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EXPERIMENTAL DETERMINATION OF THE PELVIS ROTATIONAL ANGLE AND ITS RELATION TO A PROTECTION CRITERION FOR PELVIC AND ABDOMINAL INJURIES

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ABSTRACT

A model has been previously proposed for a protection criterion for pelvic and abdominal injury in which the magnitude of the measured pelvis resultant acceleration has an injury-equivalent value. Whether the pelvis acceleration is a measure of pelvic or abdominal injury is distinguished with the aid of the pelvis rotational angle. If the rotational angle exceeds a specific, field-accident based value, the critical pelvis rotational angle, there exists an increased probability for submarining, resulting as a rule in abdominal injuries and in some cases in injuries of the lumbar spine. When the pelvis rotational angle remains under the critical angle, in the most cases the lap belt will lie under the iliac crest and pelvis injury is likely only with excessive loading.

Although the measurement of the pelvis acceleration is standard practice in the vehicle crash tests and sled tests, the measurement of the absolute pelvis rotational angle is obtained only with difficulty. In the framework of a proposed advancement, different measurement principles are therefore presented and the resulting measurement method of choice is discussed. The methodology and the interpretation of the evaluation of the test data is explained. The presentation of test results and simulation results with and without submarining concludes this investigation. These effects are evidenced in the comparison of the occupant kinematics from film analysis and the characteristic results of the measured pelvis rotational angle.

An experimental proof for submarining is thereby shown which provides a clear and understandable result regarding the avoidance of pelvis and abdominal injuries.

1 THE CURRENT STATUS OF PELVIC AND ABDOMINAL INJURIES

In 1992, a total of 527,428 persons were injured in traffic accidents in Germany; 386,446 were injured slightly, 130,351 critically, and 10,631 fatally. As far as can be determined, the total cost of the injuries sustained by people in traffic accidents in 1992 is approximately DM 48 bn, roughly one sixth of which is accounted for by occupants of passenger cars involved in frontal collisions. Current belt usage being what it is, the collective under consideration is highly likely to sustain injuries in the abdominal and pelvic region. Across the board, 3.4 % of the total number of injuries are located in the abdominal and 4.5 % in the pelvic region, while among belted occupants, the proportion of abdominal injuries is higher (4.3 %), while that of pelvis injuries is lower (2.8 %) [1].

Rather early on, it was shown [2] that injuries in the abdominal region are most frequently caused by lap belts, the rate being 60 %. Without exception, these are submarining injuries which are sustained as the pelvis dives underneath the lap belt. The next most frequent category of injuries at 21 % is ascribable to contacts with the steering wheel. Abdominal traumata mostly are soft-tissue injuries (45 %) of relatively low severity, or else organ injuries (42 %), which are of greater and even critical severity. Bone fractures, which according to [3] belong to the AIS > 2 category, are either compression or dislocation fractions of the lumbar vertebrae.

Most of the pelvic-region injuries (64 %) are soft-tissue traumata. Next to a case in which the pelvis was comminuted so severely as to be partially segregated from the torso - this case was classed as AIS 6 - the analysis of accidents in [2] lists fractures of the pelvic girdle, the ala, and the roof of the acetabular fossa which were graded as AIS 2 or AIS 3. At 80 %, injuries are most frequently caused by contacts with the webbing and/or buckle, while steering-wheel rim impacts are responsible for only 8 % of all pelvic fracture cases.

Consequently, it appears that traumata in the abdominal and pelvic region have mainly two causes: Lap belt syndromes ascribable to the so-called submarining effect, and injuries to the pelvis or hip caused by high loads impacting directly on the pelvis or the femur. The bone girdle of the pelvis is capable of absorbing extremely high loads without losing its stability, provided, however, that forces impact across a fairly large area, a condition that is normally fulfilled by lap belt impacts, and that the point of force impact remains below the crest of the ilium (cresta iliaca) during the entire crash phase. Occasionally, there are instances where in a frontal collision soft upholstery, unfavourable belt geometry, or belt handling errors may cause the pelvis to dive below the loop of the lap belt, a process called submarining, or alternatively, may cause the lap belt to slip up above the level of the ilium crest [4]. The forces occurring in such a process directly impact the abdominal wall, causing ruptures and lacerations of pelvic organs - intra-abdominal injuries, in other words - and even fractures in the lumbar part of the spine, albeit only in relatively severe crashes [5].

2 CURRENT PROTECTION CRITERIA FOR PELVIC AND ABDOMINAL INJURIES

Although pelvic accelerations are measured as a matter of course in all safety investigations in which dummies are tested, there is currently no legal test criterion for pelvic and abdominal loads. The law merely prescribes visual inspections, pointing out that during each test, the lap belt should remain located in the pelvic zone and must not be allowed to shift to the abdominal region (FMVSS 209). When child restraint systems are tested in conformance with ECE R 44, putty is applied to the abdominal region of the child dummy to check belt displacement; damage in this putty is inadmissible after the test. The draft ECE test procedure [6] will most likely contain criteria for assessing the submarining effect in so far as it will provide for hook-shaped transducers to be applied in the region of the ala below the left and right iliac spine to measure the upward displacement of the lap belt as well as the abdominal load.

Forces that may induce abdominal injuries are far less powerful than those capable of injuring the bony structure of the pelvis. Thus, in submarining situations, no abdominal injuries will result from lap belt forces as high as 2,000 N, while belt forces acting on the girdle of the ilium may be as high as 4,900 N without causing injuries. It appears that the knee will even sustain forces between 6,400 and 12,500 N without tolerance limit infringement [7], although it cannot be predicted where an injury will eventually occur in the chain consisting of the kneecap, the knee, the femur, the femoral neck, and the hip. All the abdominal injury criteria that have been discussed so far like, for instance, the force of the lap belt and its development over time as well as the pelvis rotational angle suggested for the first time by ADOMEIT [8], define the limits of sustainable abdominal loading rather less than the occurrence or avoidance of the submarining effect and its resultant injuries [9].

3 A NEW CRITERION FOR PELVIC AND ABDOMINAL INJURY PROTECTION

3.1 Admissible Pelvic Acceleration Range as a Function of the Rotational Angle of the Pelvis

The method of calculating the risk function of abdominal and pelvic injuries shown in **Figure 1** is a function of the probability of reversible and/or irreversible pelvic and abdominal injuries as distinguished by the curve describing the demarcation between severity degrees AIS 3 and AIS 4 out of the accident occurences on the one hand and the maximum resultant pelvic acceleration measured both mathematically and experimentally [9] which has been presented in an earlier paper [2]; in the simulation there was used a 50 %ile male dummy or a corresponding model respectively. These two risk functions are distinguished by the angle of pelvis rotation involved, the critical point being 20°. In other words, a pelvic rotational angle of $< 20°$ is associated with pelvic injuries, while abdominal injuries will occur at angles $> 20°$, at least under loads ranging around the limit of tolerance.

On this basis, an experimental model for computing admissible pelvic and abdominal loads may be derived. The protection criteria that apply to this region of the body, i.e. resultant pelvic accelerations of varying intensity, may be told apart on the basis of the critical pelvic rotational angle. **Figure 2** shows the load model, i.e. maximum resultant pelvis accelerations vs. pelvic rotational angles. The higher acceleration level relates to tolerable pelvic injuries, while the lower level relates to tolerable abdominal traumata. The diagram shows accelerations for both load cases that are equivalent to the tolerance threshold (between AIS 3 and AIS 4) with a 50 % confidence level. Since the rotational angle of the pelvis is not a suitable indicator of injury severity, being merely a characteristic by which pelvic and abdominal injuries can be distinguished, the smallest angle at which abdominal injuries are observed must be regarded as the 'critical' rotational angle of the pelvis. By correlating the results of crash analyses and experimental as well as mathematical simulations, this angle was found to be 20°. The transition between the validity zones of pelvic and abdominal injuries is marked by the declining straight line which transects the abdominal-load tolerance threshold at 25° [9].

3.2 Measuring Equipment

Whereas pelvis acceleration measurements are unproblematical, measuring the rotational angle of the pelvis is far more difficult. Measuring the absolute angle of pelvis rotation directly by analysing high-speed films is relatively expensive, and results are only of adequate dependability if tags are applied to identify the rotation of clothed dummies. Better precision can be obtained by measuring the relative angle between the pelvis and the femur with a rotary potentiometer, the absolute angle of the femur being derived from computer-aided film analyses. The absolute rotational angle of the pelvis is then computed by totalling all simultaneous measurements. This procedure has already been applied in sled tests [9], but its application in vehicle tests would require much technical effort since the thighs of the dummies are hidden by the doors of the vehicle.

One solution that could be applied standard is to measure the angular acceleration of the pelvis which, after double integration, results in the absolute angle of pelvic rotation during a crash. In the tests described below, an angular-acceleration transducer made by ENDEVCO was used which works on the principle of piezoresistance [10, 11]. It will measure rotation around one axis only, the transversal axis. It was found convenient to install it in the pelvic cavity of the dummy which also accommodates the translational acceleration sensor that is commonly used in such tests. This pelvic cavity is closed by an easily-accessible plate which suggests itself as a basis for installing the mounting angle of the angular-acceleration transducer. **Figure 3** shows the installed device.

To test the feasibility of the procedure, two sled tests were conducted at a velocity of 50km/h and a crash pulse of a middle class car. Both test bodies were occupied by a belted 50 % HYBRID III dummy. In the first test, the seat was reinforced, and the three point automatic belt system had no slack to avoid submarining, while in the second test, submarining was provoked by allowing a slack of approximately 40 mm only in the lap belt and installing a deformable mounting element in the seat to encourage subsidence.

3.3 Test Results

Table 1 compares the results of these two tests. The films show that in the first test, submarining was predictably avoided, while in the second, submarining was pronounced. **Figures 4 and 5** show the position of the lap belt on the dummy after both tests; the situation after submarining which is shown in **Figure 5** is characterised by the fact that the lap belt has penetrated deeply into the abdomen.

Load criteria		Test without submarining	Test with submarining
HIC	[-]	759	1652
$a_{3\ ms}$ head	[g]	66	95
$a_{3\ ms}$ thorax	[g]	59	72
a_{max} pelvis	[g]	68	60
at	[ms]	64	78
Pelvis rotational angle	[°]	8	**26**
Max. pelvis rotational angle	[°]	11	**39**
at	[ms]	75	92
a pelvis	[g]	37	23

Table 1 - Measured loads in tests with and without submarining effect

In the test without submarining, pelvic loads remained below the standard limits. The high-speed films show that the lower body moved forward only a little, and that the seat subsided only slightly. The lap belt remained in position on the pelvis and did not shift into the abdominal region. The maximum measured pelvis rotational angle of 11° is clearly below the critical angle of 20°. By the same token, the pelvis acceleration limit was around 80 g in this instance, considerably above the measured maximum resultant acceleration of 68 g (**Figure 6**). All the other loads measured at the various parts of the dummy's body also remained below protection criteria level (see Table 1).

In the submarining test, the lap belt slipped up above the crest of the ilium, penetrating deeply into the abdominal region. An analysis of the high-speed film recording shows that the dummy was displaced far forward and that the pelvis plunged into the seat. Now, although maximum pelvis acceleration in this instance was lower than in the first test because of the greater forward displacement, it was still around 60 g at 78 ms, as Table 1 shows. The appropriate pelvic rotational angle was around 26°, exceeding the critical angle of 20°. As submarining was fairly pronounced in this instance, the maximum pelvis acceleration is down to a mere 13 g. Consequently, the measured maximum acceleration at 60 g is far beyond the admissible tolerance threshold. Again, the maximum pelvic rotational angle of 39° is far above the critical angle of 20°, which brings the pelvis acceleration limit down to 13 g. As the acceleration measured at the time of maximum pelvis rotation was 23 g, we have another value here that exceeds the limit of tolerance. The acceleration-versus-rotational angle function derived from test results is compared in **Figure 7** to the limit curve. The fact that the admissible range is left behind across a wide section of the map indicates a fairly high probability of irreversible abdominal injuries being caused by submarining. As the restraint system simulated in this instance was inefficient, head and chest protection criteria levels were infringed, sometimes to a considerable extent (cf. Table 1).

4 SUMMARY

The new, experimentally-tested protection criterion relating to pelvic and abdominal injuries described in this paper is composed of two independent physical load quantities, an injury equivalent in the form of resultant gravity-centre accelerations, and a characteristic used to distinguish pelvic and abdominal loads in the form of pelvis rotational angles. Biomechanical statistics enabled us to establish that the critical pelvis load threshold permits higher accelerations than the critical abdominal threshold. Now that the critical pelvis rotational angle has been researched and established, it is possible to reconcile critical acceleration levels with kinematic parameters to such an extent that the girdle of the ilium may be exposed to 80 g accelerations without going beyond the 50 % probability limit for irreversible injuries, provided that the pelvis is held in a stable position. The probability of submarining increases, however, if the rotational angle of the pelvis compared to its original position exceeds 20°. As under these circumstances the lap belt may well come into contact with the abdominal region, the maximum acceleration admissible in this instance is no more than 13 g if grave injuries are to be avoided.

Measuring accelerations at the pelvis of a dummy was not problematical even in the past. In this paper, we were able to show not only that it is feasible to measure experimentally the rotational angle of the pelvis, but also that this angle may be used as a distinguishing mark between stable pelvis kinematics on the one hand and submarining on the other. This, in turn, opens a way towards introducing this pelvic load model, which is suitable for experimental application, as a protection criterion for pelvic and abdominal injuries, the objective being to provide unambiguous, measurable, and interpretable pelvic-load criteria to assist automotive safety engineering.

While the introduction of the airbag did have a positive influence on occupant loadings and kinematics, specially for the head and the upper torso, it did nothing to improve the hazard still associated with submarining in spite of considerable improvements in belt systems and seat pad designs. This being so, abdominal injuries are still not to be neglected, and their relevance calls for a submarining criterion.

5 ACKNOWLEDGEMENTS

Experiments to investigate pelvic rotation were conducted at TRW Repa's test site by Jörg Roßler as part of his thesis; I should like to thank him at this juncture for his untiring commitment. Similarly, I should like to express my gratitude to Heinz Bock and Thomas Mach who procured and installed the angular acceleration transducer and adapted both our measuring equipment and the test data evaluation software to the new experimental conditions, without which this investigation would have been impossible.

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7 FIGURES

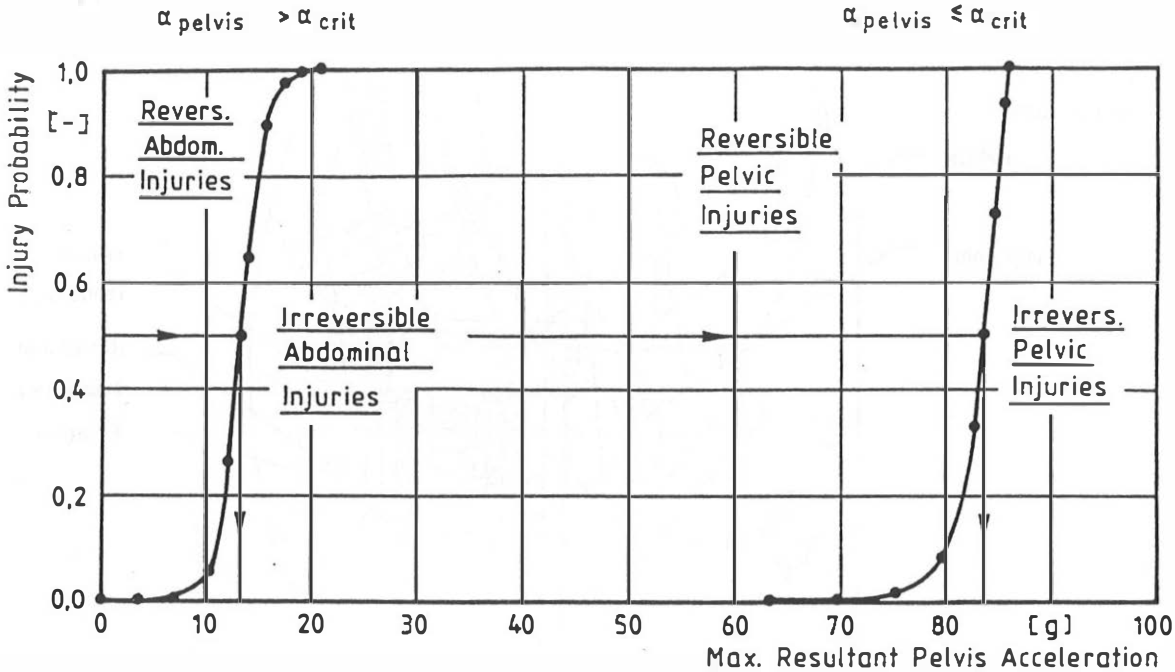

Figure 1: Risk of pelvic or abdominal injuries as a function of pelvic acceleration and critical pelvic rotational angle.

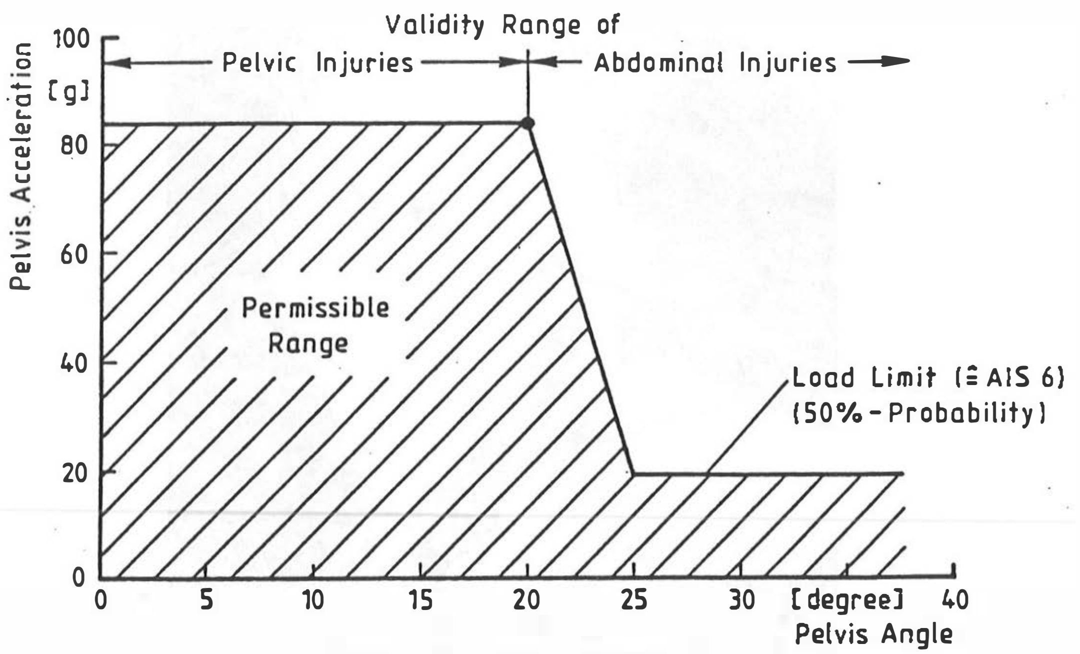

Figure 2: Model to predict pelvic and abdominal injuries at 50% confidence, using the pelvic rotational angle.

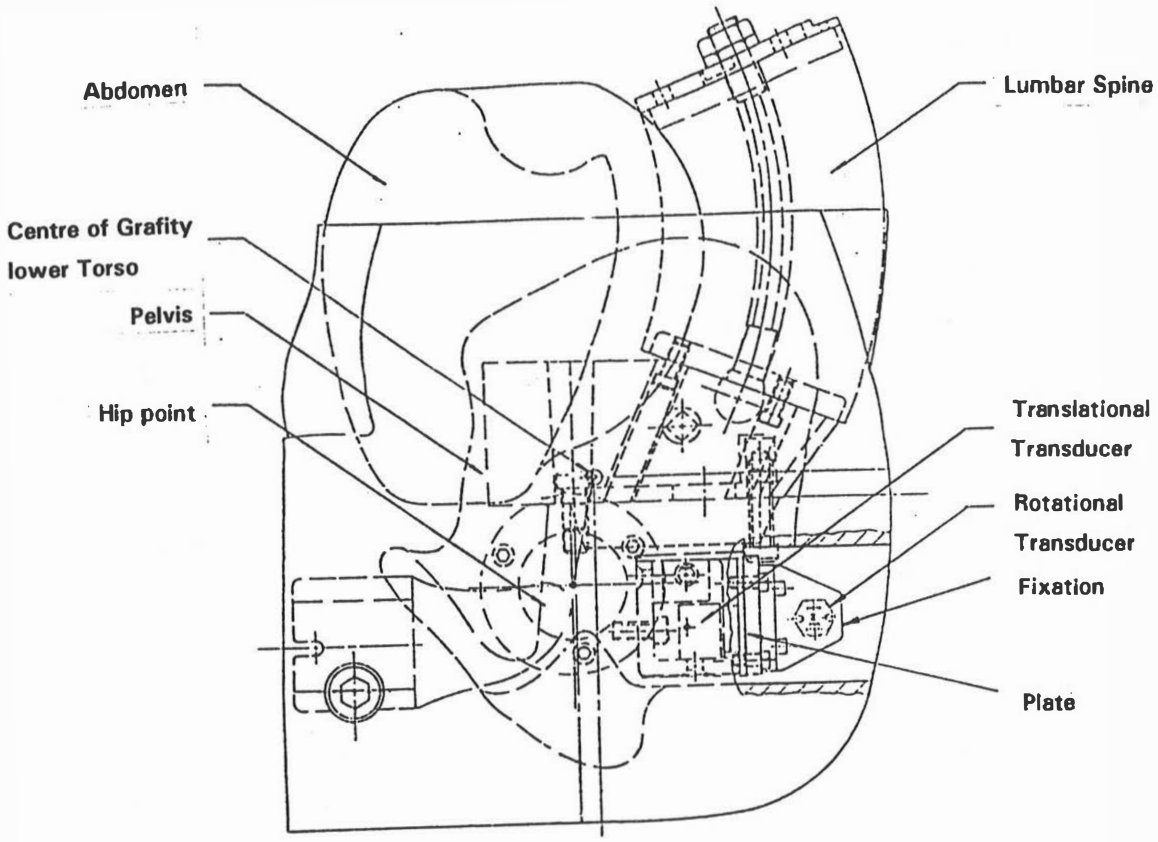

Figure 3: Dummy pelvis seen from the side, showing the translational and rotational acceleration transducers in position.

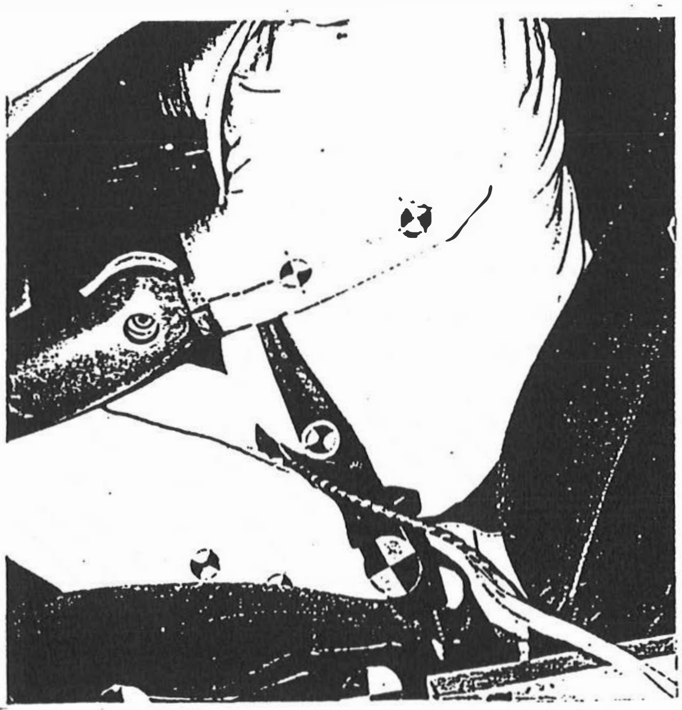

Figure 4: Position of the lap belt on the pelvis of the dummy after the test.

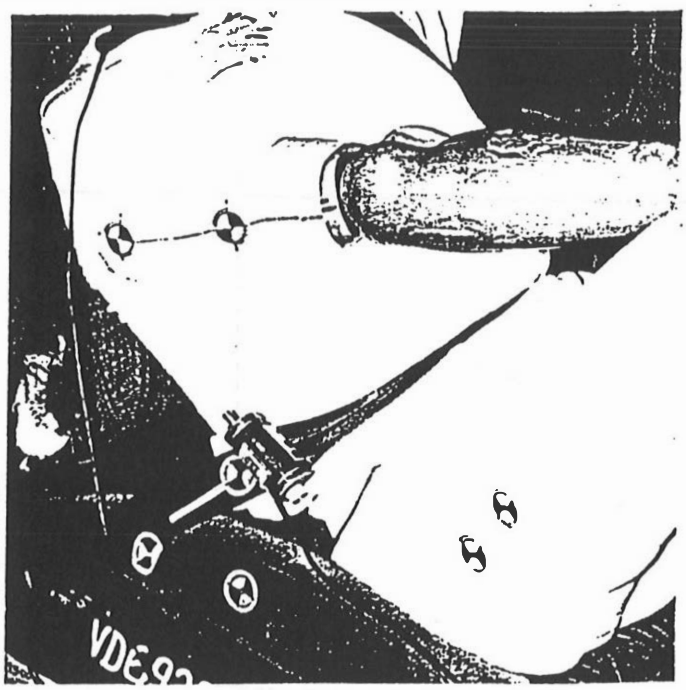

Figure 5: Position of the lap belt after the test, having penetrated deeply into the dummy's abdominal region (submarining effect)

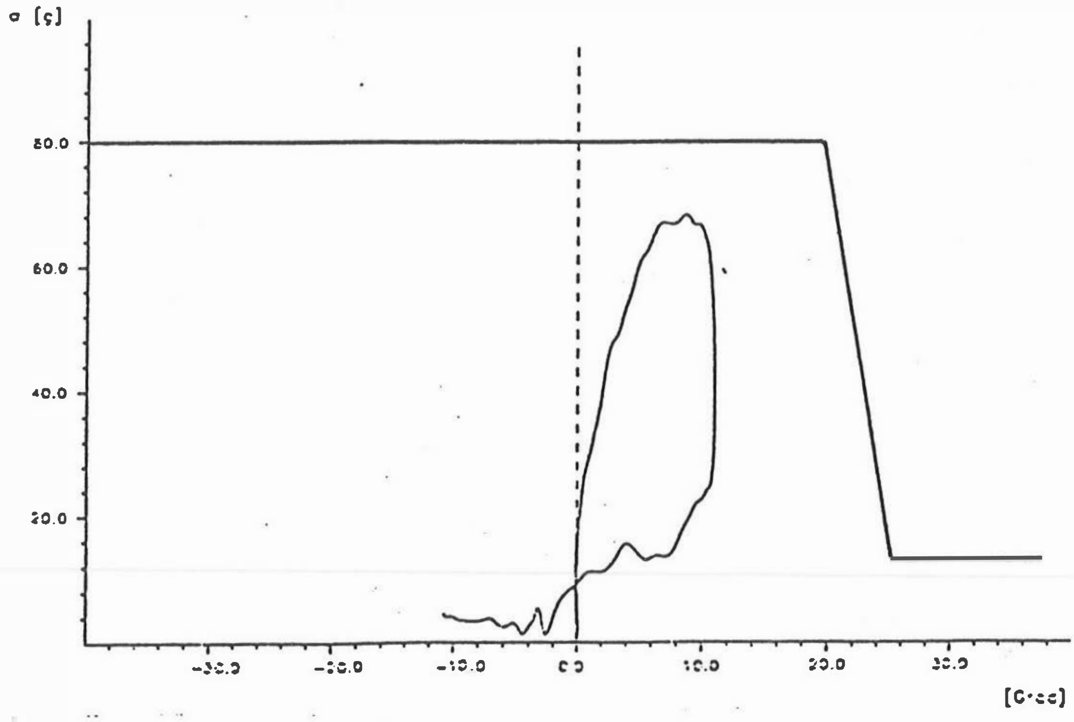

Figura 6: Resultant pelvic acceleration vs. pelvic rotational angle; limits and results of the test without submarining.

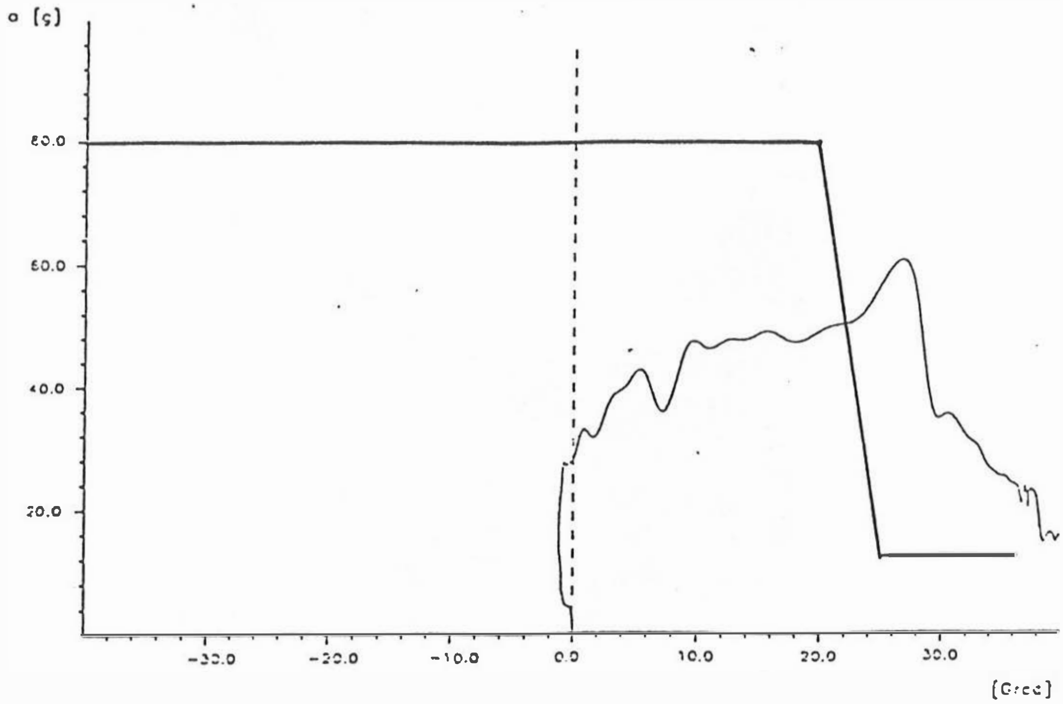

Figure 7: Resultant pelvic acceleration vs. pelvic rotational angle; limits and results of the test with submarining.