INFLUENCE OF SEAT DESIGN ON THE KINEMATICS AND LOADINGS OF THE BELTED DUMMY

by

D. Adomeit and H. Appel

Institute of Automotive Engineering, Technical University Berlin

1. BACKGROUND / OBJECTIVE OF THE STUDY

The seat unquestionably represents an important element for the vehicle occupant protection system. It indeed plays a significant role in the protective effect of the safety belt, as we shall show in the following (1, 2).

To begin, safety belt statistics themselves have revealed belt-related injury patterns which make clear the significance of the seat.

The characteristics of the lower seat framework are responsible for the kinematics of the belted-in occupant, and are therefore determining for the manner of introduction of restraint forces into the occupant's body.

A systematic study of seat-safety belt interaction is therefore urgently necessary. This urgency is all the greater since there are neither national nor international regulations or standards which stipulate minimum requirements for vehicle seats in their interaction with the safety belt under conditions of frontal crash. The well-known requirements for the *strength* of seats alone, in accordance with ECE Reg. 17/FMVSS 207, do not directly concern these interactions.

The objective of this paper is a systematic representation of the influence of seat design on the effectiveness of the three-point automatic belt system. It shall also represent a brief analysis and interpretation of parallels with results from other study sources. Investigation has been made of current production seats under frontal crash conditions.

2. TEST CONDITIONS

Tests were performed on a pneumatic catapult, similar to the Bendix system, with the advantage of easily reproducible preconditions.

Sled deceleration was an approximate 28-g, half-sine pulse lasting for 65 to 70 milliseconds, with a Δv value of approximately 40 km/h. The fully equipped dummy (a Part 572, 50% man) was used in conjunction with a sled system provided with complete measuring and filming systems.

The technical evaluation of the data gathered was performed in the conventional manner in accordance with FMVSS 208. Mention must be made, however, that the high-speed film (500 frames per second) was subjected to highly sophisticated evaluation techniques for the determination of the trajectories and rotation of the dummy head, chest, pelvis, and knee. To accomplish this, it was necessary to provide the dummy skeleton with special markings—a method described in greater detail in the next section.

Parallax distortions, unavoidable in such tests, were eliminated in the film evaluation by means of geometric plan view reconstruction.

2.1 Setup of testing

Care was taken during testing of the seats on the catapult sled that excessive simplification of the reality of actual vehicle interiors did not occur: such could change or even reverse the principal tendencies of the test results. Certain well-known influences of the individual vehicle pulse form, the rigidity of the interior structure (belt anchor points, car floor complex, etc.), and the like, on the level of loading were accepted within the context of greater stringency imposed by sled conditions less favorable than those in actual vehicles. This is justified because the kinematic variables are not basically affected thereby, as the results below will show.

The seats with their original slide mounting and occupant adjusting fixtures were rigidly mounted to the slide frame in their original angular configuration and at their original distance from the vehicle floor. Observance was taken of the installation configuration in the respective motor vehicle. The dummy seating posture was controlled at a constant angle of inclination of approximately 110° to the horizontal. An adjustable foor support enabled approximation of the dummy's legs to a realistic position of the 50% man for the respective vehicle interior.

The same standard three-point automatic belt of one ECE-approved make was mounted for all tests at a uniform, specifically defined geometrical belt configuration. In comparison to the installation geometry of the actual corresponding vehicles, the relationships achieved were either equally effective or, in individual cases, more favorable (e.g., lap belt angle steeper, buckle part shorter, etc.).

An instrument panel and a steering system were not installed on the sled—despite the significance of the lower instrument panel observed in actual auto accidents. In such actually observed accident cases, the very commonly occurring knee impact prevents more serious injuries to the abdominal area by virtue of relieving the loading of the lap belt. Measurement of the free paths open to the occupant's knees in various European vehicles resulted namely in the discovery that knee impact can occur only in a later phase at the end of the trajectory / loading sequence of the occupant. By this time, however, the seat and the belt have already predominantly determined the kinematics and the type of occupant loading. The occurrence of knee impact in present-day vehicles can be considered only as an indication that something incorrect has happened with respect to the kinematics, e.g., that excessive lower-body displacement has occurred.

Testing was therefore performed without an instrument panel: firstly, in order to be able to determine and measure the isolated seat-safety belt interaction in the critical preliminary phases. The instrument panel was left out secondly because, on the whole, a knee-instrument panel impact signifies kinematic disadvantages which in any case should be avoided by utilization of the lap belt (i.e., if no systematic utilization is made in the first place of systems *without* lap belts which are designed especially to consider the knee impact problem, e.g., the VW-RA system).

3. OBJECT OF TESTING: VEHICLE SEAT

Only the structure of the seat cushion and of the seat cushion support with console are of significance for our study of frontal crashes.

3.1 Classification of production seats

The seat cushion structure of present-day production seats can be broken down into three typical structural groups. They are, according to FIG. 1, as follows:

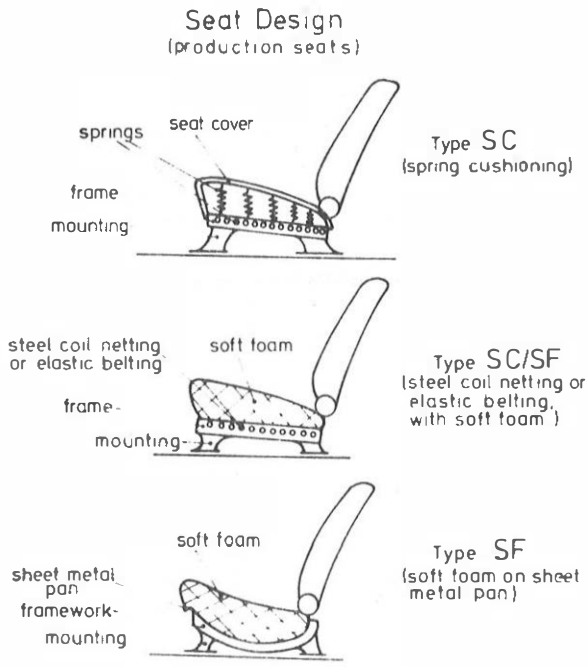

Fig 1- Seat design of 3 current production seat types

<u>Type SC</u>: <u>Spring—cushion</u>

A sheet metal frame with spring center in cushion form, and cover: the classical spring—cushion seat

<u>Type SC/SF</u>: <u>Spring—cushion with soft foam</u>

A sheet metal frame with steel coil netting or elastic belting in support of a soft foam cushion in seat form

<u>Type SF</u>: <u>Soft foam</u>

A sheet metal pan (self-supporting or mounted on tubular frame) with soft foam cushion in seat form

---

Basic differences in the design of the seat cushion structure can be easily recognized. This is evident both as far as comfort and subjective sitting "feel" are concerned, as well as for the compression and penetration characteristics observed for strapped-in passengers in the case of head-on crashes. These differences are of fundamental nature and cover a broad spectrum of design; their basic differences cannot be explained away by any alleged "adaptation" to the frequency response of the vehicle system alone.

4. EXPLANATION OF THE VALUATION TECHNIQUE

Valuation parameters must in this context be defined for valuation of the loading and of the kinematics of the loading process.

4.1 Loading criteria

The FMVSS 208 loading criteria alone are not sufficient for valuation of the influence of the seat on safety belt effectiveness (1, 3). These well-known criteria were, however, measured, calculated, and listed.

4.2 Kinematic evaluation parameters

The kinematic evaluation parameters serve the purpose of classifying the manner of occurrence of the loads on the passenger, i.e., of judging the effect of the more or less biomechanically favorable points and directions of application for restraint forces on the occupant's body.

FIG. 2 represents the dummy skeleton in its initial position, in the stationary x—z coordinate system.

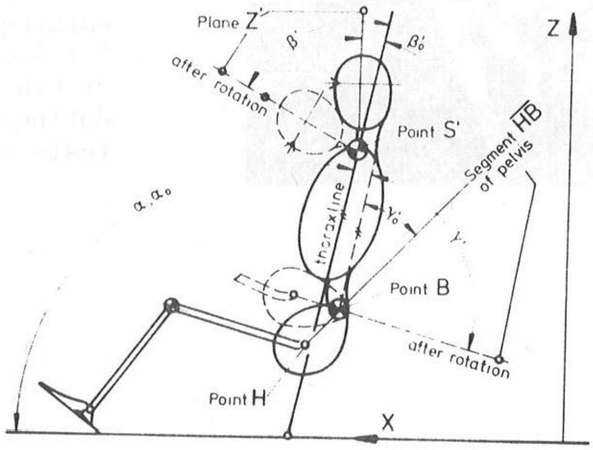

Fig. 2 Marking scheme and angle definitions for determinations of dummy kinematics

The measuring points, rigidly fixed to the skeleton, can be seen at the thorax, pelvis, and knee. In addition, directional arrows were mounted at measuring points S' (fixed thorax) and B (fixed pelvis) for clearer indication of the angles of rotation. This is shown in FIG. 2a (see next page).

The positions of installation for the points S' and B were chosen such that these points form the instantaneous center in first approximation for the crash-caused relative movements of the body segments. The measured angles γ, β', and γ' defined here in detail in FIG. 2 have proved to be easily and exactly measurable, and provide particularly conclusive data for the dummy kinematics.

4.2.1 Significance of the angle of pelvis rotation γ'

The angle of pelvis rotation γ' is defined here as the angle between the thorax line when displaced parallel up to the point B, and the cross-sectional plane through points H and B of the pelvis. It is used for direct measurement of the bending of the lumbar spine. The pelvis rotation, caused primarily by the seat characteristics, influences the entire dummy kinematics. The mechanical model of the pelvis as shown in FIG. 3 clarifies the basic and critical relationships under the influence of the lap belt.

The lap belt force F_{LB} always acts above the common center of gravity P of pelvis and femur. In this way, the force of reaction of the seat F_{Si} provided via the lower seat framework alone influences the magnitude of the internal forces M, N, and Q of the lumbar spine. The crux of the problem consists in the possible imbalance of external forces and moments which can lead

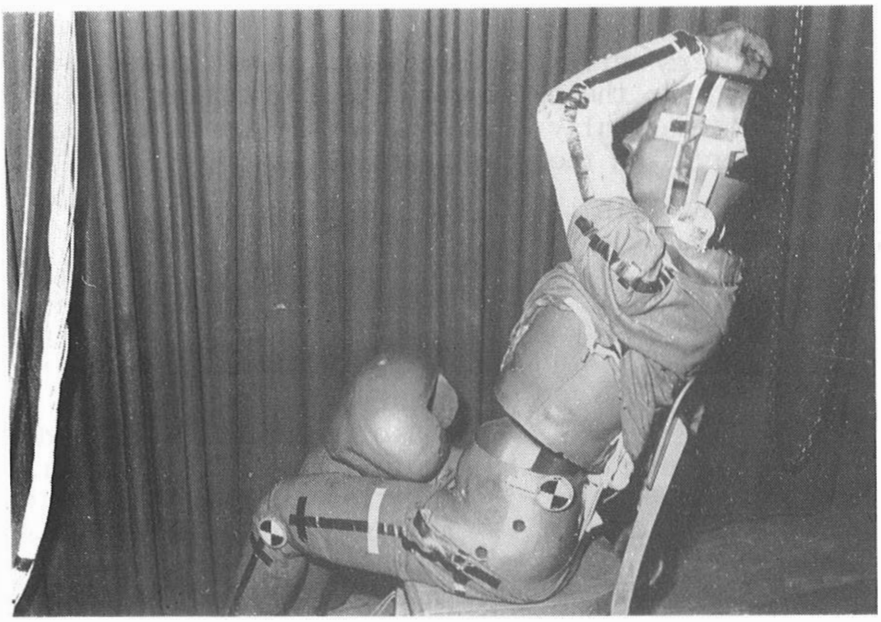

FIG. 2a

Mounting of markings and marking arrows for indication of kinematics during crash tests

to significant internal reaction loading of the lumbar spine. Excessive lumbar spine flexure signifies biomechanically unfavorable configurations of the lumbar spine and pelvis, as well as lower thorax segment, with respect to the belt. This is because the pelvis rotation, in conjunction with sinking of the pelvis contour into the seat cushioning, causes a vertically downward displacement of the thorax and leads to sliding of the lap belt up over the iliac crest.

The model representation in FIG. 5 furthermore makes clear that the kinematic behavior of the dummy relevant to the evaluation of seating characteristics must react extraordinarily sensitively to the predetermination of flexure characteristics of the lumbar spine and the other deformation characteristics involved. In the case of the

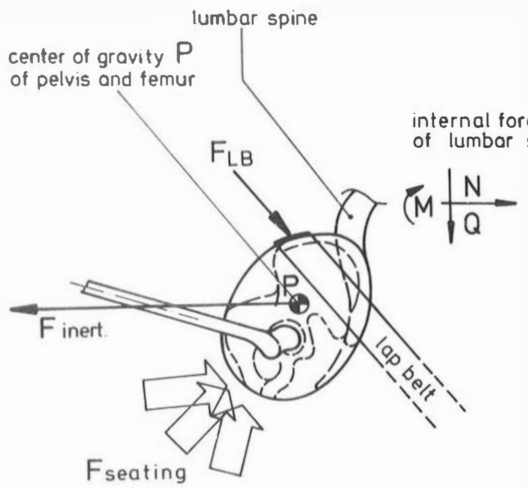

Fig. 3: Forces on a lap - belted model of pelvis and lumbar spine

TABLE 1: EVALUATION PARAMETERS FOR KINEMATICS

Evaluation parameter	Description	Responsible for influence on:	Values reached on energy-absorbing research seat
		HEAD / NECK	
$x_{H\ max}$	Maximum horizontal head displacement	Head to steering system and instrument panel impact	500 mm
$z_{H\ max}$	Maximum vertical head displacement	Head to steering system and instrument panel impact	400 mm
β'_{max}	Maximum angle of neck anteflexion relative to the thorax line	Neck injuries caused by hyperanteflexion	Static threshold of pain: approx. 75-80°; approx. 90° for dummy rubber neck!
		THORAX	
$z_{Th\ max} = f\ (x_{Th\ max})$	Maximum vertical thorax displacement at moment of max. horizontal thorax displacement $x_{Th\ max}$	Loading of lower thorax area (ribs 5-12) Increase of vertical upward component of loading direction on lower thorax area	20 mm
α_{max}	Thorax angle to the horizontal at the moment of max. upper belt loading	Loading of lower thorax area (ribs 5-12) Increase of vertical upward component of loading direction on lower thorax area	90°
		PELVIS	
$x_{P\ max}$	Max. horizontal displacement of pelvis (point H)	Thorax positioning at the moment of the max. shoulderbelt force	As per ECE R16: 150-200 mm; Research seat: 160-220 mm
$z_{P\ max} = f\ (x_{P\ max})$	Max. vertical displacement of pelvis (point H) at the moment of max. horizontal pelvis displacement	Compression and bending of the lumbar spine Vertical impact severity	30 mm
γ'_{max}	Maximum angle of pelvis rotation relative to the thorax line	Basic guidance of motion; lumbar spine loading; possibility of knee impact	40-50°

(table continued on next page):

Hybrid II, Part 572 dummy, this is a specifically prestressed cylindrical rubber block element.

If one studies experience gained with the behavior of the lumbar spine in cadaver tests, then one must carefully consider the lumbar spine characteristics of the test dummy. The dummy lumbar spine is in fact stiff in comparison: this, however, does not affect the basis for the results discussed here.

Table 1 lists the kinematic evaluation parameters and explains their biomechanical significance. In an example, measured values of these parameters are given in the last column: they were determined for a research seat with simultaneous reduction of the FMVSS loading (3, 4).

Seat-safetybelt interaction

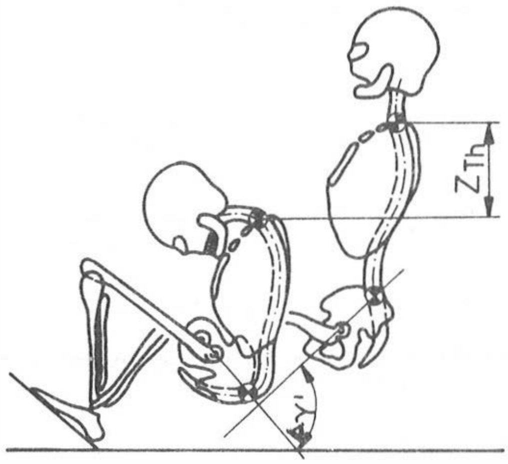

Fig. 5: Initial and final position of belted dummy sceleton on soft production seat

It is demonstrated here that the representation of loading involved is considerably clarified by the inclusion of the kinematic evaluation parameters. Furthermore, the classic loading criteria alone not only provide an incomplete picture— they can create an completely false picture of the loading process in borderline cases, e.g., for submarining cases.

5. ANALYSIS OF THE TEST RESULTS

Table 2 provides a summary of the numerical results of the individual seat tests on the basis of the uniform, easily reproducible sled test conditions described above. Two representative tests per seat type were chosen for this table.

We admit again at this point that the actual situations in the respective vehicle interiors could possibly result in slight variations in the numerical values. From our standpoint, however, there is no indication whatsoever of a reversal in the tendencies discussed below under possible actual conditions.

5.1 Dummy loading

Nothing extraordinary is to be seen in the numerical results for the loading of the dummy as shown in columns 3 to 7 of Table 2. The loading values measured are noncritical as judged by FMVSS 208, if consideration is taken of the normal distribution to be found in crash test measurements.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		LOADINGS OF:							KINEMATICS OF:						
		Head	Thorax		Pelvis		Head		Neck	Thorax			Pelvis/lumbar spine		
			Maximum decelerations		Max. decelerations		Maximum displacements		Max. bending	Maximum displacement		Max. angle	Maximum displacement		Max. bending
Type of seat	Test no.	HIC	$a_{Th\ res}$ [g]	SI	$a_{P\ x}$ [g]	$a_{P\ z}$ [g]	$x_{H\ max}$ [mm]	$z_{H\ max}$ [mm]	β'_{max} [°]	$x_{Th\ max}$ [mm]	$z_{Th\ max}$ [mm]	α_{max} [°]	$x_{P\ max}$ [mm]	$z_{P\ max}$ [mm]	γ'_{max} [°]
PRODUCTION SEATS															
SC	5	813	47	330	25	33	510	480	104	370	110	80	260	70	100
SC	23	536	49	290	37	37	550	440	96	410	160	90	350	190	82
SC/SF	3	677	51	360	30	41	540	460	97	340	120	72	270	80	99
SC/SF	4	875	50	390	20	38	480	500	110	290	90	74	260	60	87
SF	11	1036	47	270	26	28	550	500	109	390	100	72	290	160	93
SF	20	688	55	320	32	35	580	510	108	420	130	74	310	110	96

TABLE 2: NUMERICAL TEST RESULTS

Attention must be called, however, to type SC of the production seats, in test no. 23, to the extraordinarily small HIC value and the small pelvis decelerations. This can be explained as part of an extreme, classical submarining sequence and therefore stands out in comparison to the other production seats. This example is renewed evidence of the well-known and significant phenomenon that, precisely under classic submarining conditions, the FMVSS 208 limits can be especially easily observed—*with the unfortunate result, however, that the occupant will have it particularly rough.*

5.2 Kinematics of the dummy

The following analysis will attempt to clarify the significance of the kinematic evaluation parameters in accordance with Table 1.

Columns 8 to 16 of Table 2 give an overall picture. In accordance with our experience, one can obtain the first typical impression from the various sequences of dummy movement by study of the values for the maximum vertical thorax displacement, $z_{Th\ max}$, as given in column 12. These values show just how markedly the thorax has vertically displaced as a result of the vertical components of acceleration and force.

The reasons for this are as follows, as also explained by Table 1:

- The compression characteristics of the seat upholstery in the forward seat area
- The rotation of the pelvis as a result of the bending of the lumbar spine.

The results associated with the bending of the lumbar spine are listed in column 16 under γ'_{max}. It hardly requires the evaluation of orthopedic specialists to conclude that bending angles in the order of magnitude of 90° are dangerous and unacceptable, especially when one also considers that the dummy lumbar spine is stiffer than the human spine.

The data measured here for the production seats (lumbar spine flexures of γ'_{max} = 90-100°, cervical spine bending of β'_{max} = 96-115°, and x and z displacements of the head, thorax, and pelvis) enable the associated loading values (columns 3 to 7) to be subjected to more differentiated evaluation. A resulting restraining force introduced into the lower thorax half (ribs 5 to 12) and caused by a vertical component of displacement should especially be derived from these measured values—in addition to the bending loads on the spine. Under consideration of the differentiated strengths of various parts of the thorax, the loading values as presented may therefore by no means be designated as noncritical.

A more in-depth comparison of the results of this series of *production seats* with results of a test series of *research seats* which are designed for energy absorption will be published this year at the 23rd Stapp Car Crash Conference (4).

A summarizing view of this result for the test series is demonstated by FIGS. 4, 5, and 6—representations of an example from the production seat group SF.

The motion sequence photographs in FIG. 4 show how the concealing clothing of the dummy prevents visual determination of the dummy skeleton deformations. Only by the use of the measuring markers shown in FIG. 2 (not seen clearly

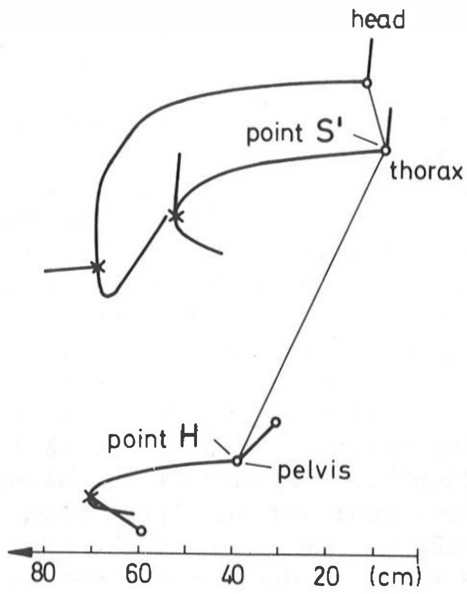

Fig. 6 : Trajectories and rotations of head thorax and pelvis on production seat type SF

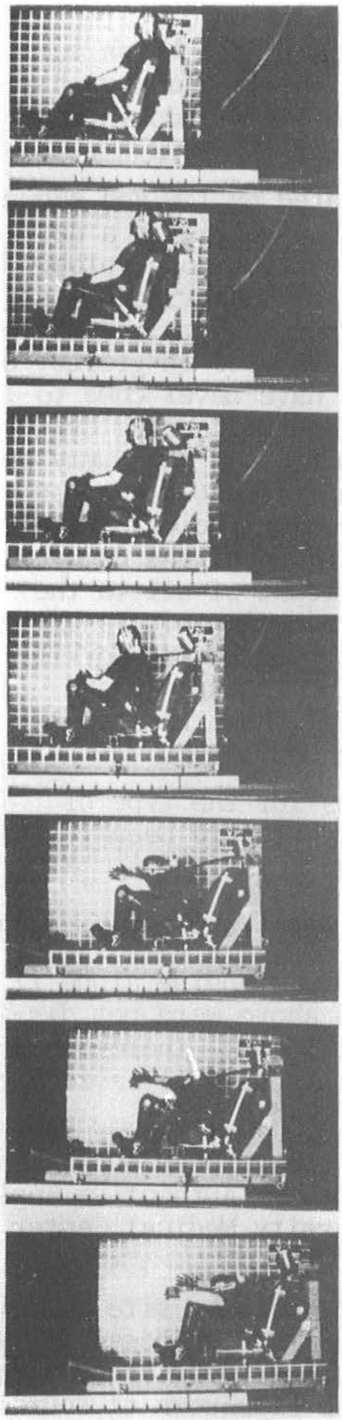

Fig. 4 : Motion sequence on production seat type SF

because of the reduction in size here) could an analysis be made which led to the results shown by FIG. 5. This figure shows the initial and critical final positions of the dummy skeleton from this test. FIG. 6 shows the trajectories of the measuring markers and the point H, with direction indicators included for representation of the body-relative rotational movements.

6. DISCUSSION OF THE RESULTS

The results of this series of tests can be said to be practically spectacular—especially since points of departure for critical analysis of the seat, and for preliminary analyses of the influence of the seat on occupant protection have existed in the professional literature since as long ago as 1970 (1, 2, and 6).

Demonstration has in fact been made here that present-day seat design, for present-day three-point automatic belt use, takes practically no consideration at all of this aspect of frontal crash vehicle safety. Instead, owing to the lack of legal regulation, seat design has instead historically developed primarily according to the standpoints of comfort, human anatomy, and styling.

The loading criteria (protective criteria) as stipulated by law and shown to be insufficient with respect to kinematic evaluation, have played a decisive role in this case, since they have allowed such a situation to develop. These criteria are responsible for the fact that standards of measuring and analysis developed along the lines of these same criteria have come into use in testing institutes and industry in such a way that required analyses in greater depth have been rendered impossible, or that shortcomings have never come to light. One example: favorable numerical values for the FMVSS 208 loading criteria in the case of submarining motion sequences. The kinematics of the dummy body or of the cadaver used cannot normally be analyzed owing to the lack of suitable measuring markers fixed to the skeleton, and of direction indicators (see FIGS. 2 and 2a) because of the blousing up and/or sliding of the dummy clothing. This year for the first time, Opel (owing not least of all to the experience gained in our work) has proposed the introduction of measuring markers fixed to dummy skeletons in their paper ISO/TC 22/SC 12/ Working Group 5: "Anthropometric Test Devices." (5) Other beginnings toward sophistication of technical measured representation of the kinematics involved can therefore be recognized in parallel with our work.

The great significance of the kinematic relationships for the type of occupant loading in the seat-safety belt system has therefore been revealed here in our study and cannot be seriously called into question.

6.1 Significance of the seat in actual accidents: results of other studies

Our evaluation of these results cannot be satisfactory standing alone if the relevance of the shortcomings of the seats described above were not discovered as well in actual vehicle accidents. At this point, therefore, correlation will be studied with vehicle belt accidents as well as recent results from other studies.

Recent analytical studies of the safety belt accident have been published in conjunction with accident research of the Institute of Automotive Engineering at the Technical University Berlin and the University Medical Center in Hanover (11, 3).

The difficulties of complete technical acquisition of data on site restricts, in the majority of the statistical belt accident studies, the possibility of drawing correlations in individual cases between loading processes for the strapped-in occupant and injury patterns. Within the framework of source no. 11 cited here, directed data to an extensive degree have been collected for a total of 88 strapped-in occupants. Especially apparent in this study are the injuries to the lower thorax half (injury frequency of approx. 30%) as compared to injuries to the upper thorax half (only 6.5% injury frequency). This area of injury, as well as individual or multiple injuries to the knee and the abdomen, was affected here with a relative frequency of 73% of all injuries. These patterns can be interpreted—as we demonstrate in this study—only through specific kinematic relationships which are directly connected to the uncontrolling supporting characteristics of the vehicle seat.

The serious safety belt accidents investigated by Havemann and Schröder (8) confirm just such injury patterns and demonstrate that the spine—especially the lumbar spine—suffers most with the increasing severity of the accident, as should be expected as a result of our investigation of seats. Purely abdominal injuries also occur with greater frequency. Personal information provided by the Swiss accident researcher Walz confirms the influence of the seat on belt-related accident patterns studied in the field. Walz's information also confirms, however, that until today, practically no systematic investigation on site has been carried out with sufficient care anywhere with respect to vehicle seats after an accident.

In the laboratory as well, there have been obvious indications of the influence of the seat on the pattern of injury. Patrick and Andersson (6) discovered as long ago as 1974 in their cadaver tests with production vehicle seats that there was a concentration of injuries in the lower thorax half. More recent cadaver tests performed by Schmidt on behalf of the FAT (Research Association of German Automobile Manufacturers) present further, especially conclusive confirmation of injury patterns and injury concentrations which is in full agreement with the results of our seat studies presented here. Schmidt as well found injury concentration in the following: lower thorax half, lumbar spine, cervical spine. [In the context of Schmidt's studies, G. Heess published in 1977 his dissertation on "Spinal Injuries on Strapped-in Cadavers." See sources (9, and 10) cited here.]

These studies directly confirm the prognoses which can be gained from the evaluation of dummy kinematics in the case of head-on crashes with modern seats.

7. CONCLUSIONS

The seat is that element in the protective restraint system which performs "control" of the vehicle occupant's kinematics. In this manner, it contributes decisively to the effectiveness of the safety protection system.

The loading measurements performed with dummies in accordance with FMVSS 208 criteria cannot provide a clear picture of the interrelationships involved in the kinematics: i.e., on the manner in which the protective restraint system introduces its restraint forces into the body of the occupant, and on how the seat and the safety belt interact.

There are no legal stipulations for the operational characteristics of the seat under frontal crash conditions. The kinematic evaluation parameters defined and introduced here as supplementary aids therefore represent a motivation for further consideration. No effort has been made in this stage of our work toward the subsequent and necessary definition of limiting values for these kinematic evaluation parameters, as would be required for safety regulations. The trends alone as described here already sufficiently clarify the importance of posing the problem of "Interaction of Seat and Seat Belt," or the topic "Kinematic Control."

Significant optimization of the present-day vehicle protective system can therefore most profitably be made in the area of the lower seat framework. Once this has been accomplished, we can expect further reduction in the frequency and severity of belt-related injuries.

BIBLIOGRAPHY

(1) States, J.D. "Trauma Evaluation Needs" in Human Impact Response, GM Symposium, Edit. Plenum Press, N.Y., London, 1973.

(2) Adomeit, D., and A. Heger. "Motion Sequence Criteria and Design Proposals for Restraint Devices in Order to Avoid Unfavorable Biomechanic Conditions and Submarining," SAE paper no. 751146, San Diego, USA, 1973.

(3) Adomeit, D. "Evaluation Methods for the Biomechanical Quality of Restraint Systems During Frontal Impact," SAE paper no. 770936, New Orleans, USA, 1977.

(4) Adomeit, D. "Seat Design: A Significant Factor for Safety Belt Effectiveness," paper now in preparation for the 23rd Stapp Car Crash Conference, 1979.

(5) Proposal for ISO/TC 22/SC 12/WG 5 N. 25, *"Dummy-Meßmarken,"* Frankfurt, 1979.

(6) Patrick, L.M., and A. Andersson. "Three-Point Harness Accident: A Laboratory Data Comparison," SAE paper no. 741181, USA, 1974.

(7) Walz, F. *"Anstoßrichtung und Verletzungen von Fahrzeuginsassen,"* Report of the 1979 convention for the *Deutsche Gesellschaft für Verkehrsmedizin e.V.*, Cologne, 1979.

(8) Havemann, D., and L. Schröder. *"Verletzungen unter Dreipunkt-Sicherheitsgurten: Ergebnisse einer Studie an Fahrzeuginsassen,"* Report of the 1979 convention for the *Deutsche Gesellschaft für Verkehrsmedizin e.V.*, Cologne, 1979.

(9) Schmidt, G., D. Kalieris, *et al.* *"Untersuchungen zur Ermittlung von Belastbarkeitsgrenze und Verletzungsmechanik des angegurteten Fahrzeuginsassen,"* Final report for research project no. 3102, Heidelberg, 1977.

(10) Heess, G. *"Wirbelsäulenverletzungen menschlicher Leichen bei simulierten Frontalaufprallen,"* Dissertation for the University of Heidelberg, 1977.

(11) Adomeit, D., S. Behrens, and H. Appel. *"Bewertung von typischen Verletzungsmustern gurtgesicherter Insassen im realen Frontalunfall,"* published in *der Verkehrsunfall*, no. 9, 9/1978.