Effects of Occupant and Vehicle Factors on Three-Point Belt Fit in Rear Seats

Jangwoon Park, Sheila M. Ebert, Matthew P. Reed, and Jason J. Hallman

Abstract Seat belt fit relative to the occupant's anatomy affects kinematics and may affect injury risk in crashes. Recent studies have shown that belt routing for drivers is significantly associated with occupant characteristics, particularly body mass index (BMI), as well as belt upper anchorage location. The current research study examined belt positioning and fit in rear seating conditions with fixed seat back angles and a range of lower extremity postures. Lap-belt and shoulder-belt fit were measured in a rear seat mockup for 89 men and women with a wide range of body size and age. On average, the participants wore the lap belt fully above the anterior superior iliac spine landmark on the pelvis. High BMI was associated with occupants wearing the belt in higher and more-forward lap-belt positions. An increase in thigh angle relative to horizontal, which may occur with lower seat heights and constrained foot positions, was associated with occupants using higher lap belt positions. Age also had significant effects on how the lap and shoulder belt was worn, as did belt anchorage locations. These results suggest that continued research is needed to determine effective interventions to improve belt wearing and fit for rear-seat occupants.

Keywords Belt fit, Body mass index, Rear seat, Age effects

I. INTRODUCTION

Three-point seat belt restraint systems in passenger cars and light trucks are effective in saving lives and reducing serious injuries. These systems are designed to engage an occupant's pelvis and clavicle in a frontal crash. This engagement directs the restraint force primarily onto the skeleton rather than adjacent soft tissues. Poor belt fit may reduce restraint effectiveness, depending on the particular crash circumstances. Direct belt loading to the abdomen has been associated with abdominal injury in experiments with post-mortem human subjects [1].

Several studies have been conducted to quantify factors affecting belt fit in driver seats [2][3] and to develop methods for assessing belt fit using manikins [4][5]. The most recent studies with human volunteers [3] have shown that individuals with higher BMI tend to place the lap belt further forward and higher relative to the pelvis than those with lower BMI. Age, stature and belt upper anchorage location also had statistically significant effects on how the belts were worn.

The current study applied similar methods to quantify belt fit for a diverse group of men and women in a fixed-seat condition typical of second- or third-row seat. The overall goal was to quantify the relationships between belt fit and occupant factors, such as stature, BMI and age, along with seat and belt configuration factors. The results are expected to be useful for improving the understanding of how occupants use safety belts in rear seats with the aim of developing future improved restraint systems.

II. METHODS

Participants

Eighty-nine adults (46 men and 43 women) were recruited through online advertisements and word of mouth. The participants ranged in age from 21 to 95 years old, with a mean of 58.7 years old (SD=18.4). Descriptive statistics of 25 standard anthropometric dimensions obtained from all the participants are summarised in Table I. Written informed consent was obtained using a form approved by the University of Michigan Institutional Review Board for Health Behavior and Health Sciences (HUM00054993). The participants wore test garments made of thin material that provided good access to body landmarks.

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TABLE I
DESCRIPTIVE STATISTICS OF ANTHROPOMETRIC MEASUREMENTS (N = 89)

(UNIT: MM)

					Percentile		
Anthropometric dimension	Mean	SD	Min	Max	5th	50th	95th
Stature with shoes	1696	106	1464	1895	1545	1696	1866
Stature w/o shoes	1672	107	1451	1877	1517	1667	1844
Weight (kg)	75.7	16.4	48.5	116.3	50.1	74.0	106.7
BMI (kg/m^2)	27.0	4.8	17.4	42.4	19.2	27.0	34.9
Erect sitting height	868	53	739	982	798	860	967
Sitting eye height	756	52	631	875	676	752	840
Acromial height	575	41	480	677	517	569	655
Knee height	522	40	431	595	462	524	583
Tragion to top of head	118	10	97	140	103	119	135
Head length	192	9	170	211	177	194	205
Head breadth	152	8	140	193	142	150	168
Shoulder-elbow length	356	29	292	436	311	359	405
Elbow-hand length	453	37	365	519	399	454	502
Hip breadth	388	35	328	515	341	382	446
Buttock-knee length	599	41	511	704	531	600	662
Buttock-popliteal length	508	37	423	601	443	510	562
Biacromial breadth	372	33	279	519	325	370	423
Shoulder breadth	452	36	382	516	399	443	512
Chest depth scapula	266	33	175	330	212	268	318
Chest depth spine	224	34	154	300	161	225	281
BiASIS breadth	232	26	180	320	192	230	268
Chest circumference	1032	108	815	1262	846	1032	1216
Waist circumference	983	135	729	1284	762	978	1183
Hip circumference	1051	88	872	1350	909	1056	1170
Upper thigh circumference	568	58	424	697	486	564	665

Note: ASIS = anterior superior iliac spine; BMI = body mass index.

Apparatus

Testing was conducted in a reconfigurable rear seat laboratory mock-up (Fig. 1) and additional data were gathered in a special purpose hardseat (Fig. 2). A FARO Arm coordinate digitiser was used to measure the locations of body landmarks and the placement of the lap and shoulder portions of the belt. The rear seat mockup was constructed using components from a 2011 minivan rear seat, which was modified to achieve a high level of adjustability. The seat height and seatback angle could be adjusted by the experimenters. The hardseat had a rigid seat pan and a back with a cutout that allowed access to posterior spine and pelvis landmarks that were inaccessible in an automotive seat. The hardseat had a 14.5° cushion angle and 23° seatback angle designed to produce postures similar to those in an automotive seat. The hardseat data were used to create a subject-specific model of the spine, pelvis and lower-extremities, which were used to aid interpretation of the data from the rear-seat mock-up [6].

Fig. 1. Reconfigurable rear seat mockup and recording a participant's ASIS landmark location using a FARO Arm coordinate digitiser.

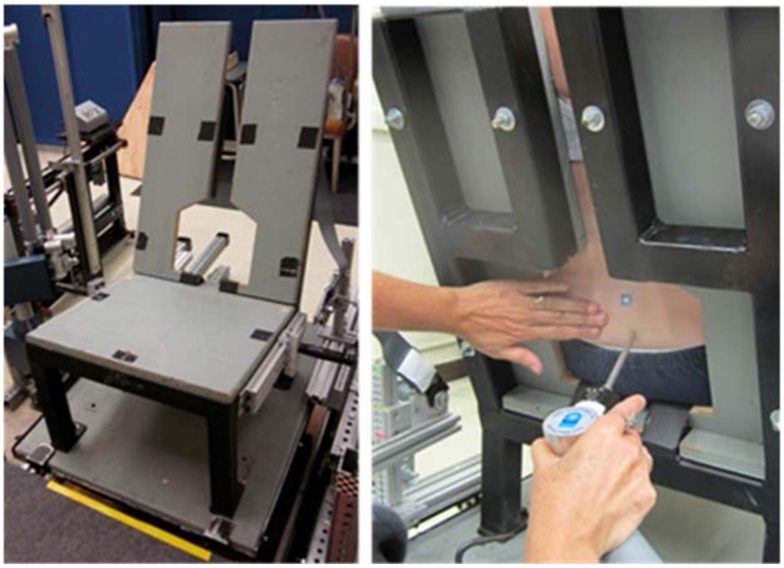


Fig. 2. Hardseat and recording a participant's PSIS landmark location using a FARO Arm coordinate digitiser.

Test Conditions

Lap-belt and shoulder-belt positions were recorded in 25 test conditions (Table II). The test conditions included three seatback angles (SAE A40: 19°, 23° and 27°), three seat heights (SAE H30: 180, 270 and 360 mm), three foot positions (*back*: pulled back as far as possible; *flat*: resting with the soles flat on the floor and with feet slid forward: and *heel*: resting on the heels; see Fig. 3), three lower anchorage XZ angles (30°, 52° and 75°; see Figure 4), and three D-ring YZ and XZ angles (22° and 41°, 28° and 35° and 35° and 27°; see Fig. 5) relative to the seating reference point (SgRP).

Among the 25 test conditions, 21 conditions (conditions nos. 1–12 and nos. 17–25 in Table II) were designed to identify effects of occupant posture on the lap-belt and shoulder-belt fit. The other four conditions (conditions no. 13, 14, 15 and 16) were manipulated to identify the effects of lower anchorage and D-ring angles on the lap-belt and shoulder-belt fit, respectively. The 3D coordinate system in the present study was defined by following the SAE practice [7]: the *x*-axis is positive rearward, the *y*-axis is positive to the passenger's right, and the *z*-axis is positive upward.

TABLE II
TEST CONDITIONS

Condition number	Seatback angle (A40; °)	Seat height (H30; mm)	Foot position	Lower anchorage angle *re*SgRP (°)	D-ring angle *re*SgRP (°)	
				XZ	*YZ*	*XZ*
1	19	270	*back*	52	28	35
2			*flat*			
3			*heel*			
4		360	*back*	52	28	35
5			*flat*			
6			*heel*			
7	23	180	*back*	52	28	35
8			*flat*			
9			*heel*			
10		270	*back*	52	28	35
11			*flat*			
12			*heel*			
13		270	*flat*	30	28	35
14			*flat*	75		
15			*flat*	52	35	27
16			*flat*		22	41
17		360	*back*	52	28	35
18			*flat*			
19			*heel*			
20	27	180	*back*	52	28	35
21			*flat*			
22			*heel*			
23		270	*back*	52	28	35
24			*flat*			
25			*heel*			

Note: SgRP = seating reference point.

Fig. 3. Illustrations of foot positions: *(from left to right) back*, *flat* and *heel*.

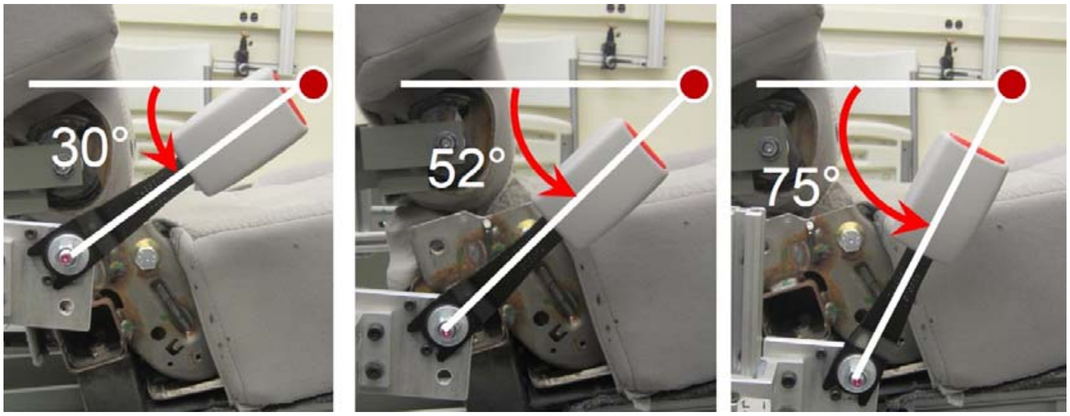


Fig 4. Illustrations of lower anchorage XZ angles 30°, 52° and 75° relative to SgRP.

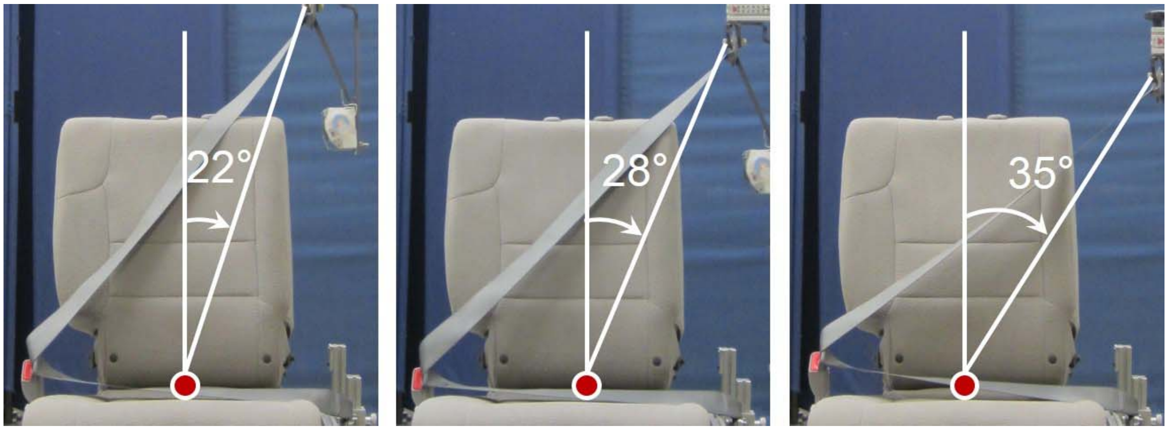
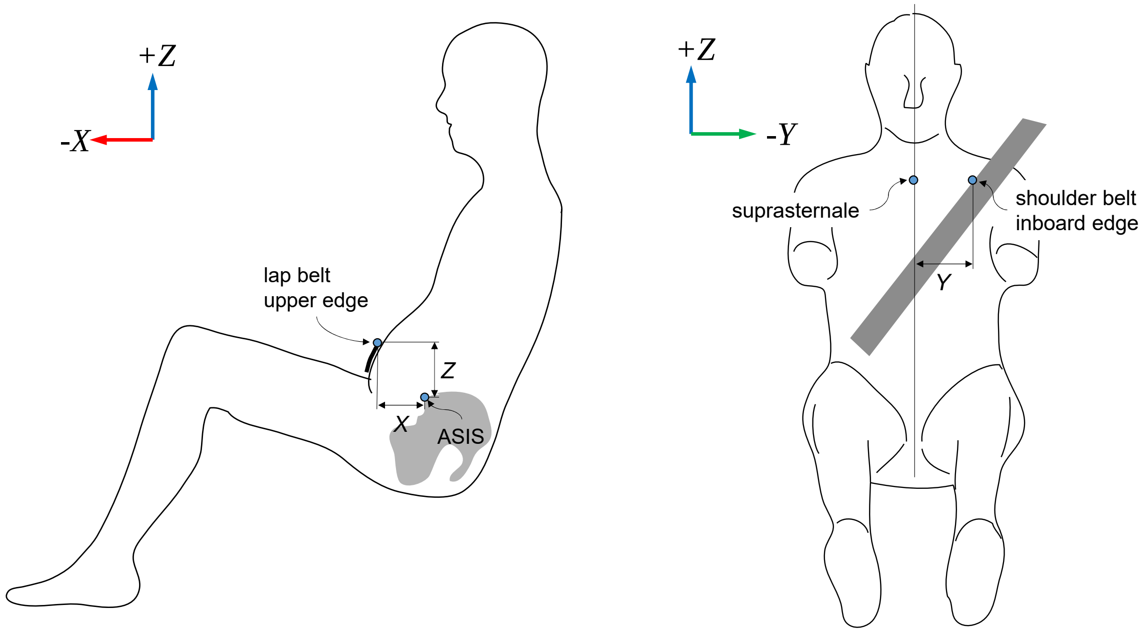


Fig 5. Illustrations of D-ring YZ (front-view) angles 22°, 28°, and 35° relative to SgRP. The corresponding D-ring XZ (side-view) angles were 41°, 35° and 27°, respectively.

Measurement of Lap-belt and Shoulder-belt Fit

Prior to measuring lap-belt fit, pelvis locations of each participant across all the test trials were estimated based on the relationships among landmarks on the body surface and pelvis bone. As flesh margins between bone ASIS and digitised body surface ASIS have been found to vary with BMI [3][6], statistical models were developed to estimate pelvis bony landmark locations (ASIS, PSIS, hip joint, and L5/S1) based on the hardseat data. An optimisation algorithm was applied to fit each participant's pelvis and femur geometry, as measured in the hardseat, to the data from the seat mockup [6]. Other joint locations such as knee joint location were estimated using previously developed statistical models [8].

Lap-belt and shoulder-belt fit were quantified using the same dimensions as in previous research on drivers [3]. Lap-belt fit (Fig. 6(a)) was measured as fore-aft (X) and vertical (Z) distances (unit: mm) from the estimated bone ASIS location on the outboard side to the upper edge of the lap belt at the same lateral position. Negative lap-belt fit X indicates that the lap belt positioned forward of the bone ASIS and positive lap-belt fit Z indicates the lap belt positioned higher relative than the bone ASIS. Shoulder belt fit (Fig. 6(b)) was measured as the lateral (Y) distance (unit: mm) from suprasternale to digitised inboard edge of shoulder belt. Negative shoulder-belt fit Y indicates that the inboard edge of shoulder belt lies outboard of the suprasternale.



(a) lap-belt fit *X* and *Z*
relative to outboard ASIS

(b) shoulder-belt fit *Y*
relative to suprasternale

Fig 6. Illustrations of the lap-belt and shoulder-belt fit measures.

III. RESULTS

Lap-belt Overview

Fig. 7 shows the lap belt fit in condition 11, the centre condition for the lap-belt matrix. On average, the upper edge of the belt was 50 mm above and 35 mm forward of the ASIS (note that negative values of lap-belt X indicate that the belt is forward of the pelvis). For obese participants, the belt was on average further forward and higher relative to ASIS than for non-obese participants. These findings were statistically significant ($p<0.01$).

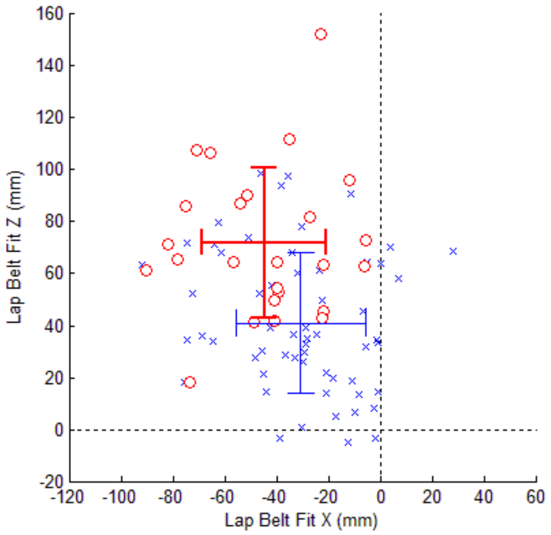


Fig. 7. Lap belt locations relative to ASIS landmarks for obese (BMI ≥ 30 kg/m^2, *n* = 25; o, thick lines) versus non-obese (BMI < 30 kg/m^2, *n* = 59; x, thin lines) participants in condition number 11. Lap-belt fit X *mean* ± *SD* = -35 ± 25 mm overall, -45 ± 24 mm for obese, and -31 ± 25 mm for non-obese. Lap-belt fit Z *mean* ± *SD* = 50 ± 31 for overall, 72 ± 29 for obese, and 41 ± 27 for non-obese. Bars shown mean ± *SD* by obesity group.

Lap-belt Regression Analysis

Conditions 1–12 and 17–25 provided the ability to analyse the effects of seat height, seat back angle and foot position. A regression analysis was conducted with these three factors and their interactions as potential predictors along with stature, BMI and the ratio of sitting height to stature (SHS) as potential predictors. Interactions between the participant descriptors and the seat and posture factors were also considered. To improve the interpretability of the foot-position effect, thigh angle with respect to horizontal, which was strongly related to foot position, was substituted in the regression analysis. Thigh angle was computed as the side-view angle of the vector from hip to knee with respect to horizontal. Mean thigh angle ranged from 15 degrees in the "heel" foot position to 32 degrees in the "flat" foot position. A stepwise regression method was used with $p<0.01$ to enter and $p>0.05$ to leave, followed by manual adjustment of the model. Only terms significant with $p<0.01$ that also increased the R^2_{adj} value by more than 0.02 were retained. The regression models are:

$$\text{Lap-belt X (mm)} = 73.6 + 0.522\ SBA - 0.017\ S - 3.30\ BMI - 0.359\ Age + 0.265\ TA,\ R^2_{adj} = 0.48,\ RMSE = 19.2$$

$$\text{Lap-belt Z (mm)} = -32.8 + 3.84\ BMI - 86.8\ SHS + 0.137\ Age + 0.714\ TA,\ R^2_{adj} = 0.53,\ RMSE = 20.2$$

where, SBA is seat back angle (degrees), S is stature (mm), SHS is the ratio of erect sitting height to stature (mm/mm), BMI is body mass index (kg/m^2), Age (years), TA is thigh angle with respect to horizontal (degrees).

More reclined seatback angles were associated with a more rearward belt position relative to the pelvis, but increased stature, BMI and age were all associated with more-forward belt positions. Higher thigh angles produced by the combination of seat height and foot position, were associated with more-rearward belt positions. The lap belt was higher for individuals with higher BMI and higher age, but lower for those with a shorter torso relative to stature. Higher thigh angles were associated with higher lap belt positions relative to the pelvis.

The effects of lap-belt angle and lap-belt fit were examined using conditions 11, 13 and 14, within which the nominal lap-belt angle varied from 30 to 75 degrees. Table III shows the mean and standard deviation of lap belt X and Z position at each belt angle. On average, increasing the belt angle from 30 to 75 degrees (more vertical in side view) shifted the belt forward by 18 mm and downward by 14 mm (both $p<0.001$). However, these effects were smaller than the within-condition standard deviation.

Table III

MEAN (SD) EFFECTS OF LAP BELT ANGLE ON LAP BELT FIT

	Lap-belt Angle (deg)		
Variable	30°	52°	75°
Lap-belt fit *X* (mm)	-30 (30)	-35 (25)	-49 (23)
Lap-belt fit *Z* (mm)	60 (26)	50 (31)	47 (27)

Effects on Shoulder-belt Fit in Rear Seats

As expected, moving the D-ring further outboard (increasing YZ angle) resulted in the shoulder belt being positioned further outboard. The mean (SD) of shoulder belt scores for the 22-, 28-, and 35-degree YZ D-ring angles were 17 (21) mm, 55 (30) mm and 180 (71) mm, respectively. A regression analysis as conducted to assess the effects of participant characteristics and to test potential interactions between the D-ring location and participant characteristics. No significant interactions were noted. Surprisingly, taller stature (or larger erect sitting height) was not significantly associated with shoulder-belt fit. The linear and squared YZ D-ring angle terms dominated the regression, but greater Age was associated with a more inboard shoulder-belt position. BMI and gender did not have important effects. The regression model is:

$$\text{Shoulder-belt Fit (mm)} = 475 - 0.624\ Age - 39.0\ DringYZAngle + 0.904\ DringYZAngle^2,\ R^2_{adj} = 0.71,\ RMSE = 45$$

The relatively high R^2 value is due primarily to the strong effects of the D-ring angle, although Age was also significant (p<0.001).

The practical importance of the statistically significant effects identified in the regression models can be assessed by considering how much the factors vary across the occupant population and range of design variables. Table IV summarises the results of multiplying the effects from the regression models by relevant ranges of the independent variables and covariates. For example, the age effect is illustrated by showing the difference in outcomes for ages 20 and 80 years (a difference of 60 years).

BMI is the most important factor affecting lap-belt fit, with higher BMI associated with higher and more-forward belt positions. Age has a stronger effect on fore-aft lap-belt position than on vertical position, and the upward displacement of the lap belt with higher thigh angles is more than twice as great as the average rearward displacement. Shoulder-belt fit was affected to a much larger extent by the range of D-ring YZ angles tested than by the range of age.

TABLE IV
FACTOR EFFECTS (MM)

Variable	Age (60 yrs)	BMI (20 kg/m^2)	Stature (300 mm)	SHS (0.08 mm/mm)	TA (25˚)	SBA (8˚)	Lap *XZ* angle (45˚)	D-ring *YZ* angle (13˚)
Lap-belt fit *X*	-22	-66	-5		7	4	-19	
Lap-belt fit *Z*	8	77		-7	18		-13	
Shoulder-belt fit *Y*	-37							163

Note: numbers in the parentheses are the range values of each factor; SBA = seatback angle (°), Age (years), BMI = body mass index (kg/m^2), D-ring YZ angle (°), H30 = seat height (mm), S = stature (mm), SHS = sitting height divided by stature, TA = thigh angle (°), Lower anchorage XZ angle (°).

IV. DISCUSSION

This study is the first large-scale study to report detailed data on belt fit for occupants in a fixed rear seat environment. Consistent with previous studies of drivers [2][3], high BMI was associated with lap-belt locations that are higher and further forward relative to the pelvis. Age also had a relatively strong effect, with older occupants typically placing the belt further forward relative to the pelvis. This is likely due to the effects of age on lower abdomen shape, although more research will be needed to determine how much of the effect is behavioural rather than anthropometric.

Lap-belt angle, determined by anchorage locations relative to SgRP, had statistically significant effects on lap belt fit that were consistent across conditions and study participants. However, across the range that is permitted under US Federal Motor Vehicle Safety Standard 210, the improvement in the vertical position of the lap belt in relation to the pelvis with steeper belt angles is less than a third of the effect of a 20 kg/m^2 increase in BMI (approximately the difference between 5th and 95th percentile BMI in the US). Moreover, the improvement in vertical lap belt location was accompanied by an increase in the fore-aft distance between the belt and the pelvis, which could result in greater excursions in a frontal crash. Hence the optimal belt angle is not clear, although these results also suggest that it may depend on vehicle packaging through the effects of thigh angle on belt placement.

The findings are similar to the findings for drivers [3]. The effect of BMI was dominant for both seating positions, although the estimated effect across the population was smaller than for drivers. The source of this difference is unclear, although it could be related to posture differences between drivers and rear passengers. The age effect in the current study is similar to that found for drivers, with the belt placed further forward relative to the pelvis for older occupants.

Shoulder-belt fit was strongly influenced by D-ring location over the range tested in this study, which was determined through measurements of vehicles [3]. Surprisingly, occupant stature and torso length did not have strong effects on belt fit. However, older age was associated with more-inboard shoulder belt fit. It is not yet clear whether this finding is due to differences in body shape, posture or belt-donning behaviour. However, it does suggest that the average pattern of belt loading to the chest may be different for senior occupants.

Combined with the finding of a significant age effect on lap-belt fit, these results suggest that further investigation of belt loading for older occupants is warranted, particularly since that cohort is known to be at higher risk of injuries in frontal impacts [9].

This research study is limited in some important respects. In particular, only one seat with minimal features was used. A seat with a short cushion length was chosen because previous research has shown that typical rear-seat cushion lengths are on average too long for many adults and cause slouching [10]. Foot placements were chosen to produce a large range of lower-extremity postures, but the data do not indicate which postures are more likely as a function of rear compartment layout. The short duration, laboratory setting may have produced postures and belt fit that are less slouched and more symmetrical, on average, than would be expected in dynamic, longer duration settings.

Future research should address the consequences of the patterns of belt placement and fit documented in this study, while taking into account the fact that rear seat belts must offer protection to a wide range of occupants, from children to adults with widely differing body sizes [11]. Other design factors that address occupant comfort and ease of child restraint installation must be taken into consideration. Some participants' high lap-belt positions are a cause for concern. A previous study of frontal impact protection in rear seats with obese post-mortem human subjects (PMHS) demonstrated poor kinematics, with submarining of the obese occupant [12]. In that study, equipping the belt with a pretensioner and load limiter improved performance. However, the placement of the belt in that study was not based on measurements of vehicle occupant belt fit. The data from the current study will be useful in obtaining realistic belt fit for simulations with computational human models of adult occupants as well as physical testing with PMHS and ATDs [13]. Data from these simulations will be useful for assessing the consequences of the belt fit observed in this study and developing future improvements that are effective, particularly for older occupants and those with higher BMI.

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