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A MADYMO STUDY OF PELVIC AND LOWER EXTREMITY INJURY IN FRONTAL CRASHES

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ABSTRACT

Recent studies suggest that there is increased risk to the pelvis and lower extremities for unbelted, front seat occupants when airbags deploy in frontal collisions. Among belted drivers, women and small adults are more likely to experience fractures of the knee-thigh-hip complex and lower leg. The occupant kinematics and impact mechanics for varying sized drivers under belted and unbelted conditions, with a deploying airbag, have not been well-investigated. The present study used occupant kinematic computer software (MADYMO) to investigate injury likelihood for the pelvis, femur and lower leg in simulations of FMVSS 208 test conditions (30 mph, rigid barrier, frontal crash) for a mid-size sedan with airbag deployment. The pelvic force criterion (PFC), femur force criterion (FFC), and Tibia index (TI) were calculated as injury predictors for 50th percentile male and 5th percentile female drivers, belted and unbelted, with variations in instrument panel angle and stiffness as well as hip abduction. The results indicated, most notably, that the unbelted 5th percentile female submarined beneath the airbag and experienced TI values that exceeded the current tolerance in nearly every unbelted simulation. Injury scores for the left leg were generally higher for both dummies, due to leg entrapment and the intruding floor pan. Hip abduction of 20 degrees led to excessive hip forces in the 50th percentile male. Seatbelts were effective at reducing injury measures in both dummies, most notably the TI score of the 5th percentile female.

INTRODUCTION

Proper seatbelt use reduces motor vehicle collision-related fatalities 40-60% (Evans, 1996). Seatbelts are not effective, however, at preventing lower extremity fractures, especially in women and small adults (Dischinger et al., 1995). The implementation of airbags has been estimated to further reduce mortality by around 24% among seat belt wearing drivers (Lund & Ferguson, 1995). Recent studies suggest, however, that airbag deployment without associated seatbelt use may actually increase the risk of injuries to the pelvis (Rupp et al., 2002) and lower extremities (McGwin et al., 2003). The kinematics of unbelted drivers in frontal collisions where an airbag deploys have not been well investigated.

The objective of the present modeling study was to investigate causation factors of pelvic and lower extremity injuries among unbelted 50th percentile male and 5th percentile female drivers in frontal impacts, in which an airbag deploys. Hip abduction, instrument panel (IP) angle and IP stiffness were independently varied to study their effects on hip, femur and lower leg injury measures. A seatbelt was added to the baseline model to examine the effect of the restraint on injury parameters. It was hypothesized that women would experience higher injury scores due to their proximity to the IP and airbag.

METHODS

MADYMO 6.0 software (TNO, The Netherlands) was used to simulate of a full frontal crash (12 o'clock) of a 1996 Ford Taurus into a rigid barrier. The simulations employed a NHTSA public domain vehicle model along with 50th percentile male and 5th percentile female crash dummy models provided by the MADYMO software. The male dummy was positioned in the driver's seat, in accordance with FMVSS 208 specifications (NHTSA, 2000), as shown in Figure 1. The driver's seat was moved forward approximately 125 mm for simulations involving the female dummy. A vehicle change in velocity (delta-V) of 30 mph was implemented. The dummies in the simulations were exposed to an inflating airbag, which deployed 20 msec after impact and was inflated by means of a single jet with a 25 mm radius. The simulations were run for 140 msec.

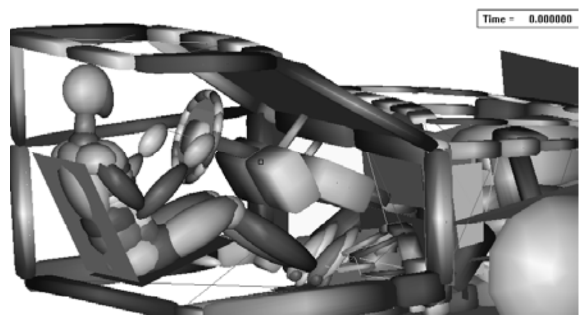

Figure 1. MADYMO model of a 50th percentile male crash dummy, seated in the driver position of a mid-sized sedan, prior to a frontal, rigid barrier collision.

A baseline model was developed, in which the IP angle was 40 degrees, the IP stiffness function was the default and the hip was abducted 10 degrees. IP angles of 30 and 50 degrees, IP stiffness functions half and twice default, and hip abduction angles of 0 or 20 degrees were individually modeled. The addition of a three point seatbelt was studied in baseline models. The belt consisted of non-linear, 3-node triangular finite elements (maximum element size ~ 35 mm) of an elastic and isotropic material ($E = 167$ kPa, $\rho = 500$ kg/m^3).

Model forces were processed using an SAE channel frequency class 600 filter (Nahum, 2002), from which the pelvis-femur constraint force (PFC), the femur force criterion (FFC), and the lower tibia index (TI) for each leg were obtained. The PFC was used to assess pelvic injury likelihood, while the FFC and the TI described injury likelihood for the upper and lower leg, respectively. FMVSS 208 stipulates that the FFC should not exceed 10 kN for the 50th percentile male and 6.8 kN for the 5th percentile female (NHTSA, 2000). Rupp et al., (2002) showed experimentally that acetabular fractures occur under axial femur loads at 5.7 kN, which was selected as a critical PFC for the present study. The final version of the ECE R 94/01 limits the value of TI to 1.3, therefore this value was selected as the critical TI. Seatbelt effectiveness was measured as a percent reduction in injury measures from the unbelted case.

RESULTS & DISCUSSION

The pure frontal impact simulations revealed asymmetric crushing of the front structure of the Taurus model, with greater amounts of structural buckling and footwell intrusion on the driver's side. This led to a general trend of higher injury measures for the left legs, especially for the female dummy. As the rigid barrier impact progressed, the rear of the car lifted off the ground (higher on the left side) and rotated clockwise. As a result, the dummies struck more to the right side of the airbag and subsequently rotated toward the center of the vehicle after impacting the airbag. Entrapment of the left leg in the collapsing front left corner of the footwell appeared to be a source of high injury measures. The right legs usually swept to the left after impacting the toe panel.

The impact simulations for the 5th percentile female dummy predicted TI values exceeding 1.3 (tolerance) for nearly every case where the female driver was unbelted. The kinematics revealed that the unbelted female submarined under the inflating airbag, exposing the lower legs to high impact forces and entrapment in the footwell. The seatbelt prevented forward motion of the upper body, eliminated the submarine effect and reduced TI values by over 55%. The female dummy model experienced PFC values exceeding tolerance in the left leg for the baseline model, when the instrument panel angle was 50 degrees, and when the IP stiffness was doubled.

Table 1. Injury scores for the 5th percentile female. Bold numbers indicates value exceeds current tolerance.

	PFC (kN)		FFC (kN)		Lower TI	
Model	left	right	left	right	left	right
IP angle = 50	**5.97**	2.8	3.88	3.13	**1.84**	**1.68**
IP angle = 30	5.28	2.69	3.78	2.99	**2.03**	**1.92**
IP stiff	**7.64**	2.14	6.61	2.94	**2.55**	**1.29**
IP compliant	4.41	2.2	3.29	3.35	**2.02**	**1.78**
Abduct = 20	4.63	2.66	2.93	3.1	**1.41**	1.06
Abduct = 0	5.66	2.25	4.07	3.02	**2.36**	**1.55**
Baseline	**5.91**	2.1	4.18	3.07	**1.83**	**1.55**
Belted	4.02	3.83	1.31	1.85	0.7	0.69

Table 2. Injury scores for the 50th percentile male. Bold numbers indicates value exceeds current tolerance.

	PFC (kN)		FFC (kN)		Lower TI	
Model	left	right	left	right	left	right
IP angle = 50	4.77	4.18	6.85	5.21	1.15	0.97
IP angle = 30	4.91	4.2	7.32	6.06	1.13	0.68
IP stiff	5.3	5.69	8.48	8.29	1.11	0.8
IP compliant	4.63	3.11	6.25	4.15	1.16	0.97
Abduct = 20	**7.31**	**6.62**	**11.02**	**9.53**	**1.73**	**1.47**
Abduct = 0	3.66	4.24	5.27	5.33	0.65	0.82
Baseline	4.78	4.33	6.93	5.46	1.13	0.82
Belted	2.63	2.52	3.42	3.86	1.17	0.52

The results for the 50th percentile male indicated that the PFC, FFC and TI were generally below current tolerances, except when the femurs were abducted 20 degrees. The higher injury values associated with the abducted hip appeared to be the result of greater hip flexion at impact, which caused earlier impact of the knee bolsters by the dummy tibias. In addition, the feet struck higher up on the intruding toe pan, the top of which intruded further than the base. The presence of a seatbelt reduced the PFC values by over 40% and the FFC values by 50% for the left leg and 29% for the right leg, as compared to the unbelted baseline conditions. The TI value for the left leg actually increased when the dummy was belted, while the right TI value decreased by 37%.

Vehicle database queries (NHTSA, 2003) list femoral forces for the 50th percentile male at 4.84 kN and 4.83 kN, for the left and right leg, respectively, under FMVSS 208 conditions. These values are 20-30% higher than our baseline, belted simulation. Similarly, our results for the female dummy are 30-46% lower than the database presents. The present trends may not be true for different sized vehicles, and those that exhibit more symmetrical crush of the engine compartment in frontal impacts. Variables not considered presently include seat height, delta-V, hip flexion/rotation and airbag inflation parameters.

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