DEVELOPMENT OF A PEDESTRIAN LOWER EXTREMITY PROTECTION CAR USING A BIOFIDELIC FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR

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Paper Number 05-0106

ABSTRACT

The Japan Automobile Manufacturers Association, Inc. and the Japan Automobile Research Institute are jointly engaged in the development of a flexible pedestrian legform impactor (hereafter referred to as "Flex-PLI"). However, a study for the development of a pedestrian lower extremity protection car using the Flex-PLI has not been reported.

In this study, development of sedan, minivan and SUV type cars for pedestrian lower extremity protection was conducted using a Flex-PLI. This study results indicated a good possibility of lower-extremity protection in collisions by pushing the pedestrian's legs forward within the extent of not causing bone fractures. However, such protection methodology is difficult for SUVs because they need high ground clearance and large approach angle as for rough road condition running purpose.

This study is the first trial study for the development of pedestrian lower extremity protection car using a Flex-PLI, therefore, additional similar studies are necessary.

INTRODUCTION

The Japan Automobile Manufacturers Association, Inc. and the Japan Automobile Research Institute are jointly engaged in the development of a flexible pedestrian legform impactor (hereafter referred to as "Flex-PLI") [1][2][3]. The bone and knee of the Flex-PLI have a bending deformation characteristic equivalent to those of the human lower-extremity. The Flex-PLI is equipped with more built-in measuring instruments than are conventional pedestrian legform impactors.

It is reasonable to consider that the Flex-PLI is more suited for the development of proper pedestrian lower-extremity protection car, however, there has been no report of such vehicle development using a Flex-PLI before. In the present study, therefore, pedestrian lower-extremity protection methods for various types of cars were examined using a Flex-PLI.

METHODOLOGY

Pedestrian Legform Impactor

The pedestrian legform impactor employed in the present study is shown in Figure 1. It is the latest-version model developed in 2004 and is called Flex-PLI 2004 [3] (hereafter simply "Flex-PLI"). As listed in Figure 2, the Flex-PLI has a total of 10 measurement items including bone core strain and knee ligament elongation. Based on the relationship between the strain and bending moment of the bone core derived from bone core calibration tests (see Appendix B), it is possible to calculate from the measured value of strain the value of bending moment applied to the bone core.

In the present study, measurement of the elongation of the lateral collateral ligament ("LCL") was omitted since the LCL could not be elongated by the types of vehicles used in the present study.

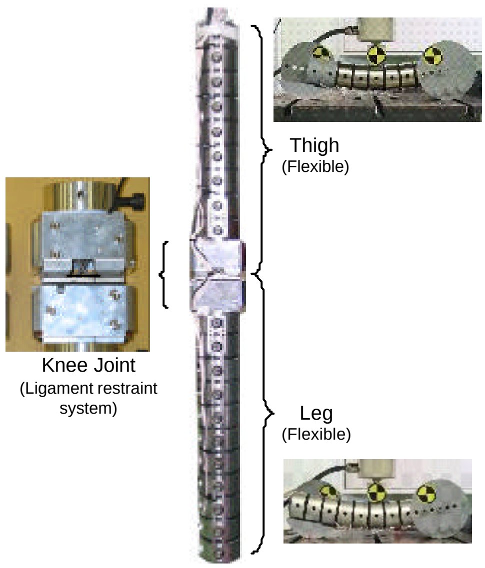

Figure 1. Overall design of Flex-PLI.

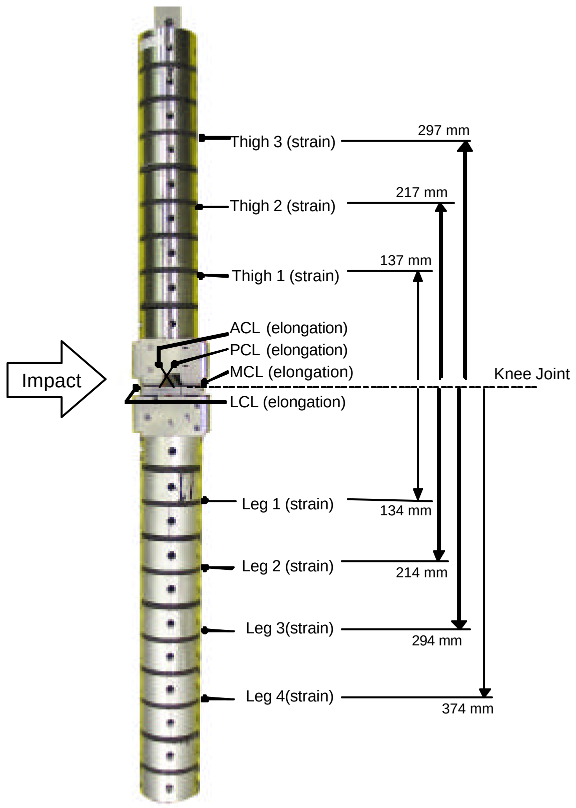

Figure 2. Measurement items of Flex-PLI (2004).

Test Vehicles

The four types of cars used in the present study are shown in Figure 3 and Table 1. They were two sedans, a minivan and an SUV (Sedan 1, Sedan 2, Minivan, SUV).

For each car type, the test was conducted with the car in its original parts. Then, based on the test results, the car was modified and tested to determine suitable methods to protect the pedestrian lower- extremity.

Test Conditions

The test conditions are introduced in Figure 4. The initial impact speed of Flex-PLI was 11.1 m/s, and the impact position was at the center of the vehicle's front face. In accordance with a conclusion drawn by the International Harmonized Research Activity Pedestrian Safety Working Group [4], the lowest point of Flex-PLI was set 25 mm above the ground to allow for the shoe sole height.

Injury Risk Levels (tentative)

The tentative 50% injury risk levels assumed for the present study are listed in Table 2. These tentative 50% injury risk levels for the American 50 percentile male were derived from available literatures for the present study [5][6][7][8][9].

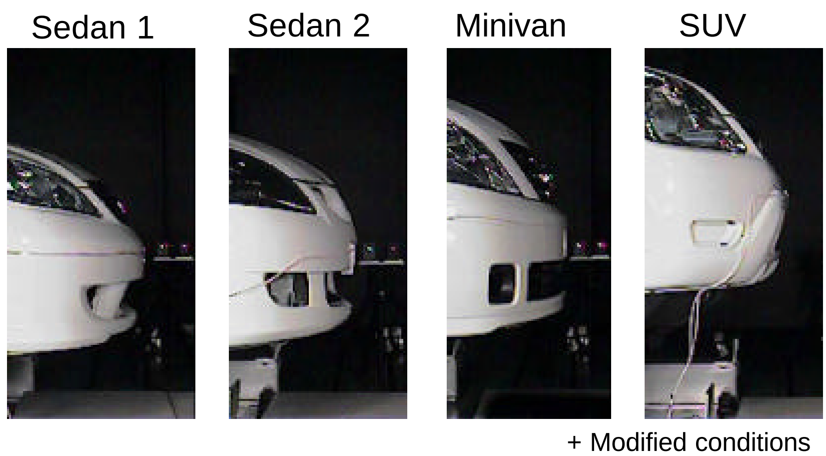

Figure 3. Test cars.

Table 1. Dimensions of test cars.

Car Type	LEH* (mm)	BL** (mm)
Sedan 1	703	157
Sedan 2	765	185
Minivan	829	164
SUV	925	211

* LEH: bonnnet leading edge height.
** BL: bumper lead.

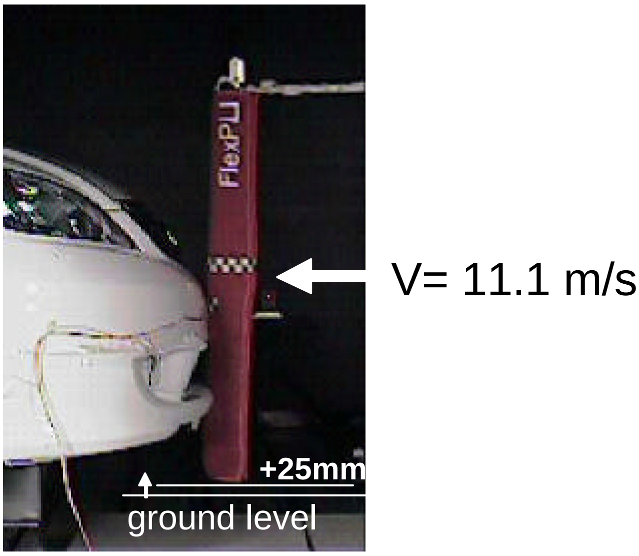

Figure 4. Test conditions.

Table 2. Injury risk levels (tentative).

Body regions		50% injury risk level for 50 percentile American male (tentative)	References
Leg		BM (312 - 350 Nm)	BM (312 Nm): Kerrigan et al., 2004 BM (350 Nm): INF GR/PS/82
Knee	MCL	EL (18 - 20 mm)**	BA (18 deg).: Ivarsson et al., 2004 BA (20 deg).: INF GR/PS/82
	ACL	EL (10 mm)***	SD (10 mm): IHRA/PS/309
	PCL	EL (10 mm)***	SD (10 mm): IHRA/PS/309
Thigh		BM (372-447 Nm)	BM (372 - 447 Nm): Kerrigan et al., 2004 BM (390 - 395 Nm): Kennedy et al., 2004

* BM: Bending moment, EL: Elongation, BA: Bending angle, SD: Shearing displacement.

** Estimated from BA (18-20 deg.), *** Estimated from SD (10 mm)

RESULTS

Sedan 1

Test results with the original Sedan 1 are given in Figure 5. In a collision with Sedan 1 the risk of causing a thigh or leg fracture to the pedestrian proved to be low, but the risk of an injury to the medial collateral ligament (MCL) of the knee might be high (located in the tentative injury risk level). The reason: although the bumper rigidity was insufficient to cause a fracture, the bumper also lacked sufficient force to push the pedestrian's legs forward, thus generating a large bending of the knee.

In view of the above results, Sedan 1 was modified as shown in Figure 6. A second bumper face and a pad were added to the bumper's lower section in order to increase the bumper rigidity.

As shown in Figure 7, the modified Sedan 1 yielded test results that were clearly below the injury risk level for the thigh, leg and knee alike, thus indicating a high pedestrian lower-extremity protection capability of the modified Sedan 1.

The test results with the original Sedan 1 and the modified Sedan 1 were compared in Figure 8. The modified sedan recorded lower bending moment and elongation values at the various positions on the Flex-PLI except the Leg 4 position, as compared to the original sedan. This was attributed to the 'leg sweeping structure' of the modified bumper, whereby the overall load on the lower-extremity was lightened by pushing the leg region forward.

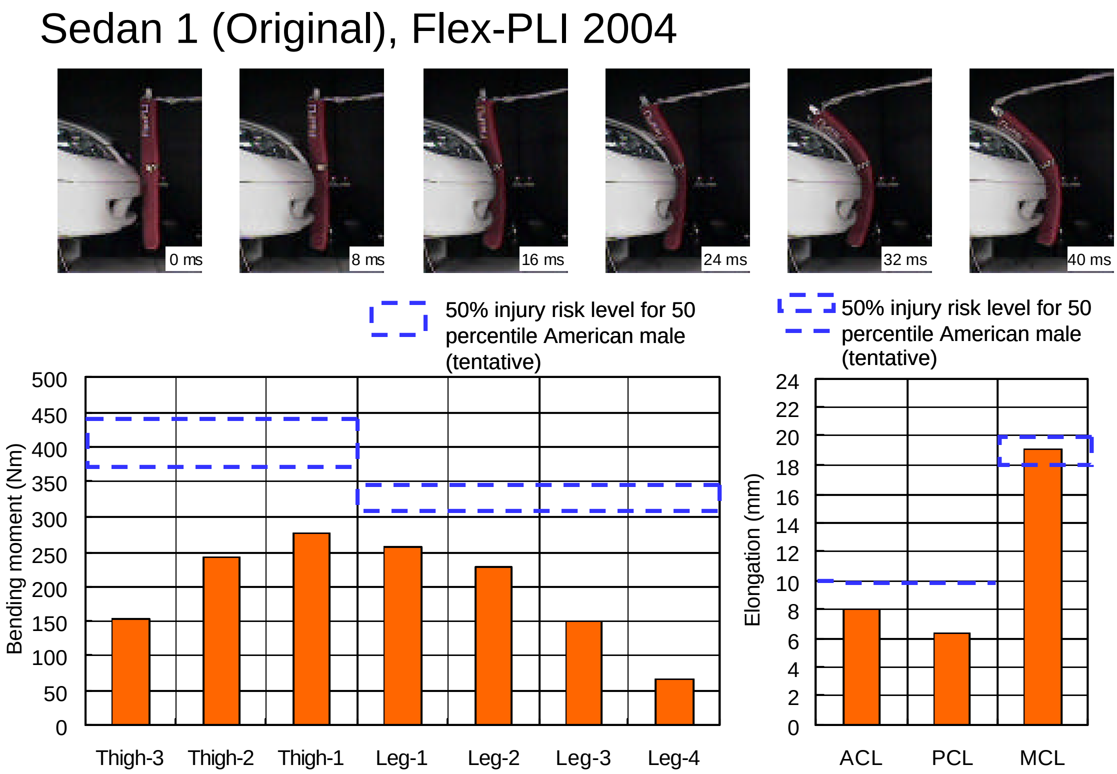

Figure 5. Test results of Sedan 1 (Original).

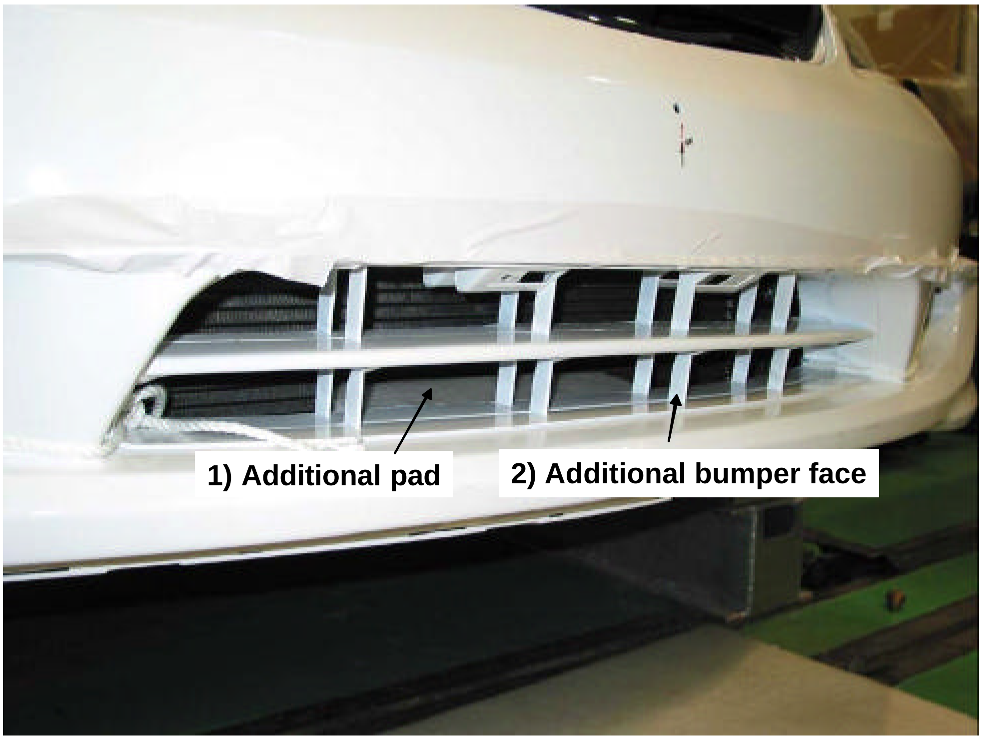

Figure 6. Modifications to Sedan 1.

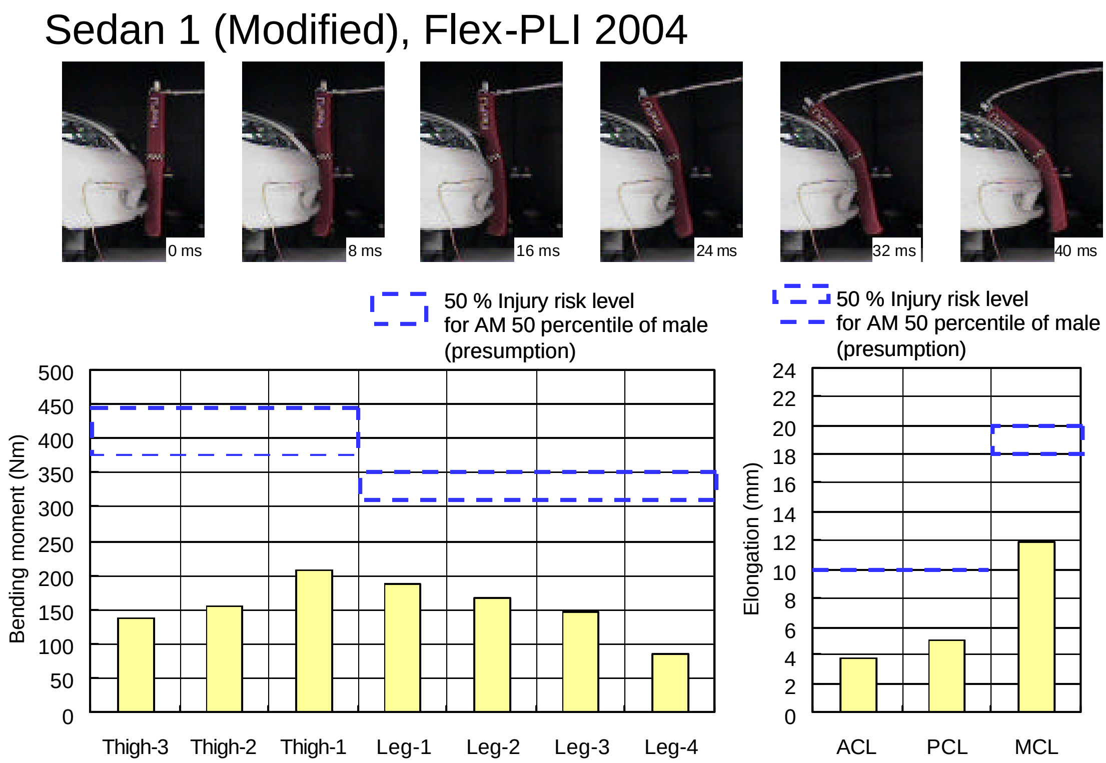

Figure 7. Test results of Sedan 1 (Modified).

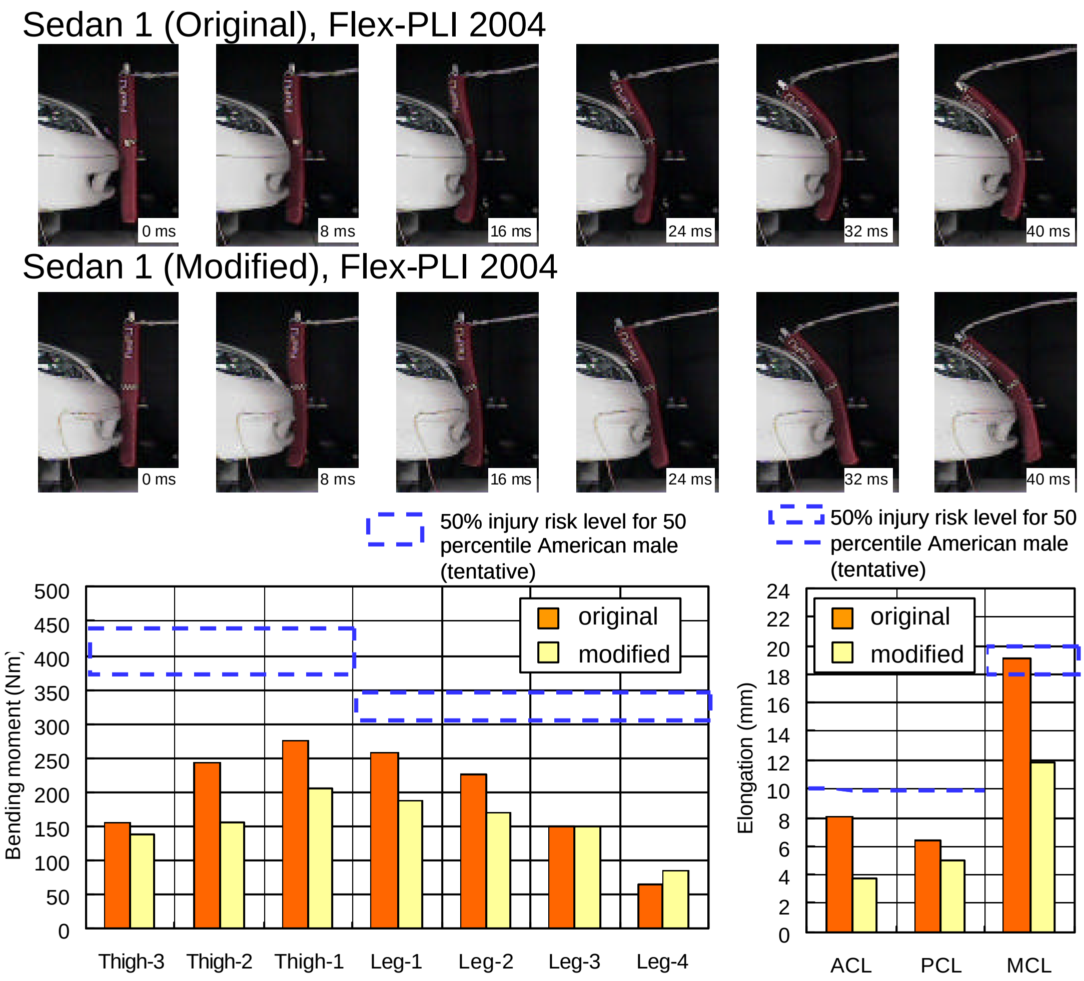

Figure 8. Comparison of the test results between the Original and Modified Sedan 1.

Sedan 2

Test results with Sedan 2 are shown in Figure 9. Sedan 2 was found to be similar to Sedan 1 in that, although the risk of thigh or leg fracture proved to be low, the risk of knee injury might to be high. The reason: similar to Sedan 1, Sedan 2 lacked a sufficient bumper force to push the pedestrian's leg forward, although the bumper rigidity was low enough to prevent thigh or leg fractures. Thus, a large bending of the knee was observed.

The pedestrian lower-extremity protection methods adopted to Sedan 2 are shown in Figure 10. A pad was added so as to increase the rigidity of the bumper's lower portion.

The test results with this modified sedan are given in Figure 11. The measured bending moment and elongation values at all the positions on the thigh, knee and leg of the Flex-PLI were measured to be below the injury risk level, thus affirming a capability of the modified Sedan 2 to protect the pedestrian lower-extremity in a collision.

The test results with the original Sedan 2 and the modified Sedan 2 were compared in Figure 12. The modified sedan recorded lower bending moment and elongation values at the various positions on the Flex-PLI except the Leg 3 and Leg 4 positions, when compared to the original sedan.

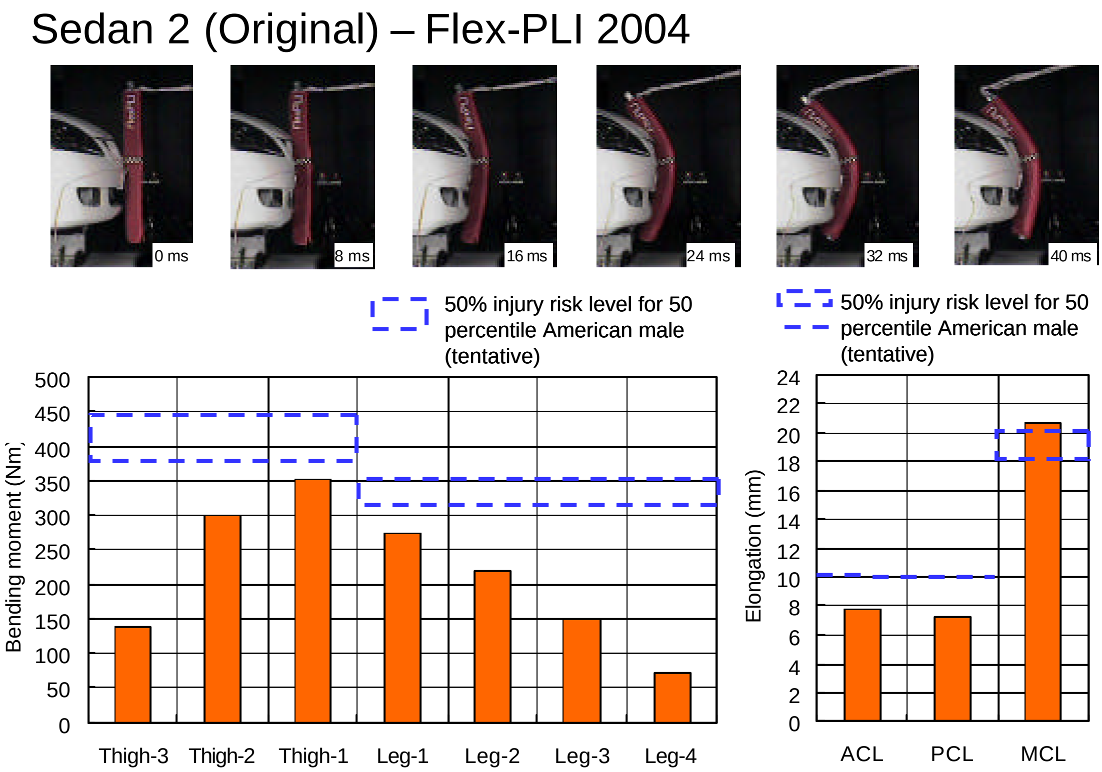

Figure 9. Test results of Sedan 2 (Original).

Figure 10. Modifications to Sedan 2.

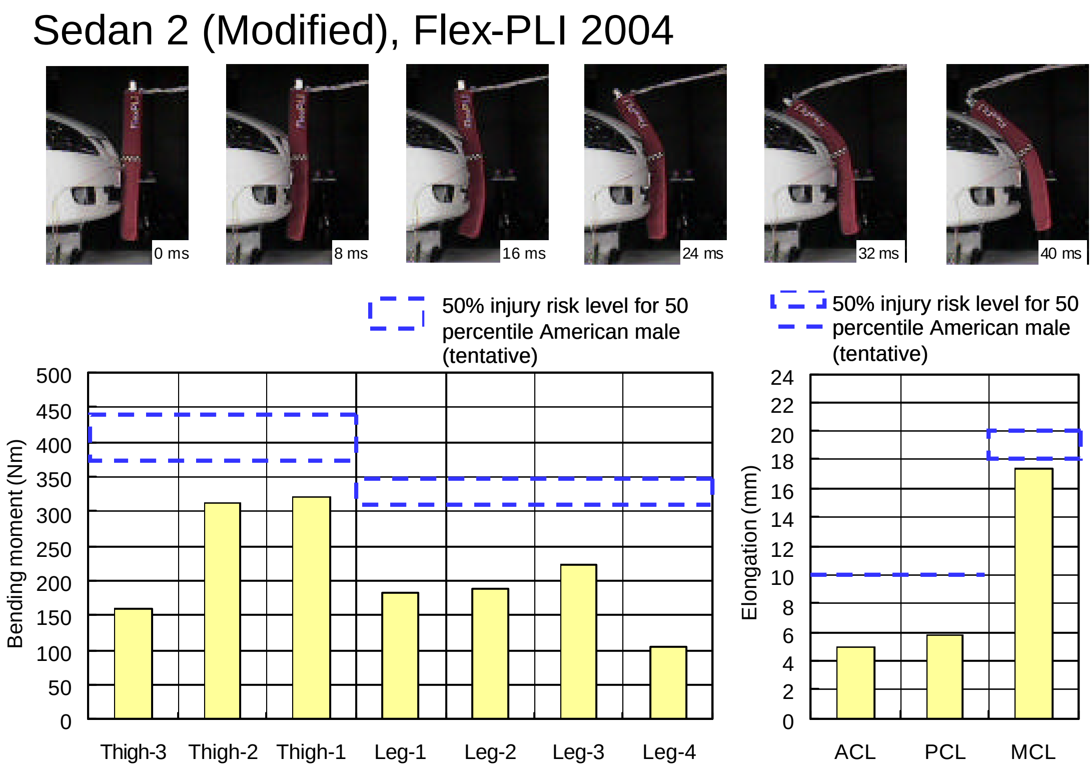

Figure 11. Test results of Sedan 2 (Modified).

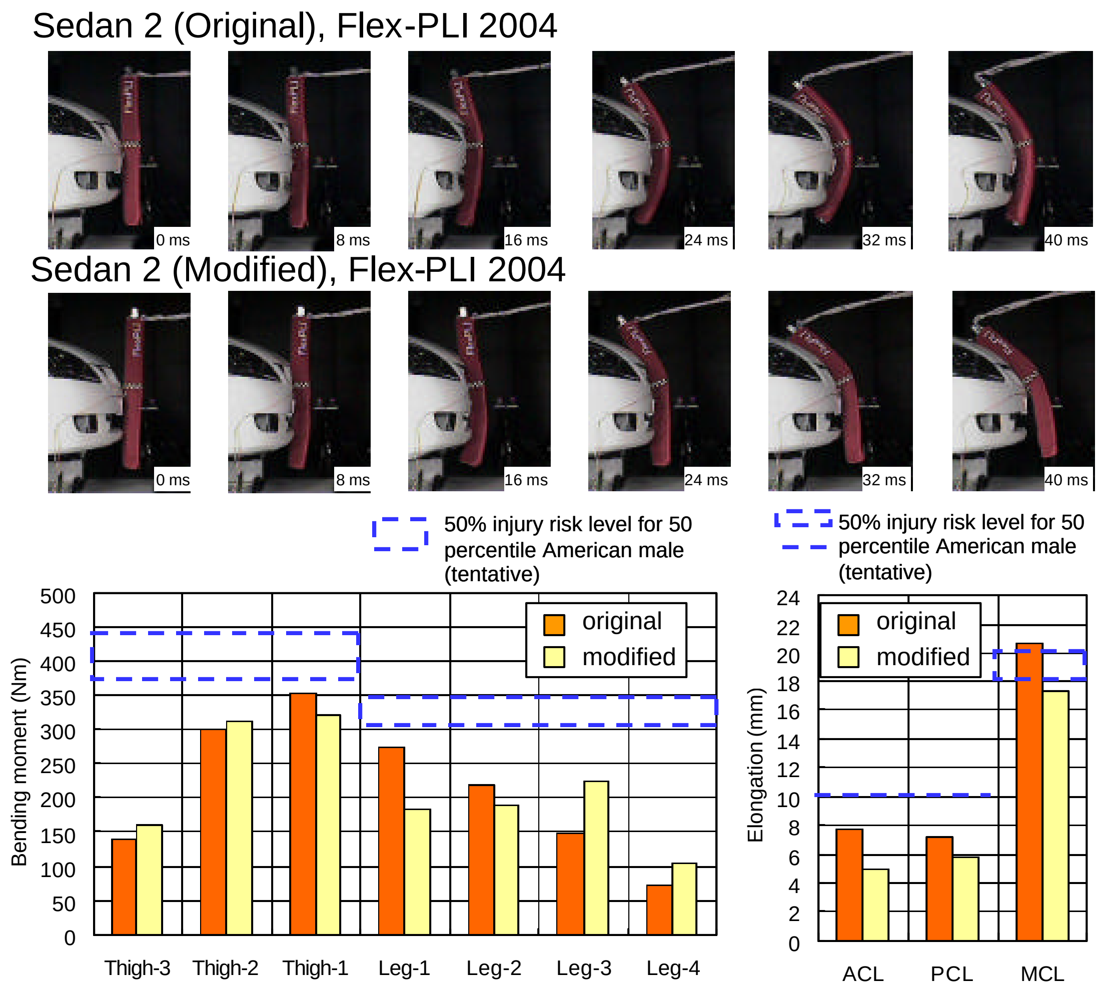

Figure 12. Comparison of the test results between the Original and Modified Sedan 2.

Minivan

Test results with the original Minivan are given in Figure 13. Similar to Sedans 1 and 2, although its bone fracture risk was low, the risk of knee injury might to be high. The reason: similar to Sedans 1 and 2, the Minivan lacked a sufficient bumper force to push the pedestrian's leg forward, although the bumper rigidity was low enough to prevent thigh or leg fractures. Thus, a large bending of the knee was manifested.

The pedestrian lower-extremity protection introduced into the Minivan is shown in Figure 14. A pad was added so as to increase the rigidity of the bumper's lower portion. The test results with this modified Minivan are given in Figure 15. The measured MCL elongation remained at the tentative injury risk level, and it was evident that the addition of the pad was ineffective.

The test results with the original and modified Minivans were compared in Figure 16. The protection employed in the modified Minivan proved to be ineffective, except that elongation values for the knee slightly improved. This was attributed to the fact that because several pads already existed in the bumper area of the original Minivan (see Figure 14), the additional pad had to be placed on top of them in a higher position comparing to the Sedan 1 and Sedan 2 (see Figure 17).

The lower the impact point on the leg, the more the rotating motion of the entire lower-extremity. To reduce the load on the knee, therefore, the position of the added pad needs to be lowered and/or the rigidity of the pads used in the original Minivan must be increased within the extent of not causing bone fractures.

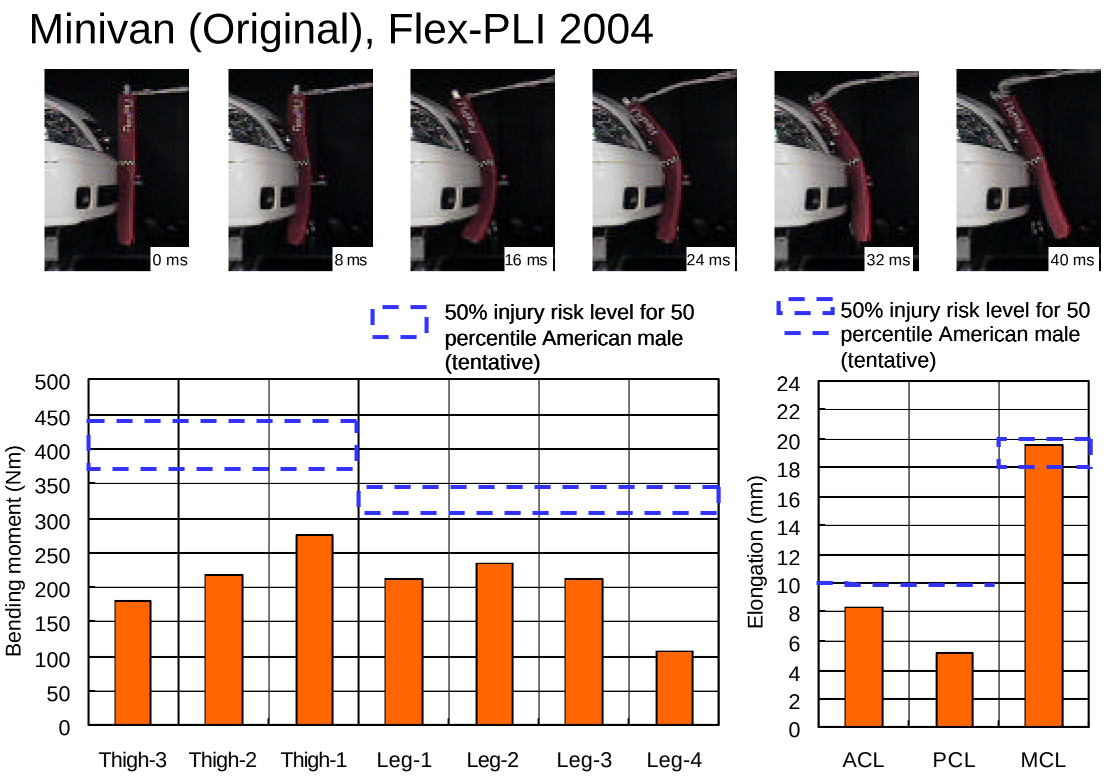

Figure 13. Test results of Minivan (Original).

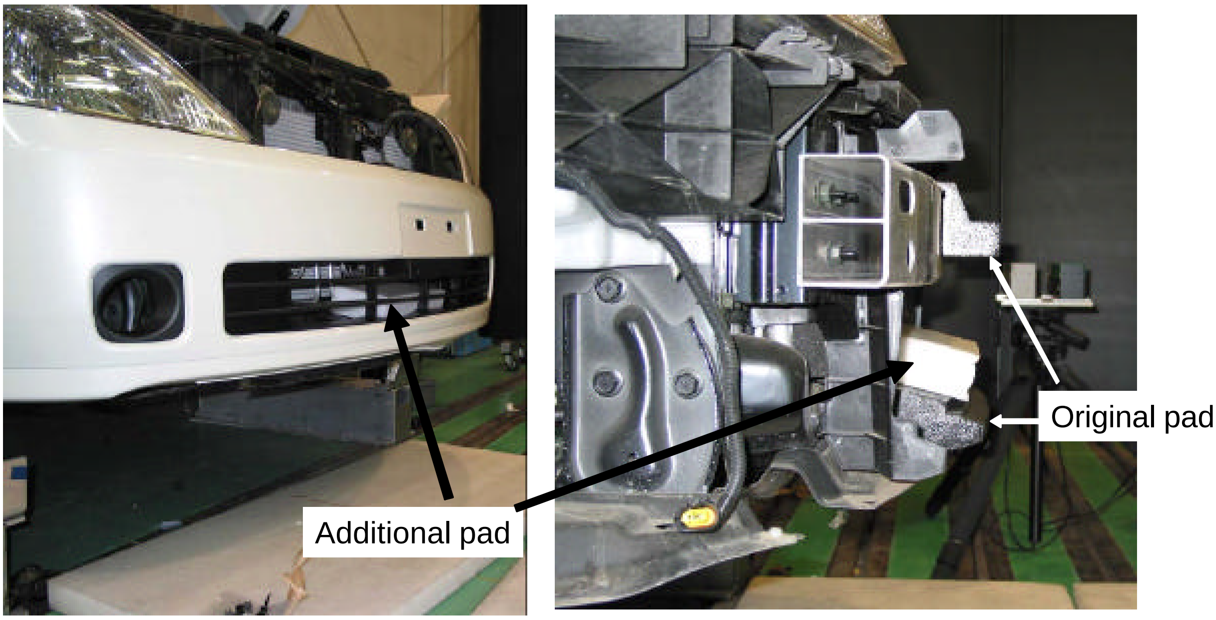

Figure 14. Modifications to Minivan.

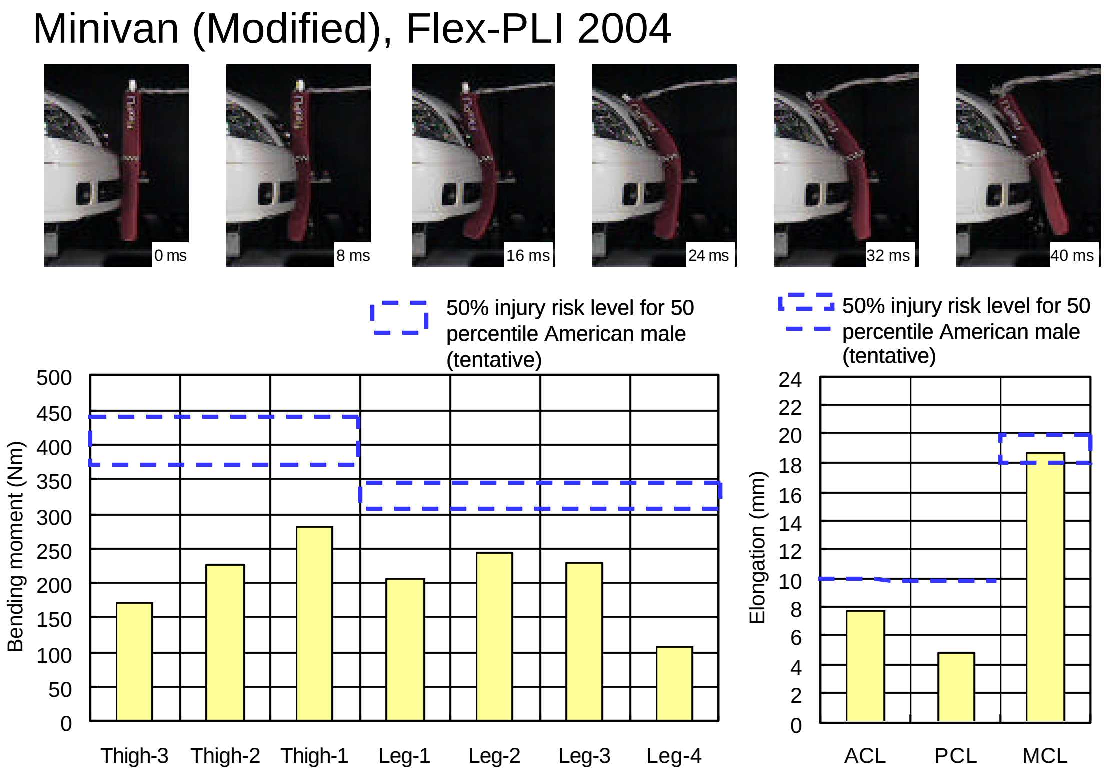

Figure 15. Test results of Minivan (Modified).

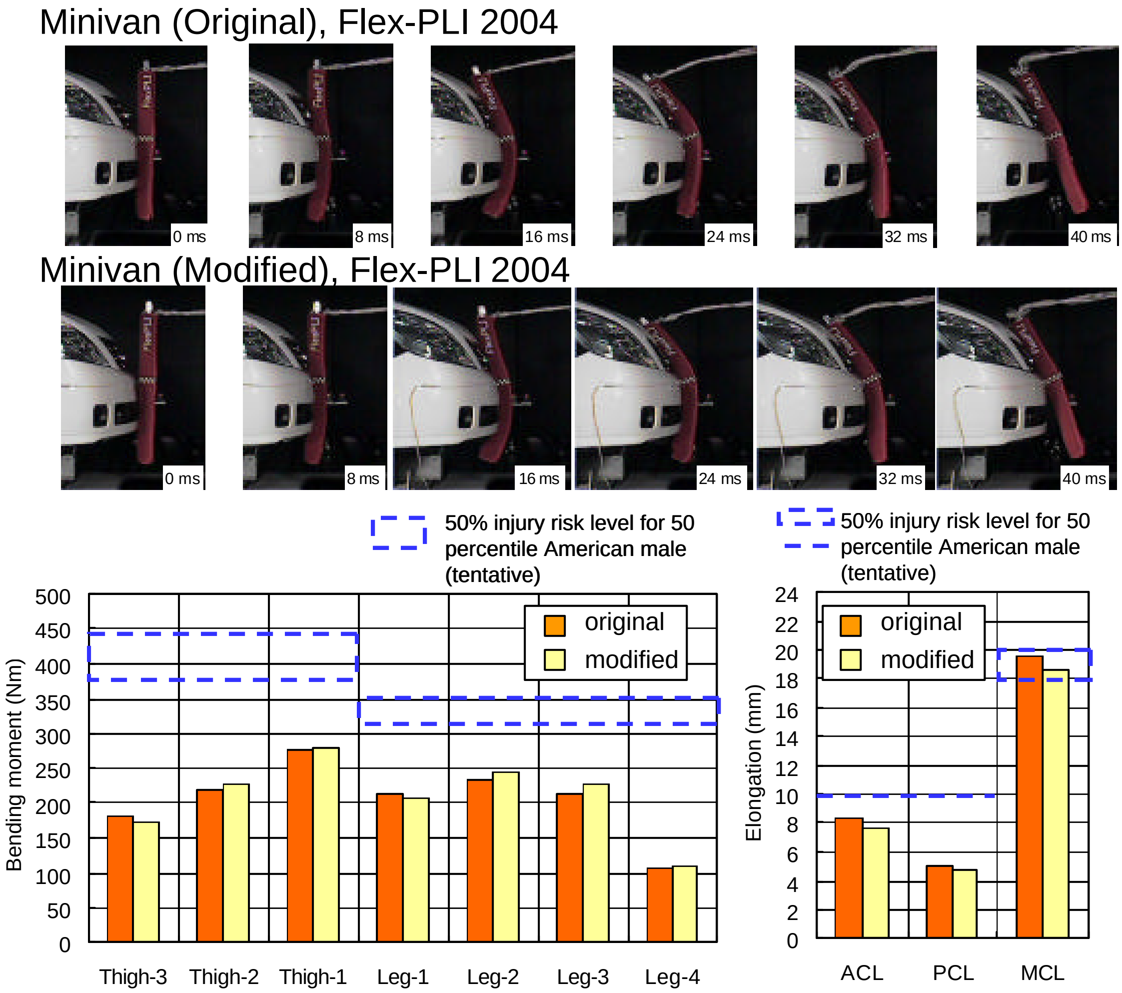

Figure 16. Comparison of the test results between the Original and Modified Minivan.

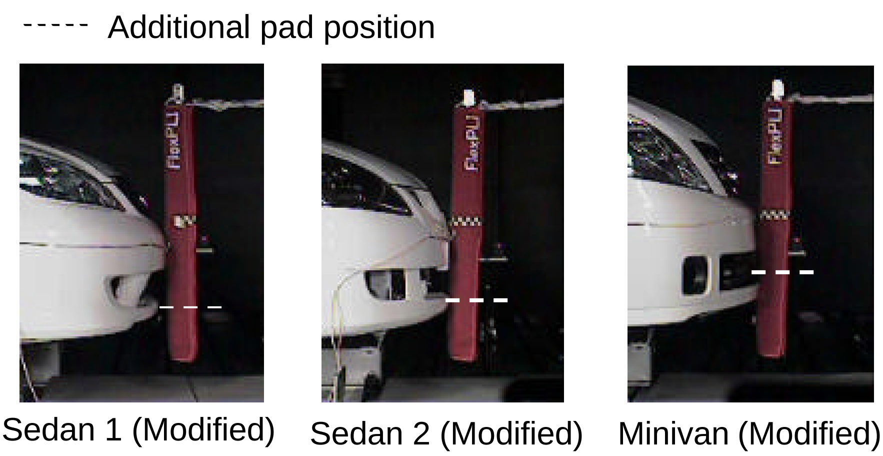

Figure 17. Comparison of the additional pad position.

SUV

Test results with the original SUV are given in Figure 18. In a collision with the SUV the risk of causing a thigh or knee injury proved to be low, but the risk of leg fracture was high. The reason: while the bumper rigidity was insufficient to cause a thigh fracture or a knee ligament injury, the original SUV lacked a structural member to support the lower part of the leg because SUVs are required to have a high ground clearance and a large approach angle. As a result, a large bending load was applied to the leg.

Accordingly, the Minivan was modified as shown in Figure 19. An additional bumper face was installed underneath the standard bumper to support the pedestrian's leg. Although the introduction of this additional bumper face may make the vehicle deviate from the definition of an SUV, this step was taken because no other effective protections could be found at this stage. As shown in Figure 20, the modified SUV clearly reduced the leg fracture risk.

The test results with the original and modified SUV were compared in Figure 21. The modified SUV was able to reduce the general lower-extremity injury risk thanks to the addition of a bumper face that supported the lower leg part. To further reduce the injury risk to a satisfactory level, however, additional steps will be necessary, for example the padding of the back of the added bumper face.

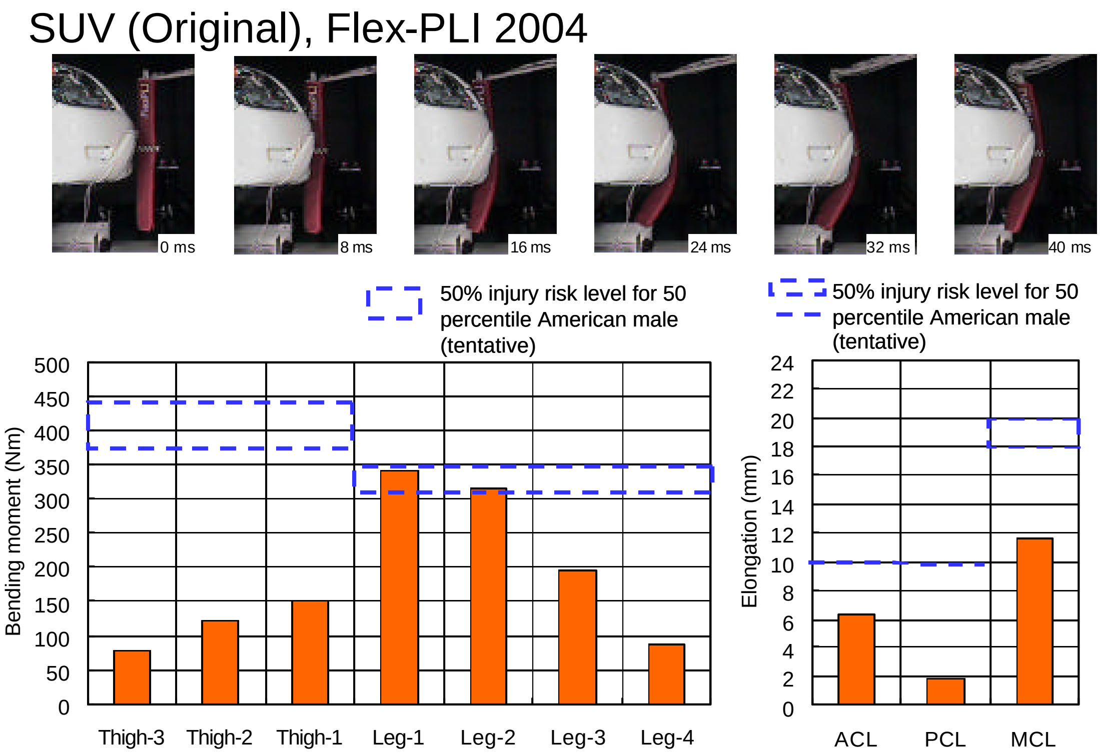

Figure 18. Test results of SUV (Original).

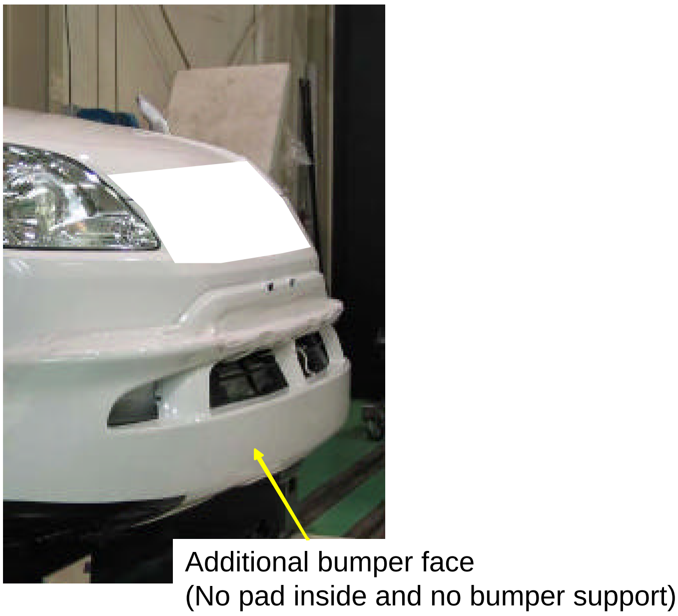

Figure 19. Modifications to SUV.

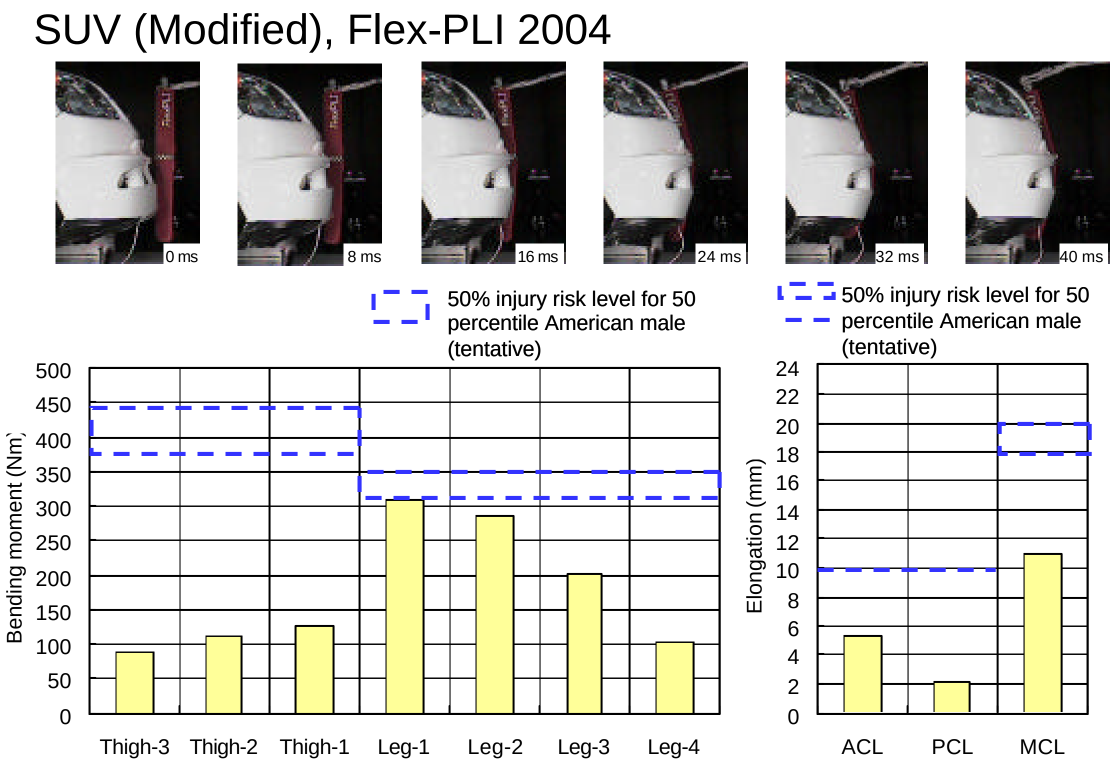

Figure 20. Test results of SUV (Modified).

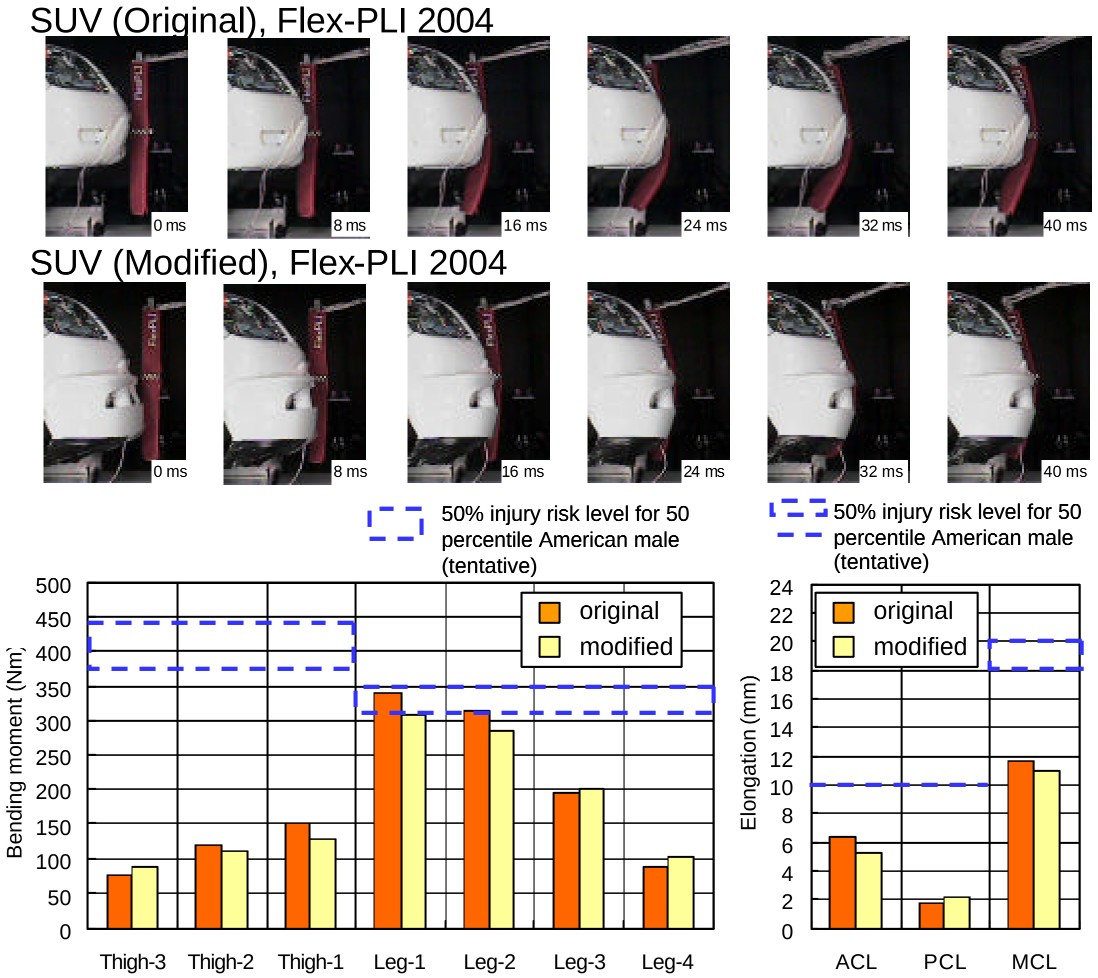

Figure 21. Comparison of the test results between the Original and Modified SUV.

DISCUSSION

In the present study, lower-extremity protection possibilities were examined for sedan, minivan and SUV types of vehicles. The results indicated a good possibility of protecting the pedestrian lower-extremities for all the vehicle types by pushing the legs forward within the extent of not causing leg fractures. This possibility was most saliently observed in Sedan 1 and Sedan 2.

In the case of the Minivan, the present study failed to obtain satisfactory injury risk values. However, to lower the position of the additional pad position and/or by increasing the rigidity of the standard pads within the extent of not causing bone fractures, the Minivan output also has a high possibility to be lower the injury risk level.

As for the SUV, it was considered difficult for this type of vehicle to provide sufficient lower-extremity protection because the requirement of a high ground clearance and large approach angle makes it difficult to introduce methods of pushing the pedestrian's legs forward.

However, this study is the first trial study for the development of pedestrian lower extremity protection car using a Flex-PLI, therefore, additional similar studies are necessary.

CONCLUSIONS

- In the present study the pedestrian lower-extremity protection performances of sedan, minivan and SUV types of cars were tested using a Flex-PLI.
- The test results indicated a good possibility of lower-extremity protection in collisions by pushing the pedestrian's legs forward within the extent of not causing bone fractures.
- In the case of SUVs, however, it was found difficult to provide such protection because of their high ground clearance and large approach angle which make difficult the introduction of methods to push the pedestrian's legs forward.
- This study is the first trial study for the development of pedestrian lower extremity protection car using a Flex-PLI, therefore, additional similar studies are necessary.

REFERNECES

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[5] Kerrigan, J.R., Drinkwater, D.C., Kam, C.Y., Murphy, D.B., Ivarsson, B.J., Crandall, J.R., Patrie, J. (2004) Tolerance of the Human Leg and Thigh in Dynamic Latero-Medial Bending, ICRASH 2004.

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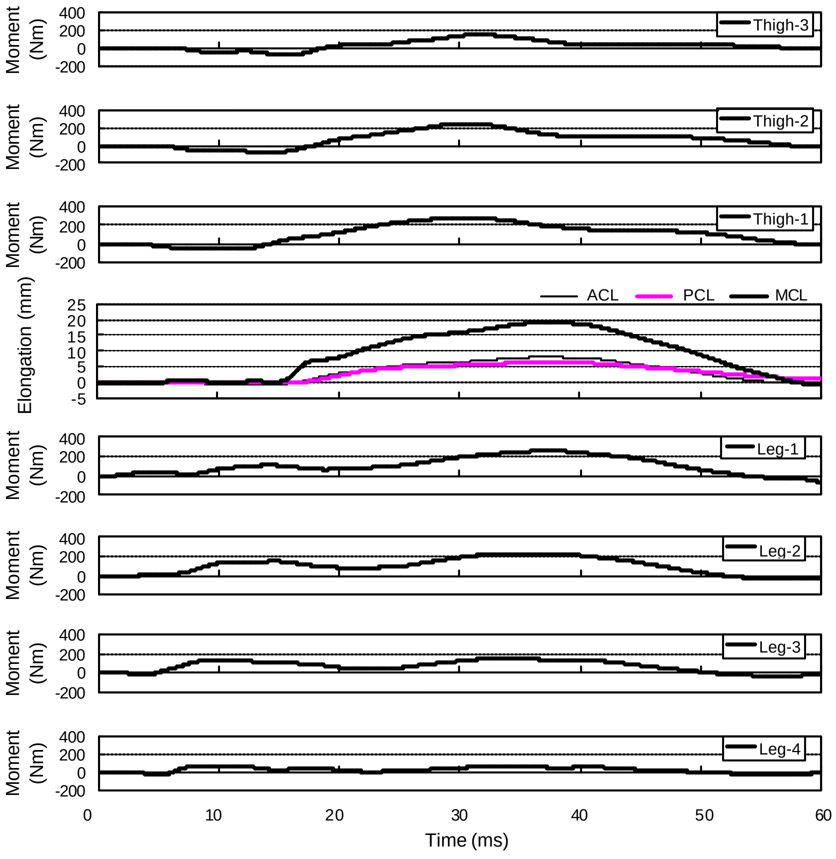
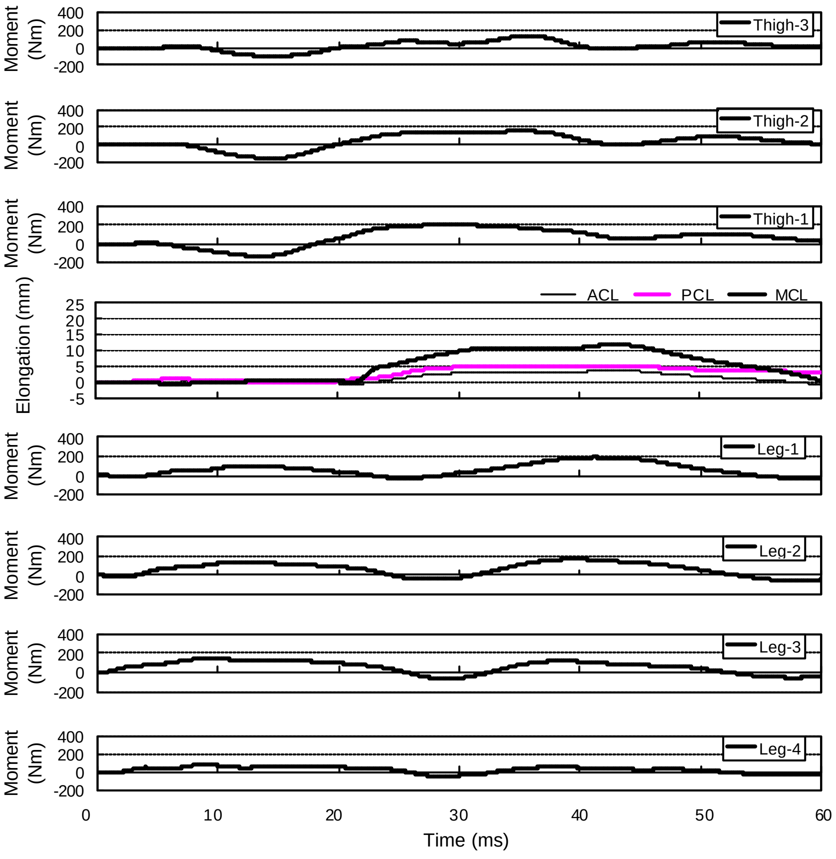
[9] Kennedy, E.A., Hurst, W.J., Stitzel, J.D., Cormier, J.M., Hansen, G.A., Smith, E.P., Duma, S.M. (2004) Lateral and Posterior Dynamic Bending of the Mid-Shaft Femur: Fracture Risk Curves for the Adult Population, Stapp Car Crash Journal, Vol. 48, pp. 22-51.

Appendix A: Measured Waveforms

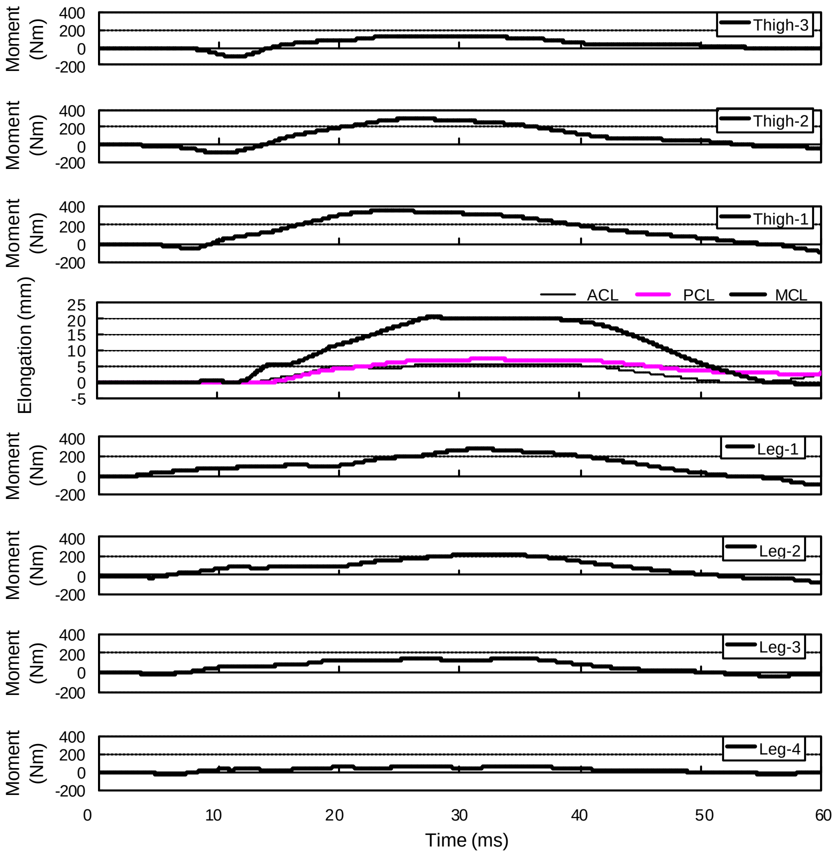
Sedan 1 (Original), Flex-PLI 2004



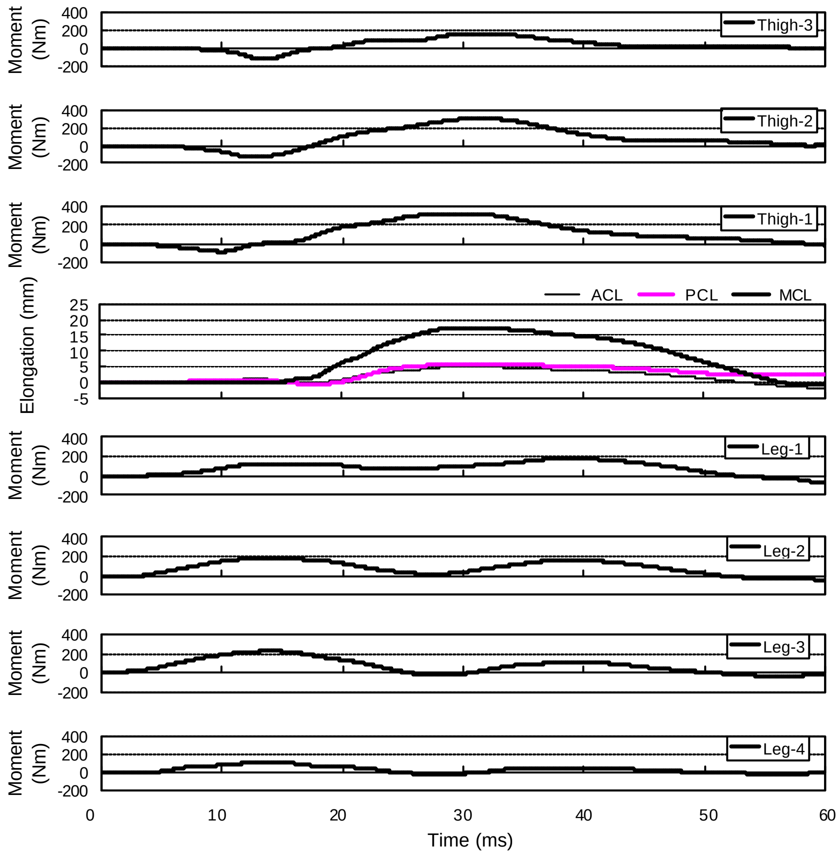
Sedan 1 (Modified), Flex-PLI 2004



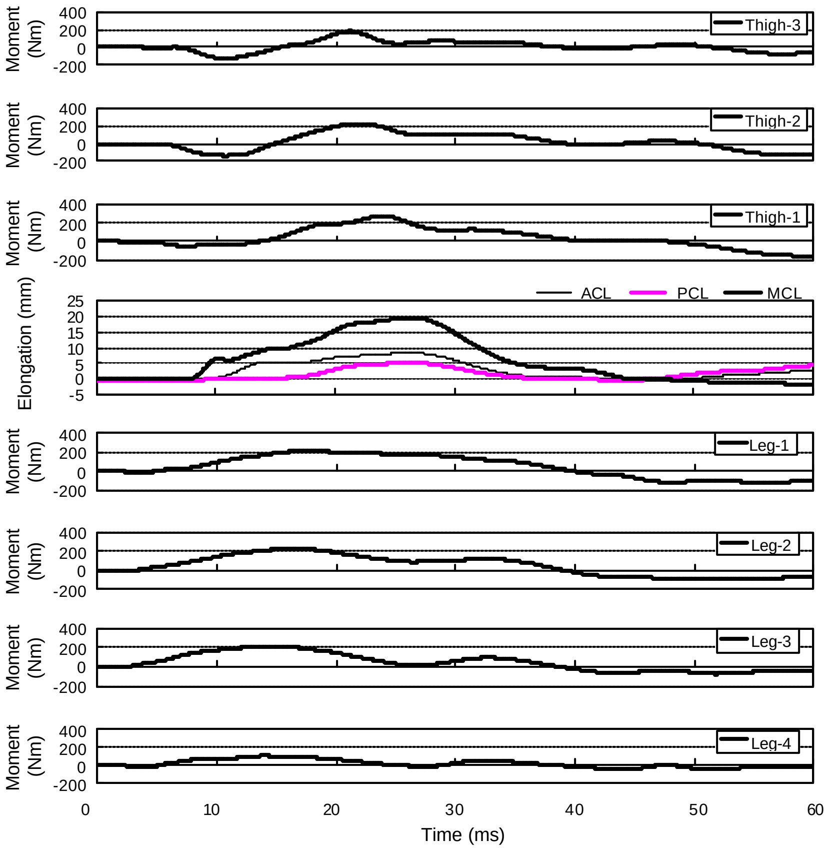
Sedan 2 (Original), Flex-PLI 2004



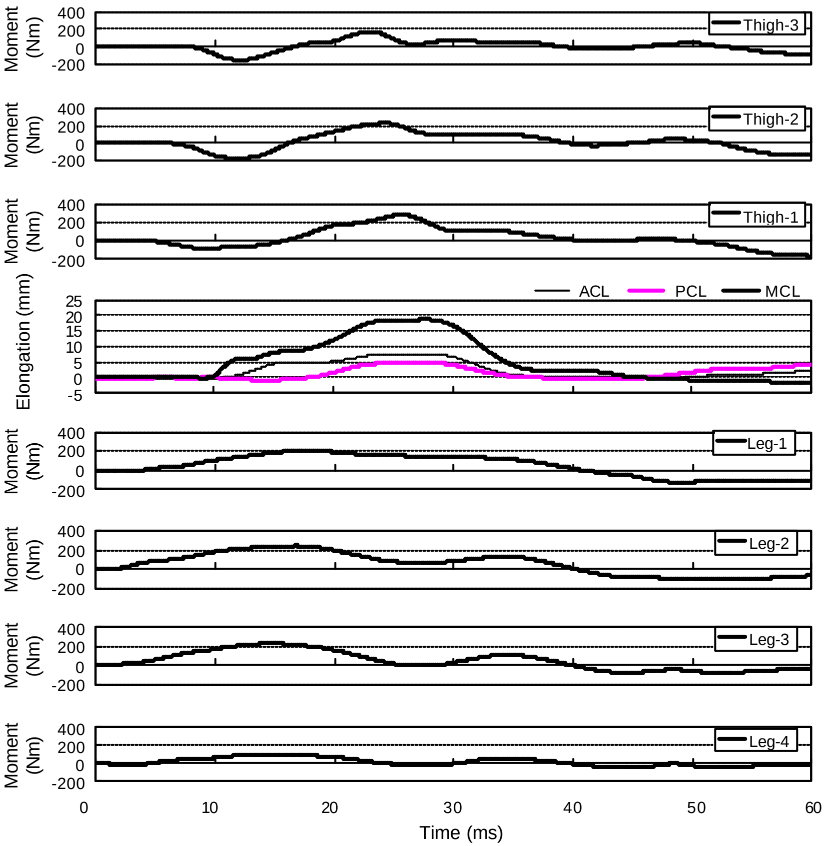
Sedan 2 (Modified), Flex-PLI 2004



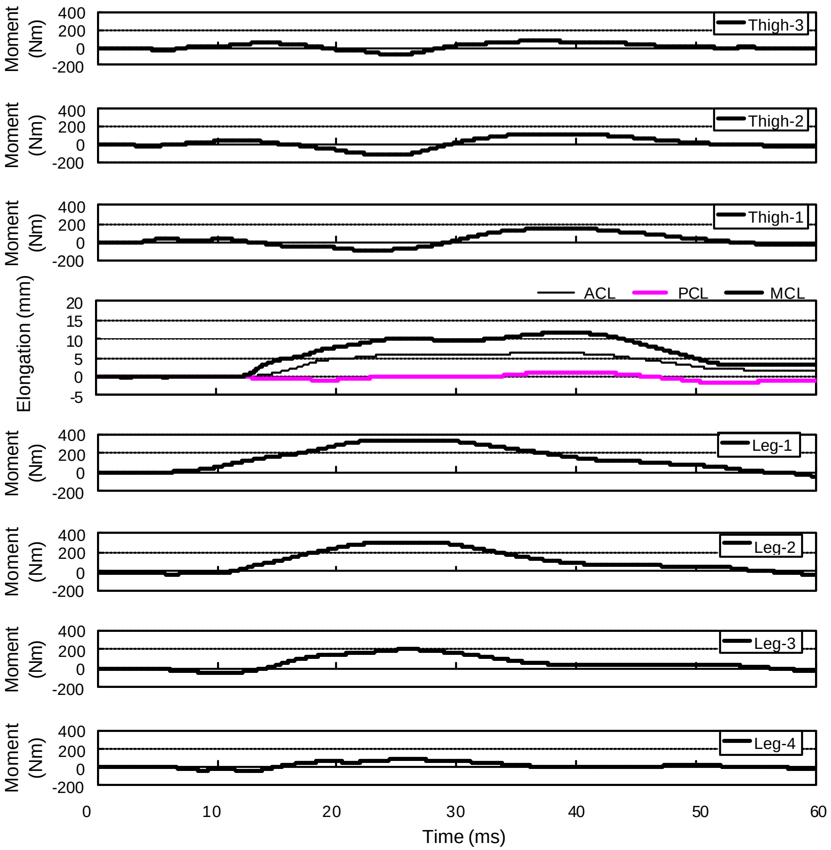
Minivan (Original), Flex-PLI 2004



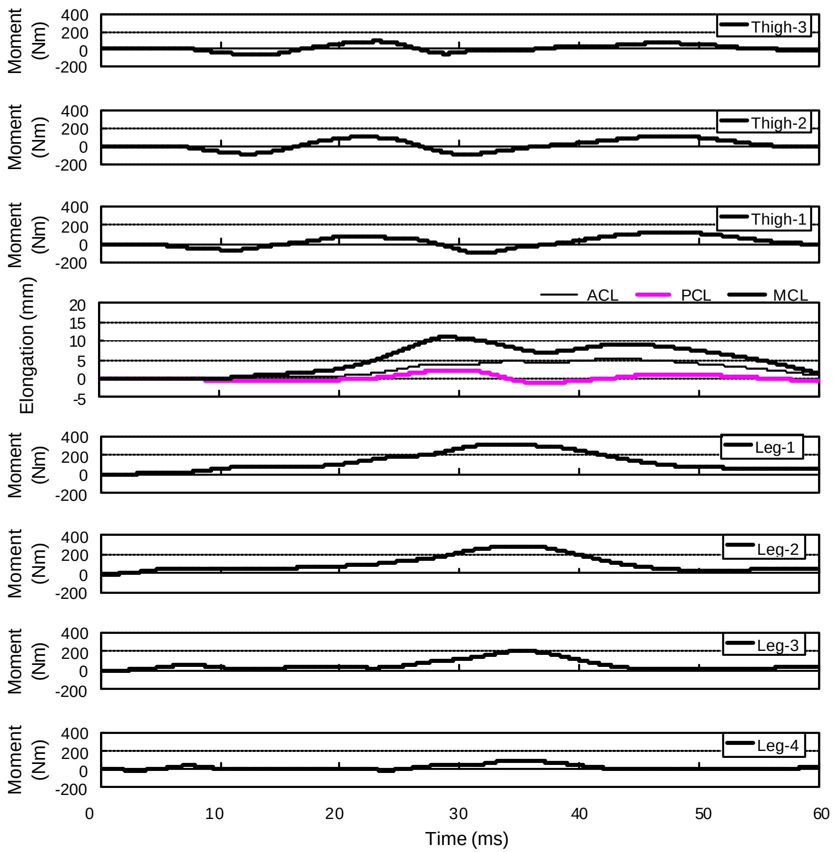
Minivan (Modified), Flex-PLI 2004



SUV (Original), Flex-PLI 2004

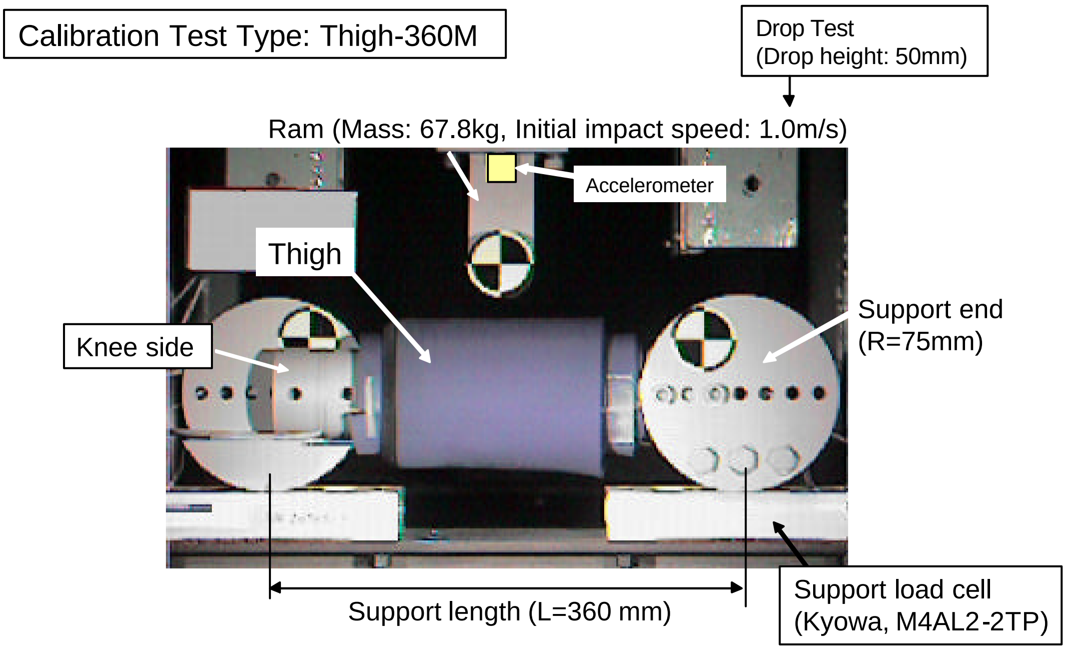


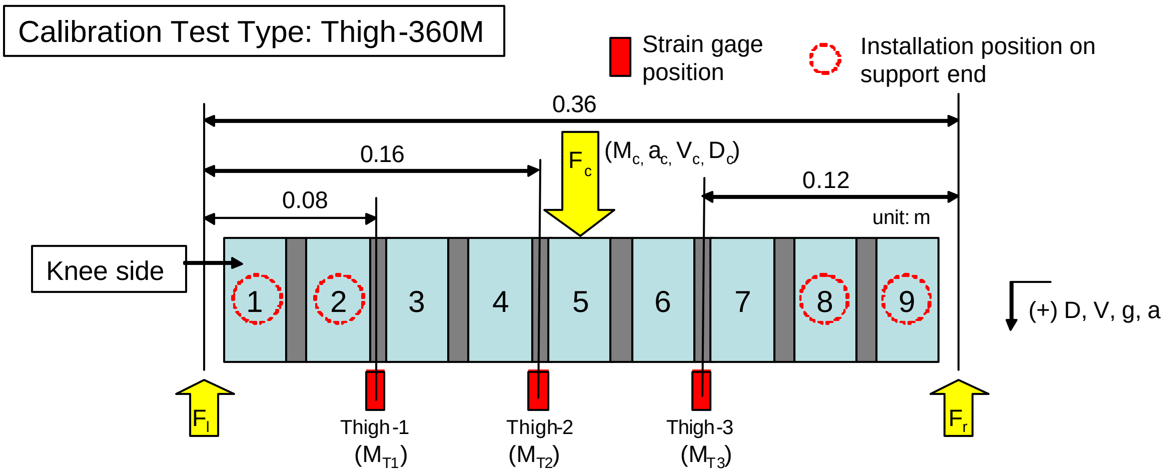
SUV (Modified), Flex-PLI 2004



Appendix B:
Dynamic Component Calibration Test Procedure
for Thigh and Leg of Flex-PLI 2004

B1: Dynamic Component Calibration Test Procedure for Thigh of Flex-PLI 2004





Bending moment estimation equation at loading center

$$M_c(t) \cong \left| \frac{F_l(t) \times F_r(t)}{F_l(t) + F_r(t)} \times 0.36 \right|$$

Deflection estimation equation at loading center

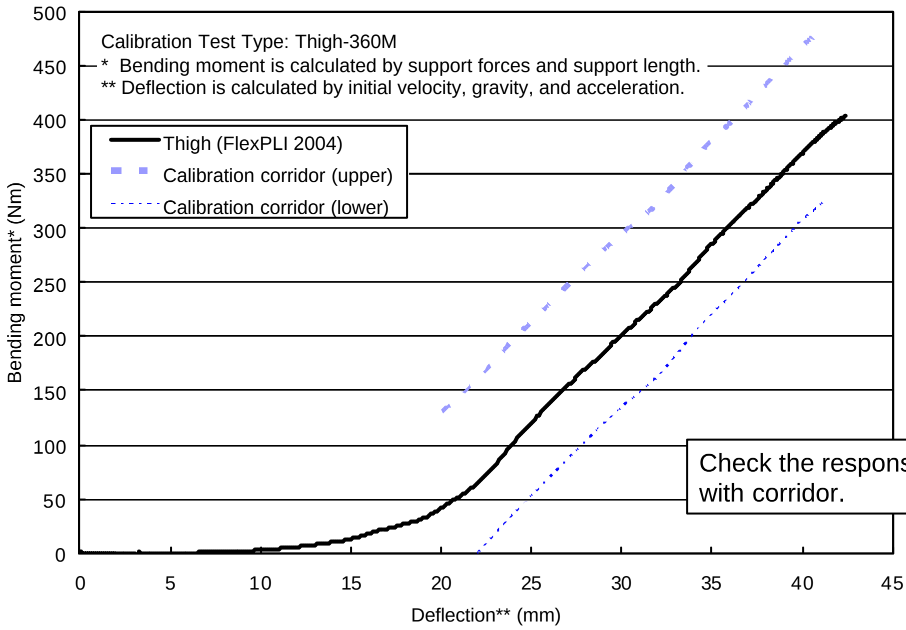
$$D_c(t) \cong V_{c\_init} t + \frac{1}{2} g t^2 + \iint a(t) dt$$

Bending moment estimation equations at strain gage positions

$$M_{T1}(t) \cong \left| F_l(t) \times 0.08 \right|$$
$$M_{T2}(t) \cong \left| F_l(t) \times 0.16 \right|$$
$$M_{T3}(t) \cong \left| F_r(t) \times 0.12 \right|$$

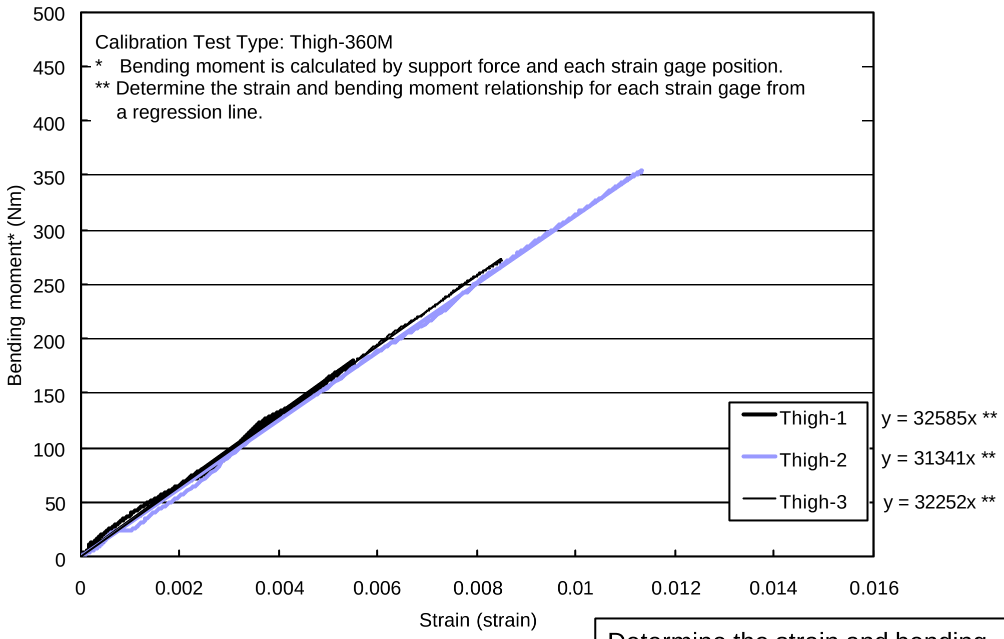
M : *Bending Moment* (Nm)
F : *Force* (N)
D : *Deflection* (m)
V : *Velocity* (m/s)
g : *Gravity* (m/s^2)
a : *Acceleration* (m/s^2)
t : *time* (s)

Step 1: Check the Bending moment and Deflection characteristics of thigh
- Comparison with a calibration corridor -



Check the response with corridor.

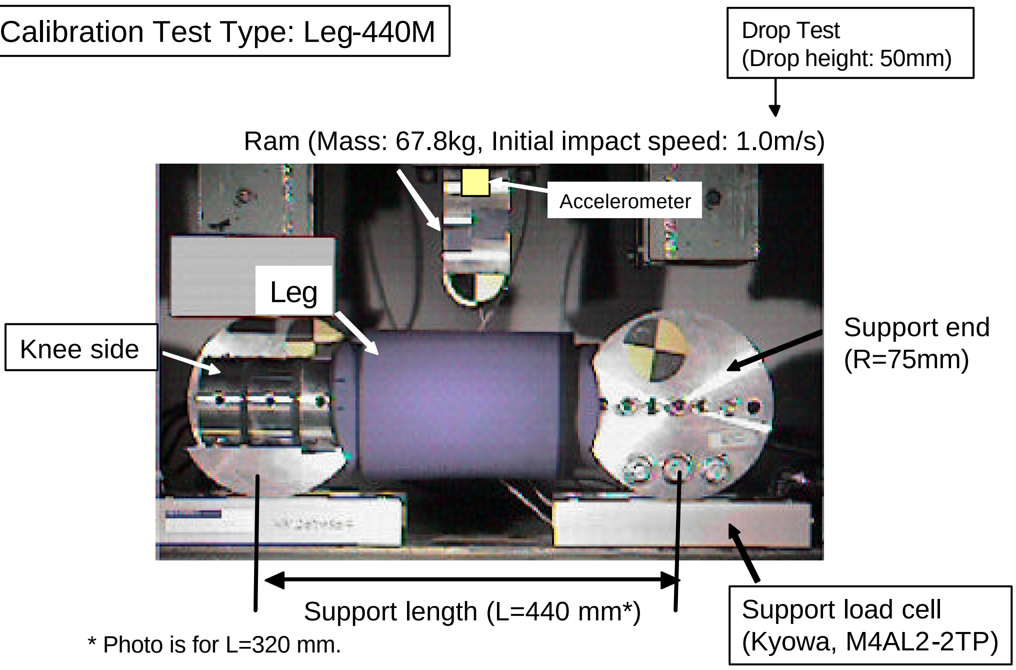
Step 2: Obtain calibration values derived from Strain and Bending moment relations



Determine the strain and bending moment relationship for each strain gage from a regression line.

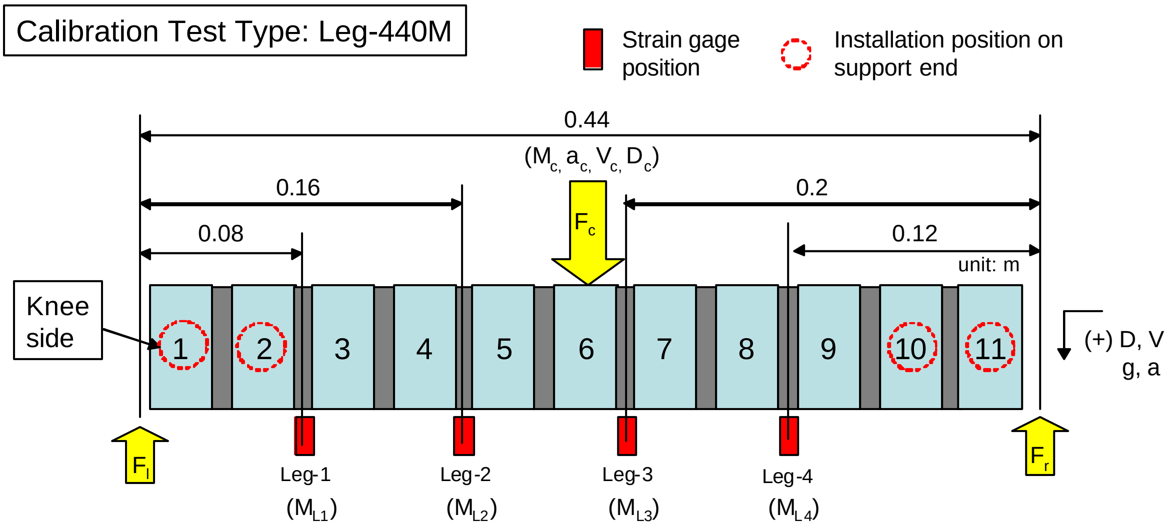
B2: Dynamic Component Calibration Test Procedure for Leg of Flex-PLI 2004

Calibration Test Type: Leg-440M



* Photo is for L=320 mm.

Calibration Test Type: Leg-440M



Bending moment estimation equation at center of loading

$$M_c(t) \cong \left| \frac{F_l(t) \times F_r(t)}{F_l(t) + F_r(t)} \times 0.44 \right|$$

Deflection estimation equation at center of loading

$$D_c(t) \cong V_{c\_init} t + \frac{1}{2} g t^2 + \iint a(t) dt$$

Bending moment estimation equations at strain gage positions

$$M_{L1}(t) \cong |F_l(t) \times 0.08|$$

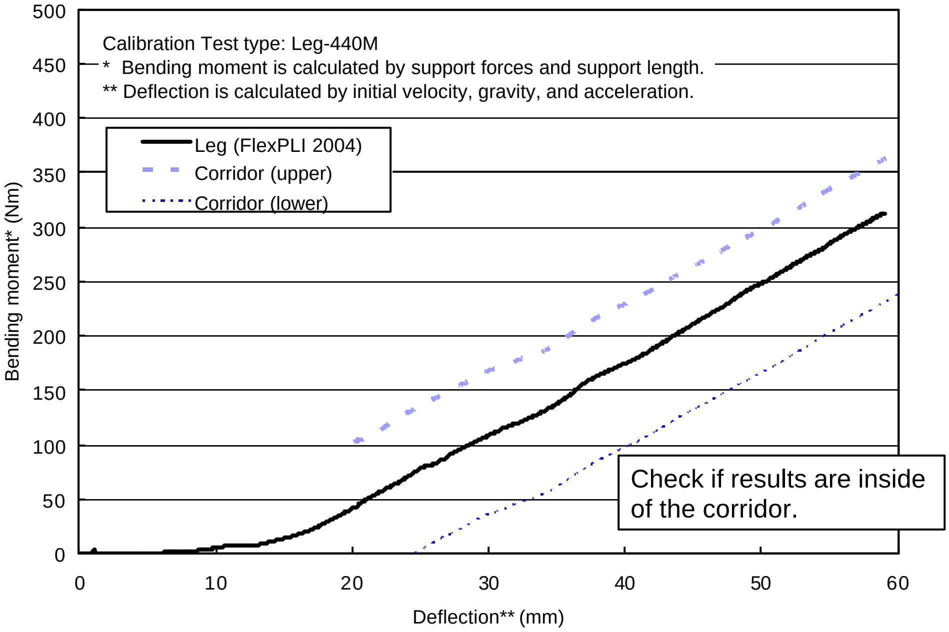
$$M_{L2}(t) \cong |F_l(t) \times 0.16|$$

$$M_{L3}(t) \cong |F_r(t) \times 0.20|$$

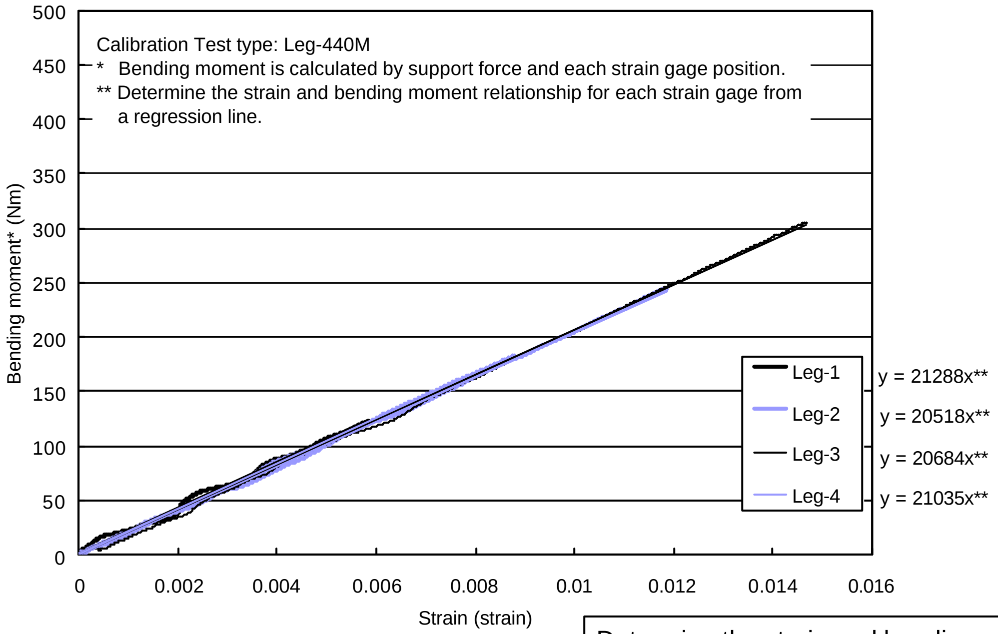
$$M_{L4}(t) \cong |F_r(t) \times 0.12|$$

M : *Bending Moment* (Nm)
F : *Force* (N)
D : *Deflection* (m)
V : *Velocity* (m/s)
g : *Gravity* (m/s^2)
a : *Acceleration* (m/s^2)
t : *time* (s)

Step 1: Check the Bending moment and Deflection characteristics of leg
- Comparison with a calibration corridor -



Step 2: Obtain calibration values derived from Strain and Bending moment relations



Determine the strain and bending moment relationship for each strain gage from a regression line.