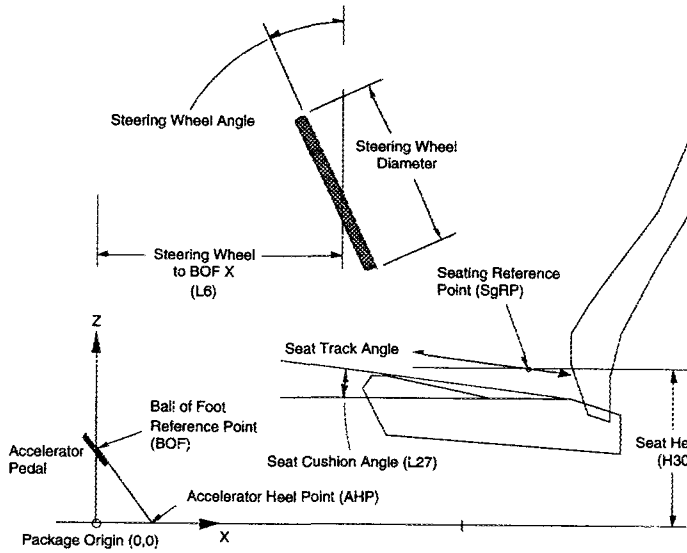

Figure 1. Vehicle package geometry. Expressions in parentheses are Society of Automotive Engineers nomenclature from SAE J1100 (SAE, 1997).

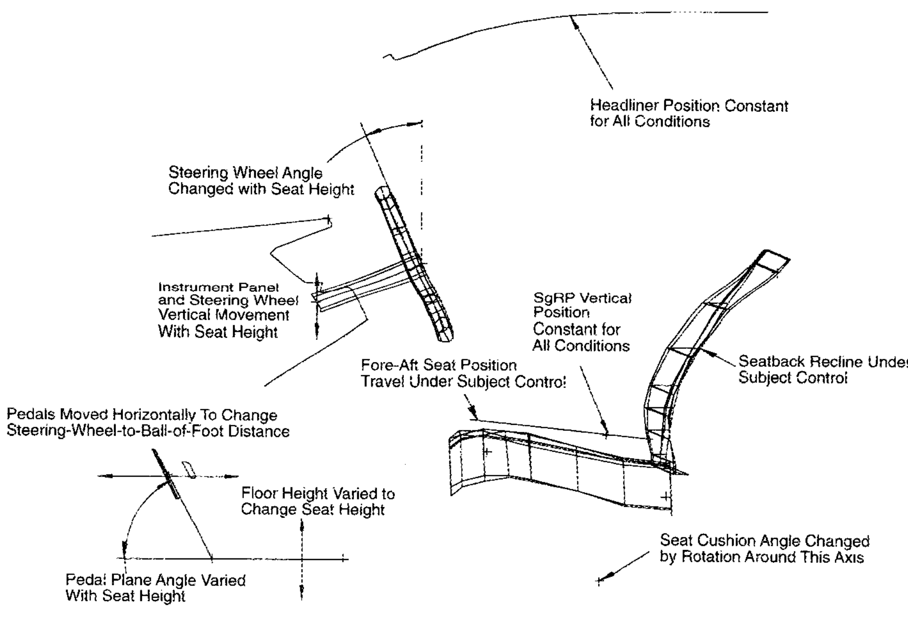

Figure 2. Schematic of vehicle mockup showing adjustment axes.

increase), and the steering wheel angle with respect to vertical was increased at higher seat heights (2°/90 mm of seat height increase). The fore-aft position of the steering wheel with respect to the pedals was varied by moving the pedals along a motorized horizontal track, rather than moving the steering wheel. This reduced the amount of seat track travel required and allowed the instrument panel and steering wheel to remain in a fixed relation.

Test Conditions

Three package and seat variables were manipulated independently, using a range of each variable intended to represent a substantial portion of the vehicle fleet. These variables were selected based on the findings of several studies of driving posture conducted at the University of Michigan Transportation Research Institute both in laboratory mockups and in vehicles (Flannagan et al., 1996, 1998). Table 2 lists the 18 configurations used in testing. Seat height (H30) was set to 180, 270, and 360 mm, corresponding to a wide range of vehicle types, from sporty cars to minivans. Seat cushion angle (L27) was set to 11° and 18°. The horizontal distance from the steering wheel center to the ball of foot reference point (SW-BOFX) was adjusted between 450 and 650 mm.

Steering wheel position with respect to BOF is correlated with seat height in this experiment design because it is not possible to manipulate both variables over a large range without correlation. At high seat heights, drivers tend to sit closer to the pedals, necessitating a more forward steering wheel position. In fact, across the vehicle fleet, a substantial correlation exists between these two variables. Figure 3 shows a plot of seat height and SW-BOFX for 158 recently produced vehicles, along with the test conditions used in this study. At each seat height level, the test conditions were selected to span a substantial fraction of the range of production vehicles. The correlation between seat height and steering wheel position in the experiment is addressed in the analysis, primarily by considering subsets of the test configurations for which the two variables are orthogonal. Figure 4 shows seat cushion angles for 65 vehicles, along with the two levels used in testing.

Phases 1 and 2 were conducted using a seat from a Ford Taurus, a typical midsize sedan seat that has minimal contouring or bolstering. The Dodge Neon seat used for Phase 3 testing was a sportier, bucket seat with a firm, prominent lumbar support. The objective in switching seats was to evaluate whether the effects of seat height, steering wheel position, or seat cushion angle differed for the two seats.

Procedures

Participants were recruited by advertisement and by word of mouth. All were licensed drivers with at least four years' driving experience. The study objectives were explained to each participant, and written consent was obtained. The participant changed from street clothes into test garb, consisting of loose-fitting shorts and a short-sleeve shirt with a slit in the

TABLE 2: Test Conditions

Configuration Number	*N*	Phase 1	Phase 2	Phase 3	Seat Cushion Angle (L27, °)	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
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

Note: Condition 11 included a modification to the seat. Data from Condition 11 are excluded from this analysis.

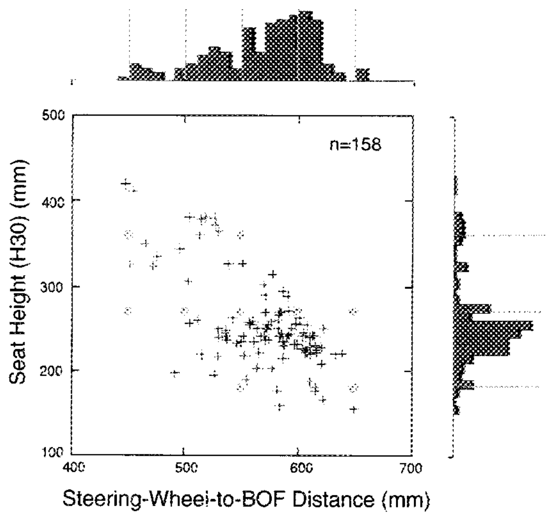

Figure 3. SW-BOFX versus seat height in 158 production vehicles. Large dots are test conditions used in the current study.

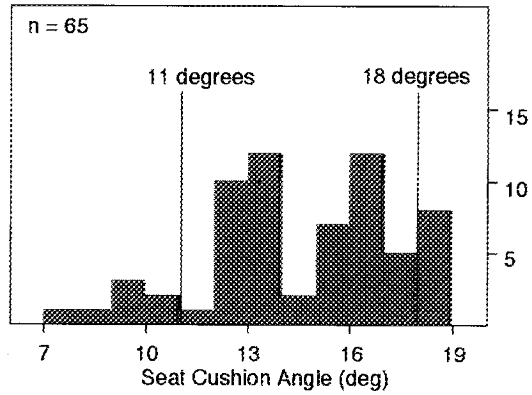

Figure 4. Seat cushion angle distribution for 65 production vehicles. Test conditions are shown with vertical lines. Vertical axis is count.

back to allow access to posterior spine landmarks. The participants wore their own comfortable driving shoes.

The test conditions were presented to the participants in random order. Table 2 lists the set of test conditions presented in each phase. In each trial, the participant was screened from the vehicle mockup while the test conditions were set by the experimenter. The seat track position was adjusted to the estimated mean population seat position, and the seat back angle was set to 23°, using the SAE J826 manikin torso angle measure. The participant entered the mockup and adjusted the fore-aft seat position using a motorized control and adjusted the seat back recline angle using a manual adjuster. The participant was instructed to operate the pedals and steering wheel and to continue to adjust until a "normal, comfortable driving posture" was obtained. A static road scene was displayed on a large screen in front of the drivers to provide consistent visual cues. In Phase 1, the participants were free to choose any hand position on the steering wheel. In Phases 2 and 3, participants were instructed to place their hands on the steering wheel at the 10 o'clock and 2 o'clock positions. Although many other hand positions are possible in driving, the 10 o'clock and 2 o'clock positions are reasonable, and standardizing the hand locations gives greater meaning to the elbow angles. There was, however, no significant difference in elbow angle for similar conditions in Phases 1 and 2.

After the participant obtained a comfortable driving posture, the experimenter recorded body landmark locations using the sonic digitizer probe. Table 3 lists the body landmarks. The pubic symphysis landmark was palpated and recorded by the participant after training by the experimenter. All other landmark locations were recorded by the experimenter. The entire measurement required approximately 60 s, after which the participant exited the mockup to prepare for the next trial. Testing with each participant lasted approximately 2 h.

Data Analysis

The body landmark data were used to calculate the locations of joints defining a kinematic-linkage representation of the body, illustrated in Figure 5. These landmark acquisition procedures and methods for estimating joint locations are described in detail in Reed, Manary, and Schneider (1999). For example, hip joint locations were estimated using the measured locations of the anterior-superior iliac spine and pubic symphysis landmarks. The resulting body segment positions and orientations were analyzed to determine the effects of the experimental variables on driving posture. Six variables of primary interest are defined in Table 4

TABLE 3: 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[a], T12[a]	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[a] (PSIS; right and left)	Depressed skin surface point at the posterior-superior iliac spine, 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 participant by palpating inferiorly on the midline of the abdomen until reaching the pubis. The participant 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.

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TABLE 3 (continued)

Landmark	Definition
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.

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

and illustrated in Figure 6. *HipX* is the horizontal location of the hip joint (average of right and left) aft of BOF. *Hip-to-eye angle* is the side-view angle of a vector from mean hip to the center-eye point with respect to vertical and is a measure of overall torso recline. The *center-eye point* (hereafter called the *eye point*) is an eye location estimate on the body centerline with the fore-aft coordinate of the infraorbitale landmark, the lateral coordinate of the glabella landmark, and the vertical coordinate of the corner-eye landmark.

RESULTS

Data from Phases 1 and 2 for Conditions 1 through 10, representing five steering wheel positions at two seat cushion angles, were extracted for initial analysis. Steering wheel positions were normalized by subtracting the midrange value at the 270-mm seat height (550 mm). Within-subject analysis of variance (ANOVA) identified highly significant effects of both test variables on most of the posture variables of interest. Table 5 summarizes effects that were significant with $p < .01$. In no case was the interaction between seat cushion angle and steering wheel position significant.

Steering wheel position had a strong effect on fore-aft hip joint location (HipX). Moving

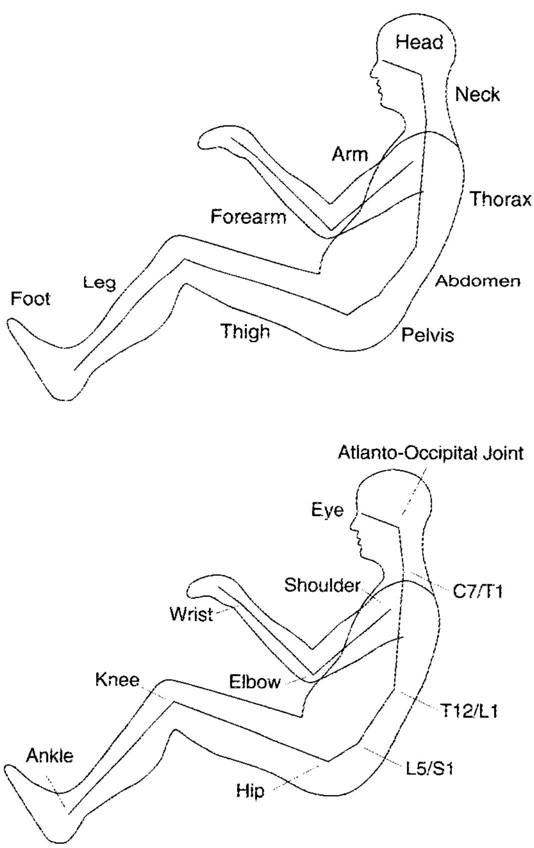

Figure 5. Kinematic linkage representation of driving posture.

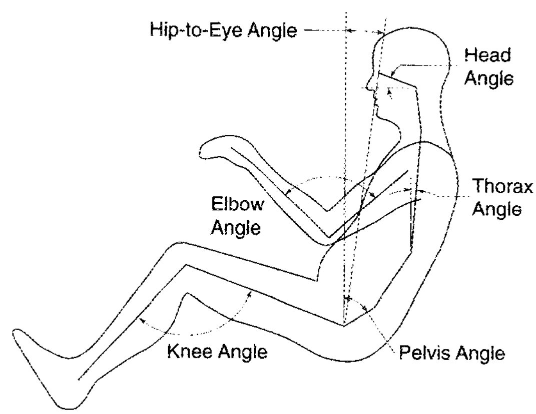

Figure 6. Illustration of posture variables.

TABLE 4: Posture Variable Definitions

Variable	Definition
HipX	Fore-aft distance from the mean hip joint location to the ball-of-foot reference point
Hip-to-eye angle	Angle in the side view (x,z) plane of the vector from the mean hip joint to the center eye point with respect to vertical
Center eye point	An eye location estimate on the body centerline with the fore-aft coordinate of the infraorbitale landmark, the lateral coordinate of the glabella landmark, and the vertical coordinate of the corner-eye landmark
Pelvis angle, thorax angle, head angle	*x,z* (side view) plane angle of the respective segment with respect to vertical
Lumbar flexion	Pelvis angle minus thorax angle
Cervical flexion	Head angle minus thorax angle
Elbow angle	Angle between the arm and forearm segments in the plane of the segments; smaller values indicate greater flexion
Knee angle	Angle between the thigh and leg segments in the plane of the segments; smaller values indicate greater flexion

TABLE 5: Effects of Steering Wheel Position and Seat Cushion Angle: Configurations 1–10 in Phases 1 and 2

Variable	Normalized Steering Wheel Position (–100 to +100 mm)	Seat Cushion Angle (11°–18°)
HipX (mm)	89.6	–6.0
Hip-to-eye angle	3.1	0.59
Lumbar flexion	*n.s.*	2.0
Cervical flexion	*n.s.*	*n.s.*
Elbow angle	–26.5	*n.s.*
Knee angle	16.3	–3.6

Note: Listed values are mean differences between conditions. Positive values indicate the indicated change in the independent variable resulted in a rearward, more reclined, or more flexed dependent variable value. *N.s.* indicates effect was not significant ($p > .01$).

the steering wheel rearward 200 mm from the most forward position resulted in an average rearward movement of the hip joint of about 90 mm. The rearward movement of the steering wheel reduced elbow angle by an average of 26.5° while increasing knee angle by 16.3°. Overall torso recline (hip-to-eye angle) increased about 3° with the 200-mm increase in steering-wheel-to-pedal distance. The significant effects of steering wheel position were largely linear. Figure 7 illustrates the steering wheel and seat cushion angle effects on HipX. The effect of steering wheel position on hip location is approximately linear over a 200-mm range, and the steering wheel effect is very similar for the two seat cushion angles.

Changing the seat cushion angle from 11° to 18° had significant but smaller average effects on posture. The higher cushion angle resulted in hip joint locations an average of 6 mm further forward and increased overall torso recline by less than 1°. Net lumbar spine flexion increased by 2°, but cervical flexion was not significantly affected. Elbow angles were not significantly affected, but knee angles were reduced an average of 3.6°.

In Phase 1, the participants were free to posi-

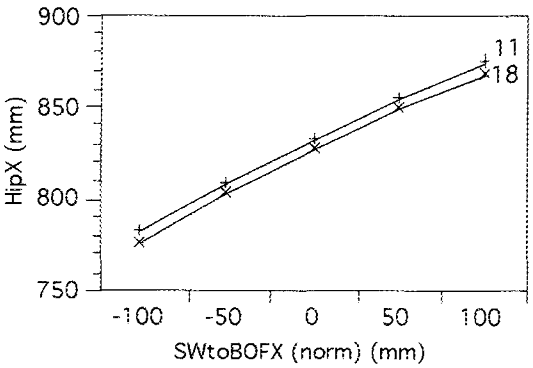

Figure 7. Steering-wheel-position and seat-cushion-angle effects on HipX in Phases 1 and 2, Configurations 1–10.

tion their hands at any location on the steering wheel, whereas in Phase 2 the hand locations were restricted to 10 o'clock and 2 o'clock. There were no significant differences in torso posture between the phases, indicating that the hand location restrictions did not have important effects on torso posture.

Seat Effects and Interactions

In Phase 3, six of the conditions tested in both Phase 1 and Phase 2 were repeated with different participants and with a different seat. Data from these conditions (2, 3, 4, 7, 8, 9) were extracted to assess differences in posture between seats and potential interactions between the seat type and the steering wheel position or seat cushion angle.

There were two significant differences in average posture between the two seats, using a between-subjects comparison. The participants in the Neon seat sat an average of 15 mm further forward (HipX) and with 3.4° less lumbar flexion than the participants in the Taurus. The difference in HipX is attributable partly to the fact that the Neon participants were about 7 mm shorter, on average, than the Taurus participants. Shorter-stature drivers are known to select more forward seat positions, on average (Flannagan et al., 1998). Torso recline was not significantly different between the seats.

More important, however, the effects of the steering wheel position and seat cushion angle on the posture variables did not differ significantly between the seats ($p > .05$ for the interaction terms). This suggests that the effects of these two variables on posture do not depend on the seat geometry.

Seat Height Effects and Interactions

In Phases 2 and 3, trials were conducted at three seat heights (180, 270, and 360 mm) and with two steering wheel positions at each seat height. Taking only the data from the Phase 3 550-mm steering-wheel conditions (Configurations 3, 8, 12, 15, 16, and 19) gives an orthogonal 3 × 2 design with seat height and seat cushion angle (24 participants). In these data, there are no significant effects of seat height on lumbar flexion, cervical flexion, or hip-to-eye angle, nor are there any significant interactions between seat height and seat cushion angle. However, there is a significant, apparently nonlinear effect of seat height on HipX. The average hip location moved forward 9 mm as the seat height was raised from 180 to 270 mm but moved forward 25 mm when the seat height was raised from 270 to 360 mm.

This analysis was expanded to examine potential interactions between steering wheel position and seat height. To eliminate the numerical correlation of the variables, steering wheel position was recoded relative to the presumed neutral position at each seat height (600, 550, and 500 mm for the 180-, 270-, and 360-mm seat heights, respectively). In the data from Phase 3, Conditions 2, 4, 7, 9, and 12 through 19 form a 3 × 2 × 2 design in seat height, SWBOFX, and seat cushion angle. Using a within-subject ANOVA, the main effects and interactions were tested for each of the dependent variables. None of the potential two-way interactions was significant, nor was the three-way interaction ($p > .10$ in all cases). The main effect estimates for the three variables were similar to those obtained using other analyses.

Gender Differences

Participant Groups 4, 5, 6, and 7 contained men and women of similar stature. Using only these groups (24 participants) and data from Phases 2 and 3, an ANOVA was conducted to determine whether or not the effects of the test variables differed between men and women. No significant interactions with gender were observed, indicating that the test variables affect the driving postures of men and women similarly.

DISCUSSION

A three-phase laboratory study was conducted to determine the effects of seat height, fore-aft steering wheel position, and seat cushion angle on driving posture. Analyses focused on three measures of torso posture and three measures of limb posture. The principal observations are as follows.

- Seat height, steering wheel position, and seat cushion angle each have significant, largely independent effects on posture.
- The effects of these three variables are independent of body size, proportion, and gender.
- Overall body size (stature) is the primary determinant of fore-aft hip position with respect to the pedals, but seat height, steering wheel position, and seat cushion angle all have significant effects.
- The ratio of sitting height to stature is an important predictor of hip-to-eye angle and elbow angle.
- Knee and elbow angles, the primary measures of limb posture, are strongly influenced by seat height and steering wheel position. Over the range studied, steering wheel position has the stronger effect.
- Seat cushion angle has a highly significant effect on both lumbar flexion and overall torso recline, but the importance of the effect is diminished by the restricted range of this variable in vehicle designs.

The most important observation from this study is that postural adaptations to changes in the layout of the driving task are accomplished primarily by changes in limb posture, whereas torso posture remains largely unaffected. Instead, torso posture appears to be determined primarily by intersubject differences that are not closely related to overall anthropometric variables. A typical sitter's spine flexion does not vary substantially across different vehicle layouts but may differ considerably from that of other sitters.

Of the three package and seat variables studied, the fore-aft steering wheel position is the most important. If the steering wheel is moved forward 100 mm, drivers respond by moving their hips about 45 mm closer to the pedals, accounting for about half the change in steering wheel position. The change in hip location is associated with an average reduction in knee angle of about 8°. The more-forward steering wheel position (65 mm farther in front of the hips) results in elbow angles that are larger by an average of 13°. In contrast to the relatively large changes in limb posture, hip-to-eye angle is reduced by less than 2°.

The two seats that were tested produced different average postures, but the differences are difficult to interpret because different participants were used. The seat with the subjectively more prominent lumbar support, the Neon, produced postures with less average spine flexion. This finding is consistent with previous studies (Reed & Schneider, 1996; Reed, Schnieder, & Eby, 1995), in which prominent lumbar supports have been found to cause statistically significant but small reductions in the lumbar spine flexion of drivers. More important, however, the effects of seat height, steering wheel position, and seat cushion angle were not significantly different for the two seats, suggesting that these effects can be considered to be independent of seat type. A small nonlinearity in the effect of seat height on fore-aft hip location did not contribute substantially to the overall regression prediction. Similar findings were reported by Flannagan et al. (1996) with regard to driver-selected seat position.

The findings of this study are directly applicable to vehicle interior design, for which the accurate prediction of occupant posture is of considerable importance. Although seat height is often set early in the design process and substantially constrained by exterior styling considerations, the fore-aft steering-wheel position and seat-cushion angle can be manipulated more readily to accomplish design goals. The findings from this study will help designers to predict more accurately the effects of these changes on driver posture.

This study was conducted in a laboratory mockup, without many of the spatial and visual cues that are present in an actual vehicle and that could affect posture, such as mirrors, doors, and seat belts. However, other studies conducted in conjunction with this work have shown that these factors may not substantially reduce the generalizability of the findings. For example, changes in forward vision restrictions resulting from varying instrument panel height do not affect driving posture in important ways (Reed, 1998). Further, comparison of posture predictions derived from these laboratory data with in-vehicle driver postures indicate that the postures measured in this study can reliably be used to predict actual driving postures (Flannagan et al., 1996; Reed, 1998).

One vehicle geometry variable not examined in this study is vertical steering wheel position. This variable was excluded because, in practice, there is little flexibility for vertical positioning with respect to the seating reference point. Examination of interior geometry data from dozens of vehicles has shown that steering wheel height above the seating reference point is a nearly constant value, because the uppermost possible position is constrained by the vision requirements of people with low eye heights and the lowermost position is constrained by knee clearance and ingress-egress requirements. In subsequent studies with a vertically adjustable seat position, the vertical steering wheel position will be examined as a potential important factor relating to driver-selected seat height.

The two most important restrictions on these findings pertain to the use of a two-way (one-degree-of-freedom) seat track. Although most vehicles are still designed initially using a two-way track, an increasing number of vehicles are being designed and sold with a larger range of adjustment, particularly so-called six-way seat tracks that allow the seat height, seat cushion angle, and fore-aft seat position to be adjusted. Although research is presently under way to quantify driver behavior when these additional adjustments are available, the data from the current study should be understood to apply only to two-way tracks. Further, the seat track in this study allowed all participants to select their preferred seat position without restriction. In many vehicles, the seat track length is insufficient to accommodate every driver at his or her preferred location, resulting in censoring of the seat position distribution and potentially changing posture in ways that are not encompassed by the findings of the current study.

In addition to seat-adjustment limitations, the postures measured in this study were obtained after the driver had been seated for only about 1 min. Postures over a longer driving session could be different, although Reed et al. (1995) found only small changes in posture during long-term driving simulations. In dynamic, on-road driving, there appear to be small but important changes in eye location associated with driving duration, probably attributable to gradual compression of the seat foam (Flannagan et al., 1996; Manary et al., 1998).

These findings are also limited by the health and age of the participants. Although the participants ranged in age from 21 to 75 years (average 35 years), the behavior of a geriatric population might differ from the relatively fit participants used in this testing.

With respect to anthropometry, the participants spanned a wide range of stature relative to the U.S. population. As noted, the effects of anthropometry on posture were largely linear and generally did not interact with the effects of package geometry. However, the small number of participants in each stature category may influence the generalizability of the findings.

This research does not purport to identify ideal or optimal locations for vehicle components but, rather, examines the effects of particular component locations on driving posture. Although vehicle design is aided by the identification of desirable component locations, particular positions are ultimately selected. At that point, accurate predictions of the resulting driving postures are necessary to complete the interior design (e.g., to locate secondary controls and displays) and to assess the potential distribution of postural comfort in the target population. Thus accurate posture prediction is required to begin the process of identifying optimal control locations.

CONCLUSIONS

Drivers adapt to changes in the vehicle and seat geometry primarily through changes in limb posture, whereas torso posture remains fairly constant. Large differences in torso posture between participants are not well predicted by anthropometric differences. Seat height, steering wheel position, and seat cushion angle have effects on driving posture that are largely independent of body size and gender.

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