PEDAL USE AND FOOT POSITIONING DURING EMERGENCY BRAKING

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ABSTRACT

Foot and ankle injuries have a high occurrence rate in car crashes. To more fully understand the injury mechanism behind these injuries, it is important to know where the feet are placed during both normal driving and braking. In this study a driving simulator with a Volvo 850 mock-up was used to present the test subject with situations that required emergency braking. The mock-up was equipped with a pedal rack and a manual gearbox. Thirty-five subjects participated in the study and two different braking situations were studied; controlled braking and emergency braking. Subjects were selected from both genders and varied with regard to age, stature and shoe size.

INTRODUCTION

It is important to consider foot and ankle injuries in car crashes. In Volvo's accident data base (comprising more than 25 000 crashes, involving Volvo cars in Sweden) about 20% of all AIS 2+ injuries sustained in Volvo 700 and Volvo 900 models are injuries to the thigh and leg (Forssell et al, 1996). The risk of suffering long-term consequences from this type of injuries is 2,4%, (mixed model, von Koch et al, 1992) which indicates the significance of leg injuries. Mc Kenzie (1986) also recognises injuries to the lower limbs as important regarding long-term consequences. Analysing NASS data, Crandall et al (1994), reported lower extremity injuries accounting for about 30% of all AIS2+ injuries for belted front seat occupants in frontal car impacts. Of those injuries, 30% were in the foot and ankle region.

Several different studies have shown that foot and ankle injuries can occur even though there has been no intrusion in the footwell area (Forssell et al, 1996; Thomas and Bradford, 1995)

According to several studies analysing accident data, pedals can affect the injury outcome (Forssell et al, 1996; Thomas and Bradford, 1995; Portier et al, 1993). The data show that drivers are at a higher risk of sustaining foot and ankle injuries than passengers being subjected to the same intrusion and delta-V levels in a car crash. Crash tests using dummies (Sakurai et al, 1996; Kuppa and Sieveka, 1995), also point out the importance of pedal contact and foot position in relation to pedals, as well as to the floor.

Several researchers have considered fracture of the right ankle as occurring while the right foot is on the brake pedal, but do not completely agree about the injury mechanism (Morgan et al, 1991; Begeman and Prasad, 1990; Lestina et al, 1992; Portier et al, 1993; Pilkey et al, 1994)

To be able to understand the mechanism of foot injuries, it is crucial to know where the feet are usually placed during both normal driving and emergency braking. At least two studies have been presented in the area of studying foot positioning in emergency manoeuvres (Crandall et al 1996 and Manning et al, 1997), both using a driving simulator.

Manning et al (1997) registered a mean peak force of 750N while braking, and found no statistical difference between men and women.

This study aims to:

- describe foot positioning during normal driving.
- describe foot positioning and movement during emergency braking.
- identify potential problems in braking behaviour according to the measured variables.

DESIGN OF THE STUDY

MATERIALS A total of 35 experienced drivers were studied (people that drive more than three days a week); 19 females and 16 males, at ages between 24 and 57 years. The average age was 38 years. The majority were used to driving a car with a manual gearbox, only four were used to an automatic gearbox. The subjects were all recruited from within Volvo. They were not informed of the purpose of the study nor were they familiar with the simulator previously. The subjects were selected according to gender, car ownership and shoe size. The breakdown according to these parameters is shown in Table 1.

Table 1: The distribution of the subjects according to gender, car ownership and shoe size (38 ~7½ ; 43 ~10½ American shoe size).

European Shoe Size	Volvo Owners		Owners of Other Brands	
	Female	Male	Female	Male
< 38	4		3	
38-43	7	5	5	5
> 43		3		3
Total: 35	**11**	**8**	**8**	**8**

The subjects wore their own shoes and the shoe types were documented by photography. The subjects were restricted from wearing high heels, to eliminate an extra parameter in the study.

METHODS The study was carried out in a driving simulator with a Volvo 850 mock-up. A pedal-rack with manual gearbox was installed in the mock-up. The simulator had an immovable base and consisted of a modified car with original controls. The car was placed in front of a panoramic screen onto which the simulated road was projected in a two dimensional view. Feedback to the drivers was engine sound and steering wheel resistance.

The simulated road was approximately 40 km long and consisted of a two lane highway with intersections and speed changes. Oncoming traffic and cars at an intersection interacted with the subject's car. The subjects were asked, before the test, to keep to the posted speed limits and to drive as they normally do. The test drive started with a five minute long familiarisation period. After that, they drove for about 35 minutes. Two emergency situations were presented to the subjects. The first was a controlled braking, with a car running through a red light; crossing an intersection. The second was an emergency braking situation, with a minibus with warning lights on suddenly backing up.

MEASURES In order to determine where the subjects positioned their feet during both normal driving and emergency braking, five cameras were installed in the simulator car. Four cameras in the footwell (top view of shoe, left side, right side, rear view) and one camera facing the upper part of the body, including the subject's face.

The measures taken were:

- placement of feet during normal driving; see variables below
- braking force
- reaction time (time from release of accelerator, *no contact*, until contact with brake pedal)
- position of right foot during braking (controlled braking and emergency braking); see definitions below
- deviation, eversion/inversion and dorsiflexion/plantarflexion of right foot during braking; see definitions below
- a questionnaire; completed by the subjects, consisting of personal data and subjective comments of the simulator drive

PLACEMENT OF FEET DURING NORMAL DRIVING Foot placement was sampled from the video tape and analysed twice during the test drive, to serve as baseline information. The sampling was done approximately one minute before each braking event.

Measures taken during the two events:

- placement of left foot: on footrest, clutch or floor
- heel position of the right foot: directly below the accelerator, between the accelerator and brake, directly below the brake pedal or lifted from the floor

- deviation, inversion/eversion, dorsi-/plantarflexion of the right foot

RIGHT FOOT POSITION   In order to locate the position of the right foot when braking, the brake pedal surface was divided into nine different areas, see figure 1.

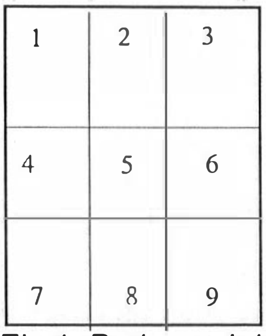


Fig.1. Brake pedal surface divided into nine different areas.

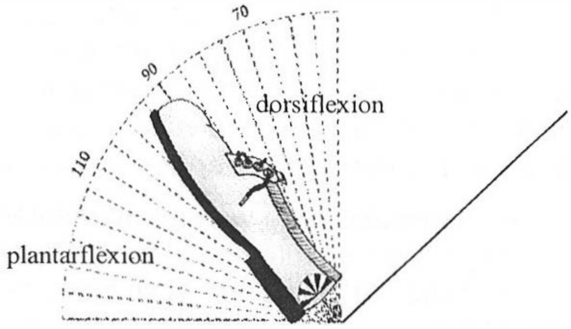


Fig.2: Picture of foot position with neither dorsiflexion nor plantarflexion.

DORSIFLEXION / PLANTARFLEXION   Angle at dorsiflexion and plantarflexion was measured on the right foot only. A foot angle of 90° to tibia is defined as neither dorsiflexion nor plantarflexion, see figure 2.

DEVIATION   The deviation from neutral was measured on the right foot, as in figure 3. For this study, no regard was taken to whether the movement was in the ankle or in the hip joint. An angle of 90° (±5°) is defined as foot straight forward. A foot with right deviation would be at less than 90°, and a foot with left deviation at more than 90°.

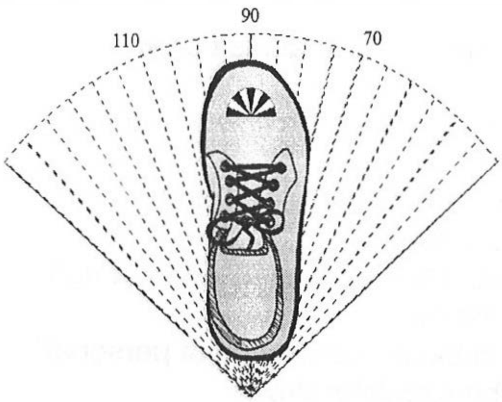


Fig.3: Picture of foot position with no deviation.

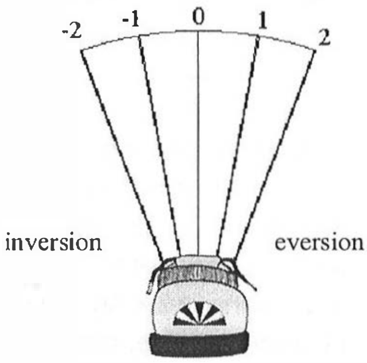


Fig.4: Rear picture of a foot in a position with neither inversion nor eversion.

INVERSION / EVERSION   The angle of inversion/eversion of the right foot was measured in intervals of approximately 10°±5°. The steps are shown in figure 4, indicating *minor (0)*, *average (1)* and *major (2)*. An inverted foot would have a positive value and an everted foot a negative value.

ANALYSIS   The video recordings in the footwell and of the subject's face, were analysed, together with data logs of the simulator data, e.g. vehicle speed and braking force. The questionnaire data was combined with the observational and simulator data.

The video recordings were transcribed initially into a spreadsheet program, and then transferred into a statistics package for analysis. The entire data set was screened for encoding errors. Descriptive and inferential statistical analyses were then conducted.

RESULTS

THE SIMULATOR All but one subject felt that they were comfortable in the simulator, and that there was enough space for their feet and legs. All subjects but two (154 and 170 cm tall) said that they could adjust their seat position enough. All subjects but one felt that the five minute test drive was long enough to get used to the simulator.

The results from the questionnaire showed that the simulator was perceived as moderately realistic (mean 2.7; SD 0.76 - scale: 1= very realistic 5 = quite unrealistic). The subjects also rated the driving as being of moderate difficulty (mean 2.3; SD 0.65 - scale: 1 = very easy to 5 = very difficult).

Driving a simulator differs from driving a car in some aspects. The subjects were asked whether or not they had felt sick to determine if this had any influence on the test results. During the driving, two felt sick the whole time, six only at the beginning, and five only at the end. The majority (22/35) did not feel sick at all. There were no significant differences between age groups or gender, regarding this aspect.

FOOT POSITION DURING NORMAL DRIVING
During 'normal' driving most subjects had their left foot on the foot rest (observation one: 74%, two: 46%).

All subjects had their right foot on the accelerator. The heel of the right foot was normally resting on the floor between the brake and accelerator (baseline one: 58%, baseline two: 46%).

The mean value of flexion of the right foot was 93° (observation 1) and 92° (observation 2). There is an indication of a plantarflexion of the foot when it is on the accelerator. The mean angles of deviation of the right foot are 76° (observation 1) and 74° (observation 2) indicating that the foot is more likely to deviate to the right. There was a significant difference in deviation between men and women. Men angle their foot more to the right (81°) than women (71°). This is consistent with another finding that men position their heel more to the left than women during normal driving.

Measurements of inversion/eversion for normal driving show that most of the subjects had their foot slightly inverted (see figure 4), 35% had their foot level; neither inverted nor everted.

BRAKING EVENTS AND GENDER DIFFERENCES Based on answers in the questionnaire, regarding how the subjects perceived the two braking events, it could be concluded that the simulated situations had caused the desired response. The first braking situation was supposed to trigger a controlled braking, and the second an emergency braking. Choosing three of ten listed words, *fear, control, excitement, panic, unsafe, helpless, stress, security, nervousness and calmness*; *calm* (17/31) and *control* (22/31) were most commonly chosen for the controlled braking event. In situation two the subjects felt more *helpless* (22/36) and *panicked* (18/36) than in situation one.

In the controlled braking event, 31 subjects managed to brake properly. Four subjects were not presented with a realistic situation because of technical problems, e.g., the event occurred before the subject's car reached the intersection. Of 31 subjects 23 pressed the clutch with their left foot in the controlled braking event. Of those 20 pressed the brake before they pressed the clutch, and three pressed clutch and brake at the same time.

In the emergency braking event, the simulated average speed was significantly greater than in the controlled braking event ($p < 0,001$; mean speed = 67 km/h, SD 10) versus the controlled braking event (mean speed = 57 km/h, SD 11). A total of 31 subjects braked in this second event, and 2 subjects managed to steer away. In the emergency braking event, 24 of 31 subjects pressed the clutch with their left foot. Of the 31 subjects 19 pressed the brake first, 2 pressed the clutch first and 3 pressed the brake and clutch at the same time.

There were no significant differences, for the braking events, according to age group, gender, shoe size, leg length or body height. However there was a tendency that more men had their heel on the floor at first touch of the brake. Also, there were no significant differences between men and women regarding deviation and inversion/eversion, neither in the controlled braking nor in the emergency braking event.

RIGHT HEEL POSITION Just before the controlled braking event most subjects (18) had their heel between accelerator and brake. At the first touch of the brake 13 subjects moved the heel position to the left and 9 subjects lifted their heel in the air. At maximum brake force 41% (13) of the subjects, mostly women, had their heel in the air as also noted by Hansson & Warell 1997. The same pattern is seen for the emergency braking event (also noted by Crandall et al 1996, Manning et al 1997).

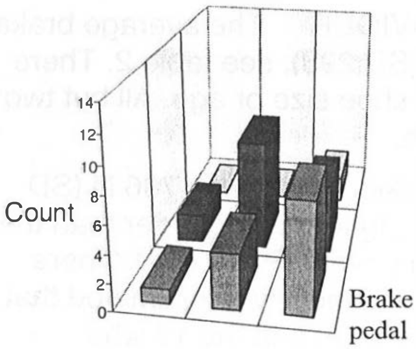
There is a strong tendency in both braking events for men to have their heel more to the left and women more in the air during braking. This was found to relate to the subject's shoe size and leg length. Subjects with large shoe size (>43) and/or long legs (mean 108 cm) tend to have their heel on the floor during maximum braking. This is consistent with similar findings by Crandall et al 1996.

During normal driving, measured approximately one minute before the emergency braking event, women had their foot significantly more to the right as compared to men ($p=0.004$). The same trend is to be found in event one.

POSITION OF FEET ON BRAKE PEDAL

Controlled braking event Figures 5 & 6, below, show the right foot positions for braking event one, according to the nine areas as shown in figure 1. The positions correspond to where the centre (the ball) of the foot was placed. The positions are at first touch on the brake pedal, figure 5, and at maximum braking force, figure 6.

Controlled Braking



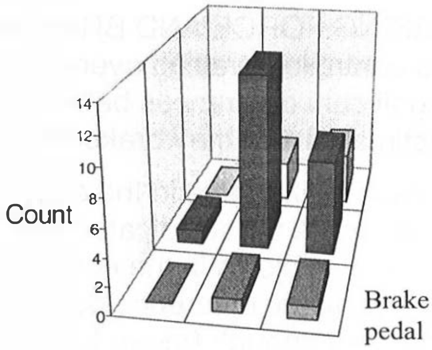
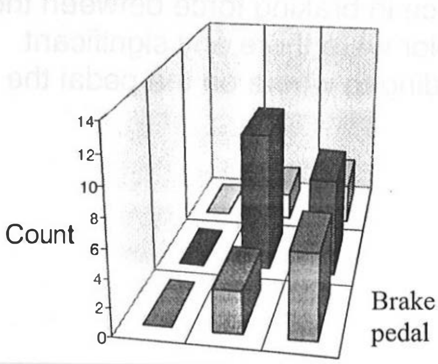


Fig.5: Position of the right foot at first touch on the brake pedal.

Fig.6: Position of the right foot, on the brake pedal, at maximum braking force.

In total, 19 subjects moved their right foot between first touch on the brake and maximum braking force. Of these 10 subjects moved their foot further up on the pedal, and 8 moved their foot to the centre. Of the 12 subjects who did not move their foot, 5 already had their foot centred. There were no significant differences in age group, shoe size or regarding gender, movement of the foot between first touch on the brake pedal and maximum braking force.

Emergency Braking



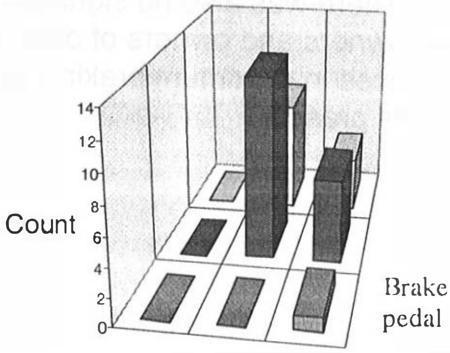


Fig.7. The position of the right foot at first touch on brake.

Fig.8. The position of the right foot at maximum brake force.

Emergency braking event Figures 7 & 8 show the right foot positions for braking event two. The tendency is similar to that of braking event one. The position at first touch is on the lower right part of the pedal, while the position at maximum force is more in the centre of the pedal, and higher up.

MAXIMUM DORSIFLEXION / PLANTARFLEXION The positions of maximum dorsiflexion and plantarflexion were recorded for both braking events, as in tables 2 and 3. Although the subjects tended to have their feet more plantarflexed during the emergency braking event, this difference was not statistically significant. Neither were there any meaningful differences in the amount of flexion regarding gender, height or leg length.

BRAKING FORCE AND BRAKING BEHAVIOUR The average brake force in the controlled braking event was 281 N (SD 293), see table 2. There were no significant differences between gender, shoe size or age. All but two subjects estimated that they braked hard enough.

Average brake force in the emergency braking event was 796 N (SD 466): see table 3. A t-test indicated that this was significantly greater than the force applied by subjects in the controlled braking event ($P < 0.001$). There was also a significant difference between the 18 subjects who estimated that they braked hard enough (mean force 967 N, SD 490), and the 15 who estimated that they did not brake hard enough (mean force 591 N, SD 349). Even the subjects who felt that they did not brake hard enough, braked more than was needed for obtaining maximum braking effect (160 N).

The subjects over 50 years of age reached their maximum brake force significantly slower, in both braking events, than the subjects below 30 years of age (1.38 s vs. 0.84 s). The difference was only significant in the emergency braking event.

There was also a tendency for subjects who moved their foot higher up on the pedal to reach a higher maximum braking force than those who kept it in the same spot (mean force "up", 970 N, SD 406 and mean force "same", 665 N, SD 509). This tendency appeared in both braking events, but the difference was not significant in the controlled braking event.

There was also no significant difference in braking force between the Volvo owners and owners of other brands. Nor were there any significant differences in maximum braking force according to where on the pedal the subjects pressed.

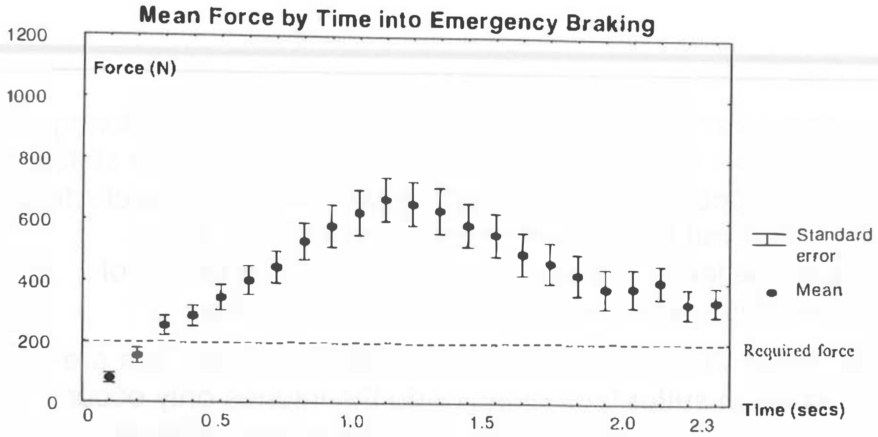


Fig.9: Mean peak braking force over time, (N=35). Maximum braking force is applied approximately one second into the braking event.

REACTION TIME The subject's reaction time was measured between lifting their foot from the accelerator until first contact with the brake pedal.

Reaction time data for the emergency braking event shows that subjects who had their foot in the centre position (position 5, figure 1) at maximum brake force reacted faster than the others. (RT "centre" 0.42 s SD 0.19 s and RT "not centre" 0.56 s SD 0.15). No difference was observed between placement and reaction time for the controlled braking event.

Table 2: Feet and brake measures, controlled braking.

Measure	N	Mean	Stand. Dev.	Max	Min
Flexion[1]	19	85	7.2	100	70
Deviation	31	92	9.3	115	75
Brake force (Newton)[2]	31	281	293	969	14
Reaction time (s)	31	0.64	0.51	3.00	0.20

Table 3: Feet and brake measures, emergency braking.

Measure	N	Mean	Stand. Dev.	Max	Min
Flexion	30	82	6.1	100	70
Deviation	31	89	6.2	110	75
Brake force (Newton)	33	796	466	1793	116
Reaction time (s)	33	0.50	0.19	1.20	0.20

[1] Flexion is measured just before braking, at max. flexion of foot.

[2] The distribution is positively skewed. The median is 124.

DISCUSSION

No problems were found in the way people braked normally or during the emergency scenario. This study did not yield any instance of a foot sliding off or twisting off the brake pedal. These results suggest that the subject's feet tended to be 'well' placed, even during emergency braking. This was unexpected, because we believed that there would be some evidence of awkward foot placement during the simulated emergency braking.

These findings raise some questions. Do the people, whose feet are in a seemingly 'correct' position suffer foot injury, or do the injuries only occur with awkward foot positioning? Alternatively, was the simulation realistic enough to evoke a real emergency braking response?

In relation to the latter question, the simulated emergency braking situations in this study appeared to cause the desired response among the subjects. They tended to feel more *calm* and *in control* in the controlled braking event and *helpless* and *panicked* in the emergency braking event. The braking force data from the two situations also suggested that people reacted in a manner that was consistent with the respective situations. The force was more gradual and light in the controlled braking event, and hard and sudden in the emergency braking event. Consequently, it is believed that the simulation in this study was sufficiently realistic to evoke braking behaviour that could accurately represent behaviour in a live road environment. Furthermore, the subjects perceived the simulation as being fairly realistic. Thus, using a driving simulator appears to be a valid and safe option for studying emergency braking behaviour.

One limitation of the two braking situations in this study was the absence of movement of the car. No movements, such as pitching forward, which occur in a real driving situation during rapid deceleration, were represented. This study shows that subjects were able to brake safely and effectively in the absence of movement and deceleration forces. It might be concluded that these forces are the cause of awkward foot positioning during braking. Sudden deceleration, from braking or an impact, might be responsible for jarring the foot off the pedal in an awkward manner. Thus, people start emergency braking appropriately but the extreme forces involved in deceleration deflect the foot into a position that is more likely to cause injury. People with their foot on the right edge of the pedal might be more at risk here. Drivers could also sustain injury through pre-impact bracing (Klopp et al 1995).

A driving simulator appears to be the only safe and controlled way of studying emergency braking behaviour. Future research could be conducted to investigate these issues, using a simulator with a mobile base. Being able to simulate the rapid deceleration forces associated with emergency braking might provide a better measure of how drivers behave. However, there may be some ethical concerns about exposing drivers to events in which they may place themselves at risk of injury.

One concern related to the video analysis is the precision of foot measurements. It was difficult to obtain a precise measure of foot position on video, particularly eversion/inversion. An attempt should be made to find a more accurate technique for measuring position. However, it is uncertain whether very small variations in foot angle would actually make a safety difference.

CONCLUSIONS

This study shows that during an emergency situation the brake pedal is used and that the foot is properly placed on the pedal. Based on this conclusion, it is not evident that the initial foot position on the pedal is injury generating. However, it could be that people start emergency braking appropriately but the extreme forces involved in deceleration displace the foot into a position that is more likely to result in injury.

There is a behavioural difference between men and women which is closely related to the size of the shoes. Men rest their heel on the floor closer to the brake pedal when pressing the accelerator. Women lift heir heel in the air when changing between accelerator and brake pedal.

In this study the right foot was generally straighter (less deviated) when braking compared to normal driving. A more deviated and/or twisted foot is subject to a higher risk in an impact.

Furthermore, it was shown that in an emergency situation it is more common to push the brake pedal before using the clutch. The average brake force in the emergency braking event (796 N) was significantly higher than in the controlled braking event (281 N). A significant difference was evident between subjects who estimated that they did not brake hard enough, 591 N, and subjects that estimated that they did brake enough, 967 N. *160 N is sufficient to obtain maximum braking power.* It was also significantly evident that subjects who placed their foot higher up on the brake pedal produced a higher maximum brake force. Subjects over 50 years of age produced maximum brake force significantly slower in the emergency braking event than the younger subjects.

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