COMPARISON OF ANKLE INJURY MECHANISM IN FULL FRONTAL AND OBLIQUE FRONTAL CRASH MODES WITH THOR DUMMY AND HUMAN FE MODELS

Kaitaro,Nambu
Hisaki, Sugaya
Hiroyuki, Mae
Honda R&D Co., Ltd. Automobile R&D Center
Japan

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ABSTRACT

It is well known that the research of co-linear and oblique crashes have progressed since NHTSA had reported that the large number of fatalities occurred in crashes involving poor structural engagement between the vehicle and its collision partner in 2009. Moreover, a new frontal crash dummy, THOR, is being developed for which a variety of new risk functions has been proposed. Especially, an ankle injury is being considered for a new injury assessment.

In this study, the main purpose is to evaluate the ankle injury risk functions based on the accidental analysis and the human finite element (FE) simulation based on NHTSA co-linear and oblique research tests. First, the accident frequency of the ankle injury in US frontal crash accidents was compared with various ankle injury risk functions. Second, the ankle injury mechanism was investigated by conducting human FE simulations focusing on the ankle behavior in order to clarify the effect of the tibia compression on the ankle injury. It was found that the ankle injury risk functions without tibia compression effect estimated higher risk than the actual accident. On the other hand, it was identified that the talus and fibula damage could change drastically by the eversion and inversion of the ankle with/without tibia compression by human FE simulation. Therefore, the ankle injury risk function proposed has better correlation with the accidental data with can consider the rotational direction and the tibia axial compression.

Introduction

The U.S. government's New Car Assessment Program (NCAP), while not actually a safety regulation, is the program the National Highway Traffic Safety Administration (NHTSA) began using in 1979 to enhance the crash safety of new cars. Since then, NCAPs have spread to other countries around the world, including developing countries where automobile ownership is on the rise in recent years. Euro NCAP, a program begun in 1997 that covers much of Europe, adds an evaluation of leg injuries, since that type of injury is so critical. The foot/ankle complex consists of such bones as the fibula, tibia, talus, and calcaneus (Fig. 1), all of which are connected to each other by ligaments (Fig. 2). The skeleton and tendons below the knee have a complex structure that enables the feet to make their sophisticated movements. Any injury to this area can be difficult to recover from, and sequelae (after-effects) tend to linger. Because the foot/ankle complex has such a complicated structure and tends to bear such heavy loads, and because severe ligament damage often leads to sequelae of joint function, this make the ankle a particularly important part of vehicle passengers' bodies to protect.

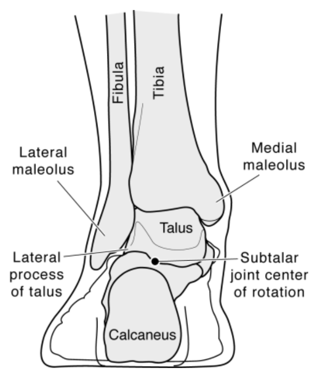

Figure 1. Bony anatomy of the foot/ankle complex. [2]

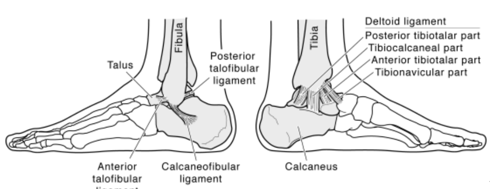

Figure 2. Ligamentous anatomy of the foot/ankle complex. [2]

Many ankle injuries happen in frontal collisions. A survey of accidents in the U.S. indicates that 9% of 168 oblique and co-linear collisions between 1959 and 2014 resulted in AIS2+ ankle injuries (Fig. 3). Narrowing that population down to oblique collisions, an area where research has been going on in recent years, shows a rather high rate of 18%.

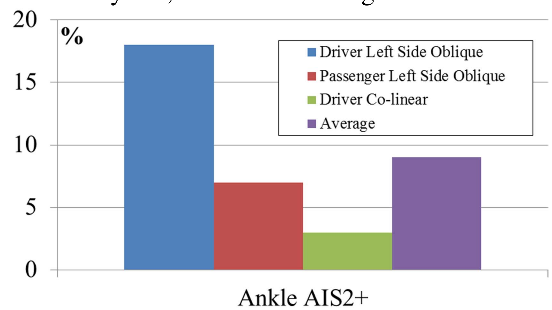

Figure 3. Percentage of cases for each crash type in which the occupant sustained AIS2+ to the ankle by crash types

Research on the evaluation of ankle injuries is going forward day by day. In 1996, Parenteau and Petit used human legs for a static evaluation of the effect of collisions on inversion and eversion injuries [4]. Their test results showed that ankle-bone fracture and ligament tearing occur when there is moment of 34.1 ± 14.5 Nm to the subtalar joint during inversion or 48.1 ± 12.2 Nm during eversion. Their study also showed that the angle of rotation at the time of ankle injury was 34.3 ± 7.5° during inversion and 32.4 ± 7.3° during eversion.

In 2001, Kuppa suggested ankle injury risk curves for inversion and eversion moment to the subtalar joint, based on Parenteau and Petit's test results [6]. According to Kuppa's test results, the probability of injury during inversion and eversion when there is moment on the subtalar joint is such that injuries occur at similar timing in the standard deviation, and that injury occurs when there is 40 Nm of moment during either inversion or eversion. According to the risk curves suggested by Kuppa, there is a 25% probability of AIS2+ ankle and ligament injury at 33 Nm of ankle moment during inversion or eversion and a 50% probability of such injury at 40 Nm.

In 2002, Funk suggested new ankle injury risk curves for inversion and eversion moment to the subtalar joint [2]. These risk curves account for inversion and eversion as well as the difference it makes whether there is an axial force input. According to Funk's test results, only during inversion, it is the calcaneofibular ligament that sustains injury; it tears at 24 ± 6 Nm (34° ± 10°). During eversion, on the other hand, the part that sustains injury is the tibiocalcaneal part of the deltoid ligament; it tears at 42 ± 15 Nm (30° ± 8°). Additionally, when the ankle sustains a force of 2 kN on the axis of the tibia from the bottom of the foot, during inversion, two places sustain injury: the calcaneofibular ligament and the osteochondral part of the subtalar joint. The moment at which ligament tearing and osteochondral fracture occur rises to 79 ± 24 Nm (44° ± 14°). During eversion, as well, the number of places injured rises to two: the tibiocalcaneal part of the deltoid ligament, and the heel. Breaking of the tibiocalcaneal part of the deltoid ligament and fracture of the heel bone occurred at 142 ± 100 Nm (41° ± 14°). Based on these test results, the risk curve suggested by Funk indicates a 25% risk of injury at 24 Nm and 50% risk at 31 Nm during inversion in an adult male while under no compression. During eversion under the same conditions, there was a 25% risk at 45 Nm and 50% risk at 58 Nm. At 2 kN of compression, there was a 25% risk of injury at 58 Nm and 50% risk at 75 Nm during inversion in an adult male. During eversion under the same conditions, there was a 25% risk at 110 Nm and 50% risk at 142 Nm.

Because there are differing opinions about ankle injuries, one must first consider the injury phenomena that occur during a collision and then select the most suitable index for frontal collisions. In this paper, we use a human finite element (FE) model to reproduce Funk's ankle test and confirm the mechanism by which ankle injuries occur. Using the results, we compare actual accident conditions with the human FE-based accident reproduction model to evaluate ankle injuries in collisions and then discuss which risk curves are appropriate.

Methods

Honda's human FE model was used in this research [1]. The ligaments in the human FE model are made from beam elements, as shown in Fig. 4. For that reason, reproducing Funk's test allowed us to estimate the amount of strain under the conditions at which each ligament tore, and from that we could set a tearing threshold for each ligament. In Funk's test, the sole of the foot was anchored to a pedestal and the pedestal was rotated to make the foot turn along the axis of the ankle. We reproduced the test, therefore, by using only the foot of the human FE model, as shown in Fig. 5. We measured the strain of each ligament under the four conditions shown in Table 1 to select the tearing threshold values.

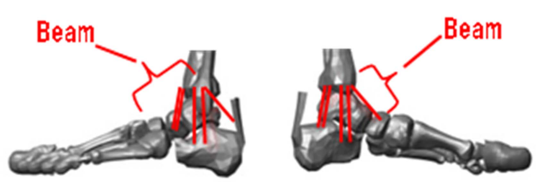

Figure 4. Ankle Model in Human FE Model

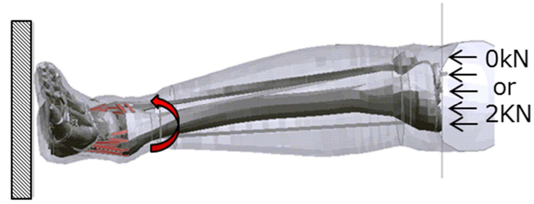

Figure 5 Ankle Test Model

Table 1
Summary of injury data for all Kuppa's test conditions[2]

Neutral flexion	direction	Moment at injury (Nm)	Angle at injury (deg)	Injured Part
No axial	Inversion	24±6	34±10	Lateral ligament tears
	Eversion	42±15	30±8	Medial ligament tears
2kN axial	Inversion	79±24	44±14	Lateral ligament tears
	Eversion	142±100	41±14	Medial ligament tears

Next, we used an occupant injury simulation model and tested a THOR dummy and human FE model under identical conditions, then compared the moment on the ankle and the amount of strain in each ligament (Fig. 6). For the calculating conditions, we used the oblique mode (in which there is a high probability of ankle injury) and a front barrier condition (in which there is little ankle injury), and used the amount of strain of the human FE ankle ligaments to determine whether there was a tear. With the THOR dummy, we substituted values into each risk curve based on ankle moment (M) and leg axial force (F) to calculate the ankle injury risk.

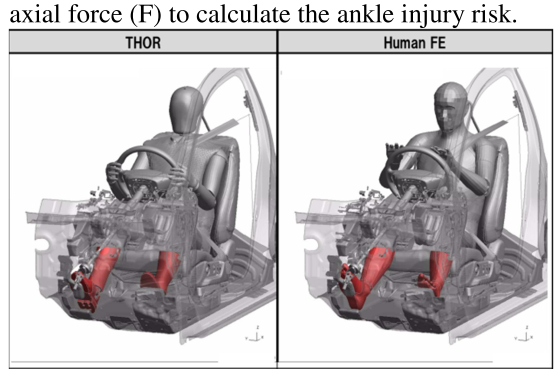

Figure 6. Full Car CAE Model

Kuppa

$$\text{Risk} = \frac{1}{10\sqrt{2\pi}} e\left\{-\frac{(M-40)^2}{200}\right\}$$ **(Equation 1)**

Funk (Inversion)

$$\text{Risk} = e^{\left(-e^{(-3.42\times\ln(M)-11.1-1.01-1.52\times F)}\right)}$$

(Equation 2)

Funk (Eversion)

$$\text{Risk} = e^{\left(-e^{(-3.42\times\ln(M)-11.1-1.01-2.19-1.52\times F)}\right)}$$

(Equation 3)

Results

First, in the model that reproduces Funk's test (Fig. 5), we confirmed that the mechanism of ligament tearing during inversion was that the greatest strain occurred in the calcaneofibular ligament, which is the farthest away from the axis of rotation (Fig. 7). Thus, we were able to estimate that the first ligament to tear during inversion would be the calcaneofibular ligament. Also, when 2 kN of compression is applied from the knee to the foot, the fibula and calcaneus are compressed, which reduces the length of the ligament in the axial direction. Therefore, comparing cases with and without compression, it seems there would be less ligament strain when there is 2 kN of compression than when there is none (Fig. 8). This is thought to be the reason why, in Funk's test, the angle of rotation at which ligament injury occurred when the specimen was under axial force was smaller than the case when no axial force was applied.
Next, we confirmed the eversion direction. Here, a high degree of strain occurred in the tibiocalcaneal part of the deltoid ligament, which is far from the axis of rotation, similar to the case during inversion (Fig. 9). Also, similar to the case during inversion, the amount of ligament strain depended on whether there was 2 kN of compression. When there was 2 kN of compression from the knee to the foot, the tibia and calcaneus were compressed, reducing the length of the ligament in the axial direction, so that there tended to be less ligament strain than if there had been no compression (Fig. 10). Based on these test results, we set the beam tearing strain to 0.12 for the calcaneofibular ligament and 0.18 for the tibiocalcaneal part of the deltoid ligament; at these values, there would be a 50% probability of injury. Therefore, strain below this threshold would mean an injury risk of less than 50%, while strain above this threshold would mean an injury risk of more than 50%.

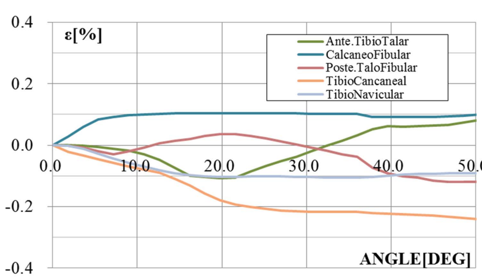

Figure 7. Average Stress-Angle Response in Inversion

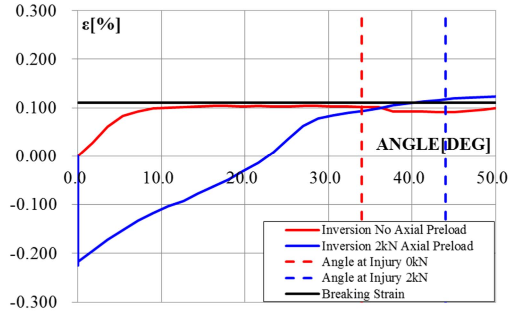

Figure 8. Stress-Angle Response in Different Compression Situation

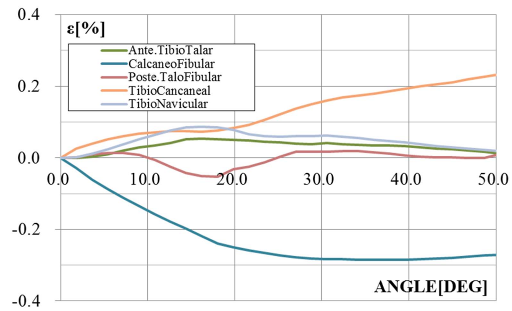

Figure 9. Average Stress-Angle Response in Eversion

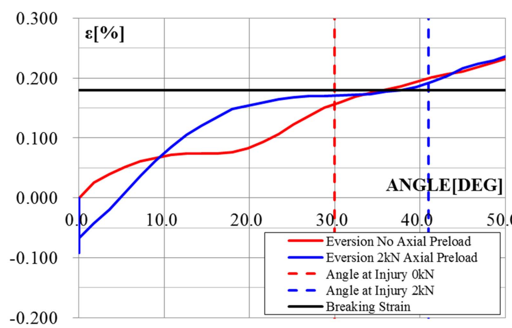

Figure 10. Average Stress-Angle Response in Different Compression Situation

Next, using occupant injury simulations, we checked ankle behavior with a THOR dummy and the human FE model. The results indicate that the oblique test mode entailed more footwell deformation than the co-linear, and therefore, in oblique mode, the moment on the THOR dummy's ankle and the amount of ligament strain in the human FE model are also greater than in the co-linear. However, the results showed the probability of injury as calculated from the THOR dummy's ankle moment was different from the probability of injury found from the strain in the human FE model. The calculated probabilities of injury are given in Table 2. The risk found by Kuppa and Funk for both the left and right ankles during a co-linear and the left ankle in an oblique test approximated that found by the human FE model. On the other hand, for the right ankle in the oblique test, only the Funk risk curve that accounts for axial force when calculating risk produced results similar to the human FE model.

Table 2
Summary of Injury Risk Data for All Test Conditions.

Risk Curves of Inversion/ Eversion Moment		Full Scale Simulation Ankle Injury Probability			
		Flat 56 km/h		Oblique 90 km/h	
		L Ankle	R Ankle	L Ankle	R Ankle
Kuppa (2001)	THOR	21.5 Nm (3%)	-10.9 Nm (0%)	-81.0 Nm (99%)	-64.7 Nm (99%)
Funk without Axial (2002)	THOR	21.5 Nm (0%)	-10.9 Nm (0%)	-81.0 Nm (100%)	-64.7 Nm (61%)
Funk with Axial (2002)	THOR	21.5 Nm (0%)	-10.9 Nm (0%)	-81.0 Nm (78%)	-64.7 Nm (3%)
-	Human FE	No Injury (<50%)	No Injury (<50%)	Injury (≧50%)	No Injury (<50%)

Discussion

In a co-linear, the vehicle's occupants move straight in the vehicle's direction of movement, so there is likely to be little inversion or eversion moment. In oblique mode, however, occupants move to the left, outer side of the vehicle, so the behavior shown by the right foot was to turn in the direction of eversion while that of the left foot was to turn in the direction of inversion. In the risk curves suggested by Kuppa, the moment at which injury occurred was approximately the same for both inversion and eversion, so the difference between ankle injury risk curves for the left and right sides would likely be small in oblique test mode. The risk curves suggested by Funk, on the other hand, take account of the effect of the ligaments during inversion and eversion, so the direction of rotation for the left and right ankles is different in oblique mode, which could be the reason why a gap appeared in the risk of ankle injury between left and right. In oblique mode, moreover, there is more footwell deformation than in the co-linear. And since the left foot sustains 1.6 kN of compression and the right foot 2.3 kN of compression in the axial direction, risk curves that account for axial force are more likely to accurately evaluate the effect on the ligaments.

A comparison of oblique research test results [3] to the respective risk curves shows that the probabilities of ligament tearing as found in risk curves other than Funk with axial force taken into account are very high (Table 3). However, 18% of 104 oblique mode collisions that occurred in the U.S. between 1959 and 2014 resulted in AIS2+ ankle injuries, which is close to the risk curve that accounts for axial force (Fig. 3).

Table 3
Summary of Injury Risk Data in OBLIQUE Research Test.

Vehicle Make	Vehicle Model	MY	Injury Prob. (%)				
			Kuppa	Funk w/o Axial Load		Funk W Axial Load	
				I.M.	E.M.	I.M.	E.M.
BUICK	LACROSSE	2011	100	100	100	74	67
CHEVROLET	CRUZE	2011	100	100	100	61	7
CHEVROLET	CRUZE	2011	100	100	100	9	6
VOLVO	XC60	2013	100	65	100	1	27
DODGE	DART	2013	100	100	97	97	4
HONDA	CIVIC	2013	100	100	97	9	4
SUBARU	FORESTER	2014	100	100	100	16	8
VOLVO	S60	2012	100	57	100	1	7
MAZDA	MAZDA3	2014	100	67	97	1	3
MAZDA	CX-5	2014	100	100	78	11	2
HONDA	ACCORD	2014	100	99	76	5	1
TOYOTA	CAMRY	2014	100	100	42	30	1
HONDA	ODYSSEY	2014	100	78	97	2	4
HONDA	FIT	2015	100	80	82	2	2
NISSAN	VERSA	2013	100	100	11	15	0
HYUNDAI	ELANTRA	2013	100	100	93	8	3
TOYOTA	CAMRY	2012	100	100	100	43	15
FORD	TAURUS	2013	100	38	100	1	7
HONDA	CRV	2012	100	87	100	2	37
HONDA	ODYSSEY	2012	91	66	40	1	1
CHEVROLET	SILVERADO 1500	2012	100	100	100	42	13
OTHER	OTHER	2013	100	100	100	8	11
OTHER	OTHER	2013	100	100	44	13	1
OTHER	OTHER	2013	31	66	0	1	0
TOYOTA	YARIS	2010	100	100	100	7	9
CHEVROLET	CRUZE	2011	100	100	100	15	18
FORD	EXPLORER	2011	100	100	33	53	0
DODGE	RAM1500	2011	100	100	100	54	8
OTHER	OTHER	2013	100	98	100	4	11
HONDA	ACCORD	2013	100	100	61	38	1
OTHER	OTHER	2013	84	52	33	1	0
Average			97	84		15	

Conclusion

We used a human FE model to reproduce Funk's ankle test and confirm the mechanism by which ankle injuries occur. The results for this research confirm an extension and retraction mode for each ligament of the ankle in collision mode, and suggest which ligaments are the most likely to tear. We also found that when there is force on the leg in the axial direction, the ligament contracts, which lowers the risk of ligament tearing. Although force in the axial direction increases the risk of bone fracture, such as in the heel, it is estimated it would help lower risk for some parts. According to the injury mechanism confirmed by this research, it is necessary for injury risk evaluations to consider axial force under collision types such as in oblique tests, or any collision where there is lateral occupant movement.

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