COMPONENT LEG TESTING OF VEHICLE FRONT STRUCTURES

Ann Mallory
Transportation Research Center Inc.
Jason A. Stammen
National Highway Traffic Safety Administration
United States of America
France Legault
Transport Canada
Canada

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ABSTRACT

Current and proposed pedestrian test procedures in Europe and Japan evaluate lower extremity injury risk by using a projectile legform to impact the bumper of a stationary vehicle. Although there are no pedestrian regulations in North America, bumper design is affected in both the United States and Canada by regulations limiting damage in low-speed impact testing. The main objectives of this study were to (1) evaluate differences in instrumentation capability and kinematic response of two pedestrian legforms (FlexPLI 2004, TRL), and (2) determine if and to what extent vehicles designed to conform to North American bumper regulations are more aggressive toward pedestrians than similar vehicles designed to conform to European bumper impact requirements. The results indicated that none of the North American bumpers were able to achieve the level of pedestrian lower leg protection required by future European Union regulations. It was also found that both legforms have limitations in testing the North American bumpers. The bumpers damaged the FlexPLI legform in repeated tests and exceeded the measurement limits of the TRL legform.

INTRODUCTION

On average, 374 pedestrians and 55 cyclists are fatally injured in Canada every year, making up 14.9% of fatalities among all road users (5-year average 1999-2003) [1]. In the United States, 4,749 pedestrians and 622 cyclists were killed in 2003, comprising 12.6% of all motor vehicle-related fatalities [2]. Combined international statistics from the United States, Europe and Japan indicate that approximately 30% of moderate to catastrophic pedestrian injuries involve the lower extremities, with the front bumper identified as injury source for the majority of those injuries [3]. Transport Canada is investigating whether its bumper regulation is detrimental to the safety of pedestrians. Because bumper designs for the Canadian market are largely similar or identical to those sold in the United States, this research has potential implications for all vehicles in the North American fleet.

The Canadian Motor Vehicle Safety Standard (CMVSS) 215 for bumpers is based on a series of 8 km/h longitudinal impacts and 4 km/h corner impacts after which the safety systems of the vehicle have to function as intended [4]. The United States CFR 49 Part 581 standard and the United Nations Economic Commission for Europe Regulation No. 42 (ECE R42) have lower impact speeds, with longitudinal impacts conducted at only 4 km/h. Both regulations apply only to passenger cars. The U.S. criteria are for no cosmetic or safety system damage, whereas the European requirements are for no damage to safety systems only. Thus, Canada’s higher test speed and the broader U.S. damage limitations make the bumper damage criteria in both countries different from the European requirements. Research and testing was deemed necessary to determine if bumpers designed to meet the North American bumper regulations are more aggressive toward pedestrian lower extremities than their European counterparts designed to meet UN ECE Regulation No. 42.

The European New Car Assessment Program (EuroNCAP) includes pedestrian testing to assess aggressiveness of vehicle frontal areas [5]. The procedure calls for a free-flight bumper impact at 40 km/h with a legform developed by the Transport Research Laboratory (TRL Limited, Berkshire, UK). This legform is a simplified device that approximates human anthropometry while using frangible steel knee ligament surrogates designed to deform plastically during impact [6]. The legform’s instrumentation allows it to measure tibia acceleration, shear displacement, and bending angle at the knee.

European Union regulations specify tests relating to the protection of pedestrians and other vulnerable road users in Directive 2003/102/EC [7]. The procedure includes tests for legform to bumper evaluation, as well as for head impact testing and leg to bonnet edge testing. The lower legform to bumper test performed at 40-km/h limits maximum dynamic knee bending angle to 21 degrees, maximum dynamic knee shearing displacement to 6 mm and acceleration at the upper tibia to 200 g. Although the TRL legform is not explicitly named in the directive, the required injury measures correspond exactly to the values that the TRL legform is equipped to measure.

The FlexPLI 2004 has been more recently developed by the Japanese Automobile Research Institute (JARI). This legform has been described to have improved biofidelity over the TRL legform as well as increased instrumentation capabilities [8]. This device is more complex than the TRL legform, with 14 hollow cylindrical steel segments along its length that surround two surrogate bone cores representing the femur and the tibia. These cores are made of glass reinforced plastic (GRP) and are equipped with strain gauges mounted at defined locations. The FlexPLI is also equipped with four cabled surrogate ligaments at anthropometrically accurate locations within the knee structure. It is designed to be completely non-frangible, and it is able to measure bending moments in the upper and lower segments as well as knee ligament displacements and individual segment accelerations.

The objective of this study was to use the TRL and FlexPLI legforms to assess the pedestrian aggressiveness of a sample of North American model bumper systems and then compare those systems to their European counterparts.

METHODS

Pedestrian lower extremity testing was performed by impacting the front bumpers of five different passenger car models with projectile legforms. All bumpers in the test series were tested using a TRL legform impactor. Selected bumpers were also tested using the FlexPLI 2004.

Legforms were launched in this test series by a carriage mounted to a hydraulic linear ram. During acceleration, the legforms were suspended from a pin at the top of the carriage and supported horizontally by padded fixtures mounted on the carriage adjacent to the upper leg and the lower leg (Figure 1).

Figure 1. Test setup.

Legform acceleration to free-flight speed was achieved over a distance of approximately 24 cm for the TRL legform and 28 cm for the FlexPLI legform. Legform height at the time of impact with the bumper was such that the bottom of the legform was within ±10 mm of ground reference level, which is defined as the horizontal plane that passes through the lowest points of contact for the tires of the vehicle in normal ride attitude. As defined in the EuroNCAP procedure, the legform was vertical in the sagittal and coronal planes and aligned about the z-axis so that the lateral side of the legform contacted the bumper.

Target impact speed was 11.1 ± 0.2 m/s (40 ± 0.7 km/h) for all testing with the TRL legform. Target impact speed for the FlexPLI legform was initially the same as for the TRL legform but reduced in subsequent tests to 8.3 ± 0.2 m/s (30 ± 0.7 km/h). Velocity was measured by integrating upper tibia acceleration data.

The TRL legform was equipped with angular displacement transducers in the lower femur and upper tibia components that allowed calculation of shear displacement and bending angle in the knee [6]. Tibia acceleration was measured by a 500 g uniaxial accelerometer mounted on the non-impact side of the upper tibia. The FlexPLI's instrumentation consisted of 3 pairs of strain gages mounted on the thigh bone core, 4 pairs of strain gages mounted on the lower leg bone core, and three linear potentiometers across the knee joint. The strain gages were used to measure bending moments along the length of the femur and tibia, while the knee potentiometers measured stretch of the ACL, PCL, and MCL ligaments. In addition to this standard instrumentation, a uniaxial accelerometer was mounted on the non-impact side of the FlexPLI's upper tibia. All data was sampled at 20 kHz, pre-filtered at 3 kHz, then filtered using CFC 180 (300 Hz). Lateral and overhead high-speed video documented the tests at 1000 frames per second.

The five vehicles tested were the following North American models:

- 2000 Volvo S40
- 2001 Ford Focus
- 1999 Volkswagen Beetle
- 2001 Honda Civic
- 2002 Mazda Miata

All vehicles were purchased in the United States and selected because the corresponding European models of each one had been previously evaluated in EuroNCAP pedestrian testing. These vehicles have similar bumper systems in Canada and in the U.S.

In total, 28 impact tests (23 with TRL, 5 with FlexPLI) were conducted in this study (Table 1).

Table 1.
Test matrix (impacts at full speed unless noted otherwise)

Vehicles	TRL		FlexPLI	
	Center	Lateral	Center	Lateral
Volkswagen Beetle	2	3	--	--
Mazda Miata	2	3	--	1[A]
Ford Focus	2	3	--	--
Volvo S40	2	2	1[A]	2[A]
Honda Civic	2	2	--	1

[A] Tests were done at 30 km/h

Bumper impacts were targeted at the areas near the left and right side bumper supports and centrally at the bumper midline. Figure 2 illustrates the impact points on each vehicle bumper. The locations of the off-center (hereafter referred to as “lateral”) impacts on each vehicle were symmetrical about the vehicle centerline. No impact points were within 65 mm of the bumper corner, as defined in the EuroNCAP procedure. Tire pressure was set according to manufacturer’s instructions. The emergency brake was engaged. No additional ballast was added to the vehicle weight. Tests were performed at all three locations before replacing the entire bumper system.

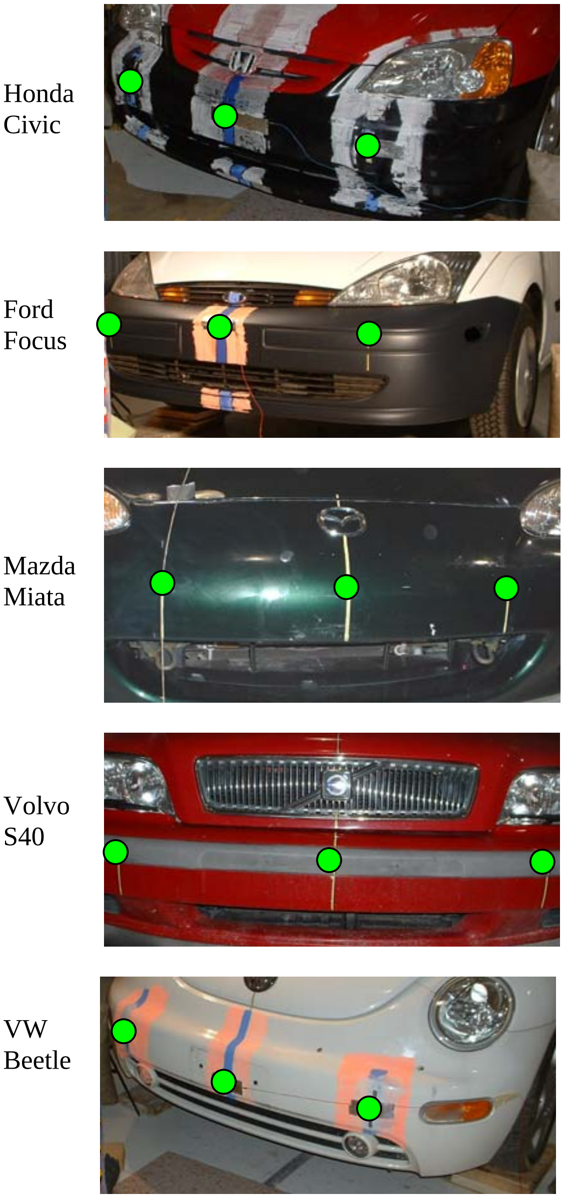


Figure 2. Impact points on each bumper system.

External inspection of the bumper systems for damage was done immediately following each test, and internal inspection was performed after bumper replacement. Post-test inspection of each legform was carried out according to manufacturer’s instructions.

RESULTS

TRL Legform Impacts

Kinematics during the first 20 milliseconds after impact are shown in Figure 3. These video frames show the moment of initial contact between the lateral side of the legform and the bumper, followed by the legform's position 10, 15, and 20 milliseconds after impact. Initial interaction between the bumper and the legform is visible at 10 milliseconds when the legform tends to follow the contour of taller bumpers that are more rounded (such as the Ford Focus and Mazda Miata) while narrower or more angular bumpers (such as the Volkswagen Beetle or Volvo S40) tend to produce a more pronounced bend at the knee.

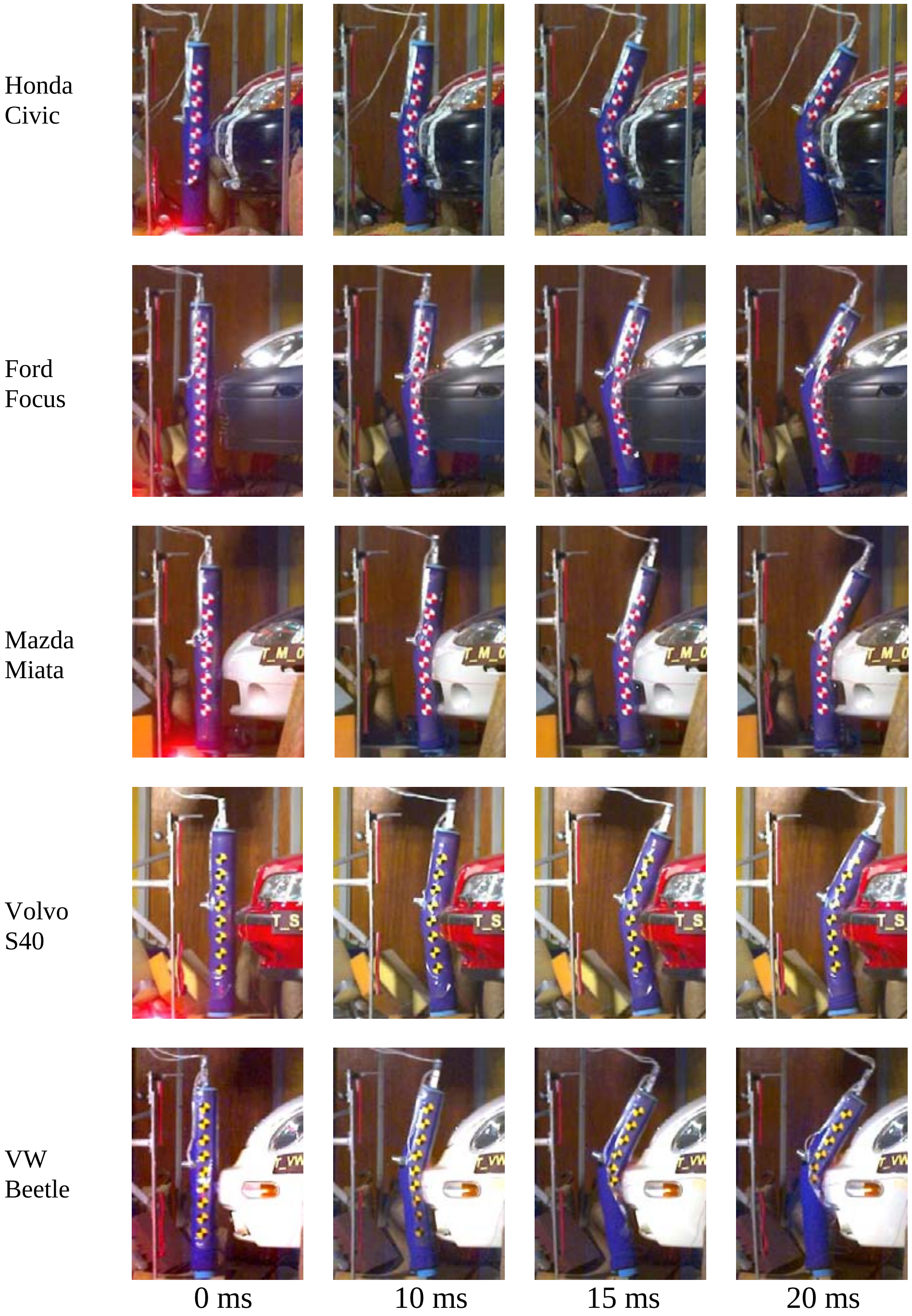


Figure 3. Kinematics of TRL legform for five vehicles.

At 15 milliseconds, the effect of lower bumper shape on lower leg motion is visible. By this time, the tibia component of the legform has reached its maximum forward angle against the inward slanted lower bumpers of the Ford Focus and the Honda Civic. The more vertical front face of the Mazda Miata bumper has limited the bending of the knee even more than the Ford Focus or Honda Civic bumpers. The legforms impacted into the Volvo S40 and Volkswagen Beetle bumpers have not yet impacted the lower bumper structures at 15 milliseconds and are still free to wrap under the bumper and increase knee bending angle. The frame at 20 milliseconds represents the approximate time of maximum bending for each legform as the femur component reaches the grille or hood area. The vehicles with more upright grille or hood structures appeared to limit forward femur movement the most, effectively limiting knee bending.

Post-test inspection of the TRL legform revealed no major structural damage after any of the tests. Instrumentation damage that required repair between tests was limited to a torn femur potentiometer wire and a displaced tibial potentiometer shaft that was press fit back in place. Neither affected the usable portion of data. Deformed frangible knee ligaments were replaced after each test.

In most tests, the vehicle and bumper systems showed either no damage or damage limited to fine scuffing, scratching, or cracking of the paint related to contact with the legform or instrumentation. No deformation was found to the internal bumper structures or energy absorbing elements.

Impact speed measured in the TRL legform tests was 10.9 ± 0.2 m/s, which was slightly slower than the nominal target range of 11.1 ± 0.2 m/s. Orientation of the legform at impact was as specified according to review of lateral and overhead high-speed video.

For each test, upper tibia acceleration, knee shear displacement, and knee bending angle were measured. In all tests, peak values of these measures were recorded in the first 30 milliseconds after bumper contact. Time histories for acceleration, shear displacement, and bending angle are shown for typical impacts with each vehicle in Figures 4 through 6.

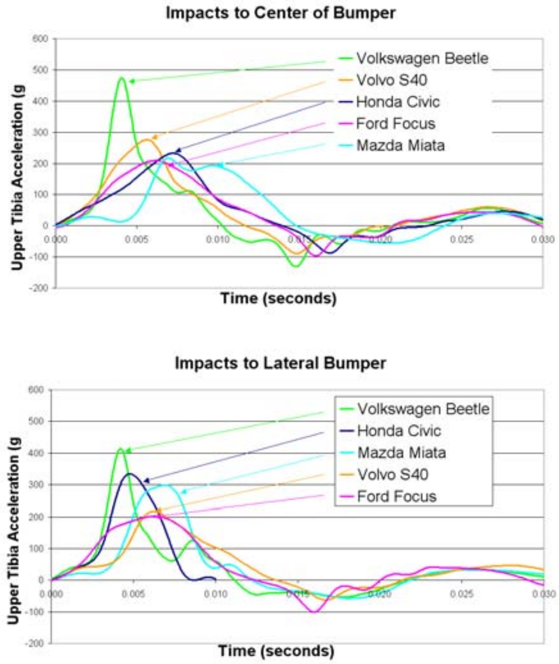


Figure 4. Upper tibia acceleration.

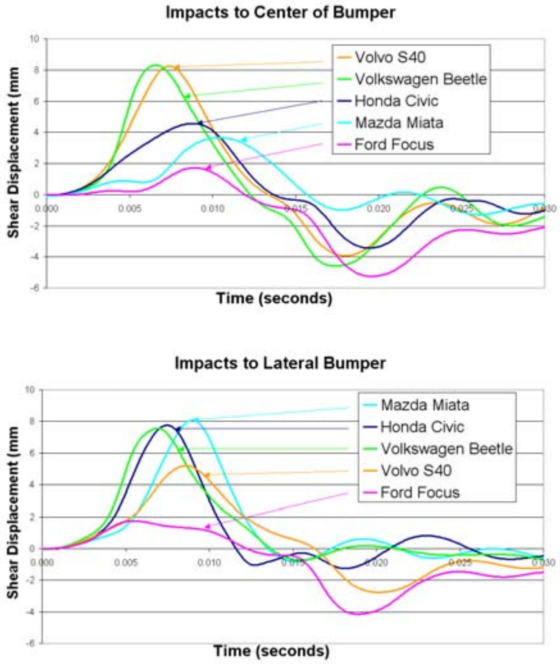


Figure 5. Knee shear displacement.

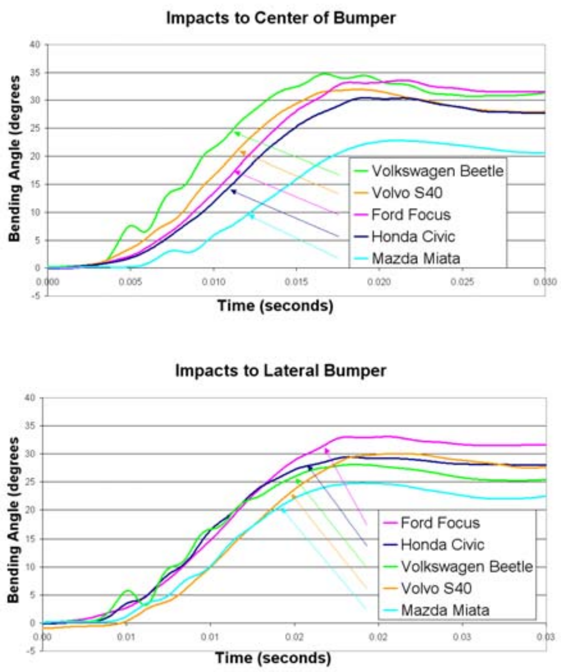


Figure 6. Knee bending angle.

Although the bending angle measurements shown in Figure 6 indicate peak bending angles in excess of 30 degrees, the limit of bending angle accuracy for the TRL legform is considered to be 30 degrees because of contact between the tibial and femoral components at this angle [9]. Subsequent to that contact at a knee bending angle of approximately 30 degrees, resistance to bending is expected to increase. Although measurements above 30 degrees are expected to correspond to progressively worse actual bending angles, the exact value of any peaks above 30 degrees is uncertain.

Two center-bumper impacts and two or three lateral-bumper impacts were performed for each vehicle. No significant variation was found between left-sided and right-sided impacts or between impacts performed on an untested bumper versus impacts into a bumper tested previously in a different location. Repeatability analysis of injury measures for testing on vehicles for which three lateral impacts were performed showed coefficients of variation ranging from 2% to 15%. Because of this range of test result variation, comparisons between bumpers were made using averaged values of peak injury measurements for all center impacts to each vehicle (Table 2) and for all lateral impacts for each vehicle (Table 3).

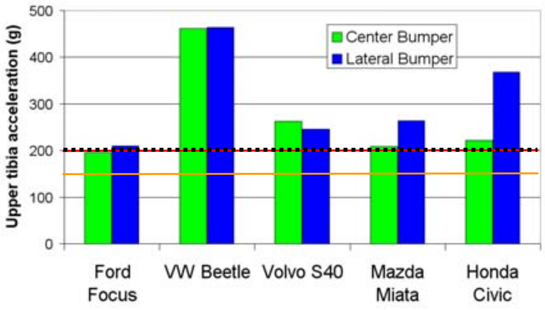
Table 2.
Average peak injury measures for all center-bumper impacts.

Vehicle	Average Peak Acceleration (g)	Average Peak Bending Angle (degrees)	Average Peak Shear Displ. (mm)
Ford Focus	195.0	33.4	-4.9
Honda Civic	221.4	31.0	4.7
Mazda Miata	208.8	24.7	3.4
VW Beetle	461.9	34.7	8.3
Volvo S40	262.9	31.1	8.2

Table 3.
Average peak injury measures for all lateral-bumper impacts.

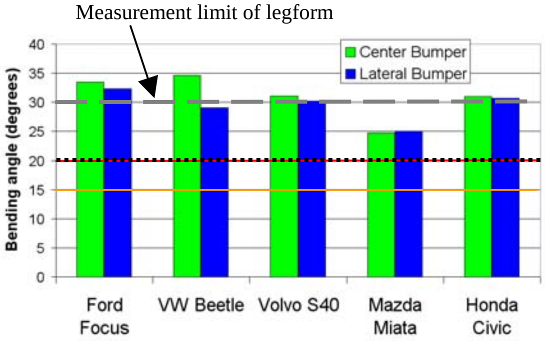
Vehicle	Average Peak Acceleration (g)	Average Peak Bending Angle (degrees)	Average Peak Shear Displ. (mm)
Ford Focus	209.3	32.3	-3.8
Honda Civic	368.5	30.7	7.7
Mazda Miata	264.3	25.1	7.4
VW Beetle	464.2	29.1	8.2
Volvo S40	246.0	30.2	6.2

Figures 7 through 9 compare the averaged peak values for each vehicle and impact location to European Union requirements [7] and to the more stringent and less stringent performance limits used to rate vehicles in the EuroNCAP point system. In the EuroNCAP system, injury measurements meeting the more stringent limit receive 2 points, measurements between the two limits receive an interpolated point value, and measurements exceeding the less stringent limit earn 0 points [5]. The total point value awarded for an individual test is equal to the lowest of the calculated acceleration, bending and shear point values. The point values for three lower extremity tests are added to the point values earned in head impact and upper leg press tests to calculate the vehicle's overall pedestrian star rating.



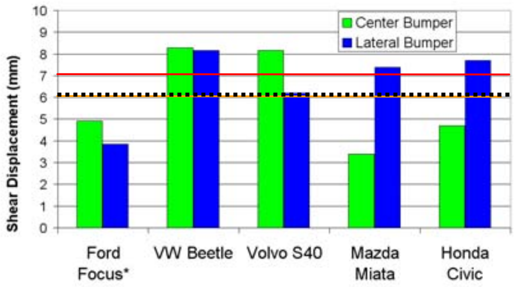
.... European Union Limit (200 g)
———— EuroNCAP Less Stringent Limit (200g)
———— EuroNCAP More Stringent Limit (150 g)

Figure 7. Peak upper tibia acceleration



.... European Union Limit (20 degrees)
———— EuroNCAP Less Stringent Limit (20 degrees)
———— EuroNCAP More Stringent Limit (15 degrees)

Figure 8. Peak knee bending angle averaged for all impacts at each location.



*Peaks were negative

.... European Union Limit (6 mm)
———— EuroNCAP Less Stringent Limit (7 mm)
———— EuroNCAP More Stringent Limit (6 mm)

Figure 9. Peak knee shear displacement averaged for all impacts at each location.

Since no impacts in the current series produced a bending angle lower than the less stringent limit of 20 degrees, the bending angle point value for all tests would be zero. Therefore, all impacts in this series would result in overall EuroNCAP lower extremity point values of 0. In order to compare the performance of the tested vehicles in the current study to each other, rather than to vehicles previously tested under EuroNCAP procedures, a modified version of the EuroNCAP point system was used. Under the modified point system, point values were interpolated between 2 and 1 for injury measurements between the EuroNCAP less stringent and more stringent limits, and interpolated between 1 and 0 for injury measurements that exceeded the EuroNCAP less stringent limit but were less than double that limit. For example, an injury measurement that exceeded the less stringent limit by 50% earns 0.5 points while an injury measure that was two times that limit would earn 0 points. Modified point values calculated for the averaged results at each vehicle location are listed in Table 4.

Table 4 shows that by the modified EuroNCAP point system the Mazda Miata bumper (0.76 center and 0.68 lateral) was least aggressive toward pedestrian legforms. It was followed in order of increasing aggressivity by the Volvo S40 (0.49 lateral and 0.45 center), the Honda Civic center bumper (0.45), the Ford Focus (0.38 lateral bumper and 0.33 center bumper), the Honda Civic lateral bumper (0.16), and the Volkswagen Beetle (0.0 lateral and center).

Table 4.
Modified point values earned for each injury measurement, averaged for each vehicle/location (final overall modified score in *italic bold*)

Vehicle	Location	Upper Tibia Accel.	Bending Angle	Shear Displ.
Ford	Lateral	0.95	***0.38***	2
Focus	Center	1.90	***0.33***	2
Honda	Lateral	***0.16***	0.46	0.9
Civic	Center	0.89	***0.45***	2
Mazda	Lateral	***0.68***	0.75	0.95
Miata	Center	0.96	***0.76***	2
VW	Lateral	***0***	0.55	0.83
Beetle	Center	***0***	0.27	0.82
Volvo	Lateral	0.77	***0.49***	1.12
S40	Center	0.69	***0.45***	0.83

Of the three EuroNCAP injury criteria, shear displacement was the easiest for the vehicles to meet. The Ford Focus (both lateral and center), Honda Civic (center), and Mazda Miata (center) all met the more stringent shear displacement requirement of 6 mm and no other impact locations resulted in a modified score lower than 0.82.

Bending angle was the most difficult limit to meet, with no impact location achieving a modified score above 0.75. The widest range of modified scores was in tibia acceleration, from a score of 0 by the Volkswagen Beetle in both the center and lateral locations to 1.90 by the Ford Focus at the center location.

The impacts at each vehicle location were also evaluated against limits defined in the European Union directive 2003/102/EC. The maximum acceleration limit of 200 g was exceeded for all impact locations except the center bumper of the Ford Focus, which produced upper tibial acceleration of 195 g. The 21-degree bending angle limit was exceeded for center and lateral impact locations for all vehicles tested. The Ford Focus was the only vehicle tested to remain under the maximum shear displacement angle of 6 mm for both center and lateral impacts, while the Mazda Miata and Honda Civic were able to stay below that limit for the center bumper location only. The Volkswagen Beetle and Volvo S40 shear values were over the limit at both locations.

FlexPLI Legform Impacts

Five bumper impacts were performed with the FlexPLI legform: one impact to the Honda Civic at full speed (nominally 40 km/h or 11.1 m/s as in the TRL tests), one to the Mazda Miata at a reduced nominal target speed of 8.3 m/s (30 km/h) and three to the Volvo S40, also at a target speed of 8.3 m/s. The legform sustained damage in the Honda Civic test, necessitating the reduction in speed. It was also damaged in the Mazda Miata test and the third Volvo S40 test at the lower speed.

Kinematics of the FlexPLI are shown for tests into the lateral bumper of the Honda Civic, Mazda Miata, and Volvo S40 in Figure 10. The frames at 10 to 20 milliseconds show the knee end of the femur, and to a lesser extent the tibia, bending away from the bumper after contact in the knee area. The resulting convex curvature of the thigh and leg away from the bumper is followed by concave curvature toward the vehicle by 20 to 30 milliseconds after contact. As the knee flexes around the front of the vehicle, the upper and lower leg segments also bend, essentially wrapping under the bumper and around the hood leading edge. The lower leg bending appears greater for the Honda Civic and Volvo S40 bumpers where their recessed lower structures allow the lower leg to wrap under the bumper. The more flat-faced Mazda Miata bumper restricts tibial bending below the bumper structures. The upper leg bending appears most limited by the Volvo S40 bumper, which has a more upright grille area than the other vehicles.

Post-test inspection of the FlexPLI legform showed major damage following three tests. After the impact into the right lateral bumper of the Honda Civic at 40 km/h, routine inspection of the tibial bone core showed an anterior-posterior crack through the tibial bone core. Dismantling of the lower leg structures revealed that the linear crack started at the top of the tibia, but did not extend down to the bottom of the bone.

A replacement FlexPLI legform underwent two subsequent tests into the lateral and center bumper of a Volvo S40 at a reduced speed of 30 km/h without sustaining damage. A third impact into the lateral bumper of the Volvo S40 produced a small crack in the distal femoral bone core. A final impact into the lateral bumper of the Mazda Miata, also at reduced speed, resulted in an additional fracture of the tibial bone core.

Time histories of the moments measured at each level in the thigh and lower leg are shown for the first impact into the Volvo S40’s lateral bumper impact location at reduced speed (Figures 11 and 12). Positive moment in the leg and thigh corresponds to moment that produces concave lateral bending, as when the femur wraps around the hood leading edge or the tibia wraps under the bumper. Negative moment corresponds to moment that produces convex lateral bending, as when the knee is initially pushed medially.

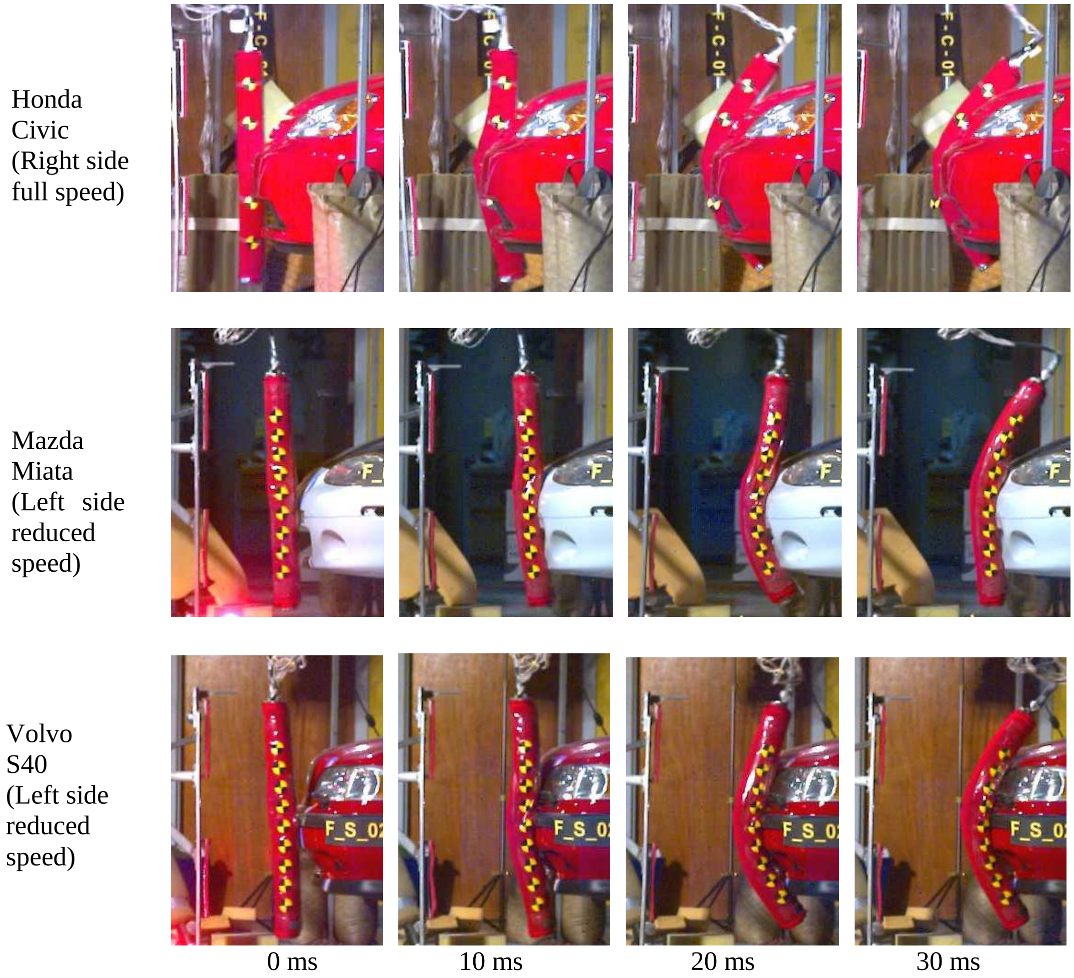


Figure 10. Kinematics of FlexPLI legform for three vehicles.

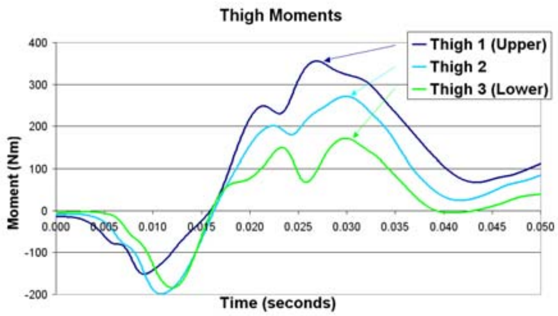


Figure 11. **Thigh bending moments for right lateral impact into Volvo S40 bumper at reduced speed.**

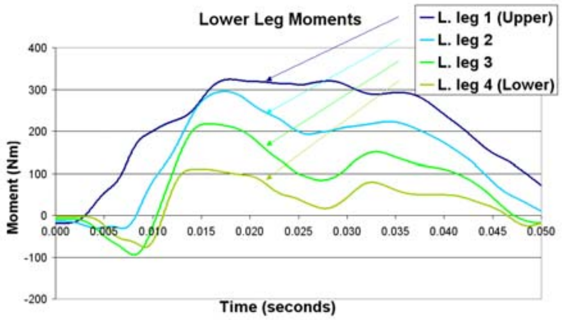


Figure 12. **Lower leg moments for right lateral impact into Volvo S40 bumper at reduced speed.**

Figures 13 and 14 compare the peak magnitude of moments measured in all tests performed with the FlexPLI. In all tests run with the FlexPLI, the peak positive moments were greater in magnitude than the peak negative moments in the leg and for the upper two moment sensors in the thigh. In the lowest moment sensor in the thigh, positioned closest to the knee, negative moment was greater in magnitude than positive moment. Peak bending moment in the thigh tended to be greatest for sensors further from the knee, while peak bending moment in the lower leg tended to be greatest for sensors closer to the knee. Values are compared to preliminary proposed injury limits for the FlexPLI legform [10]. The full-speed Honda Civic test and the reduced speed Volvo S40 tests all exceeded the moment limit at the upper thigh sensor, while the Mazda Miata was within moment injury limits in the thigh. In the lower leg, the only measurement to exceed the injury limit was the bending moment adjacent to the knee in the final Volvo S40 test.

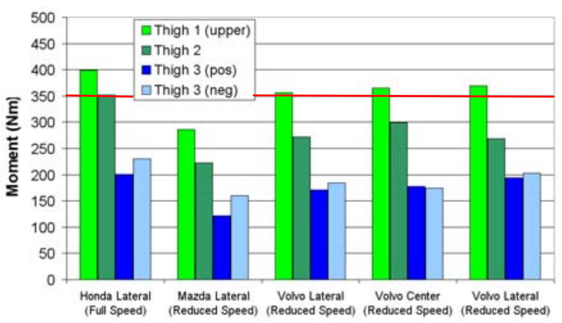


Figure 13. Thigh moments for all impacts with FlexPLI legform (proposed injury limit of 350 Nm).

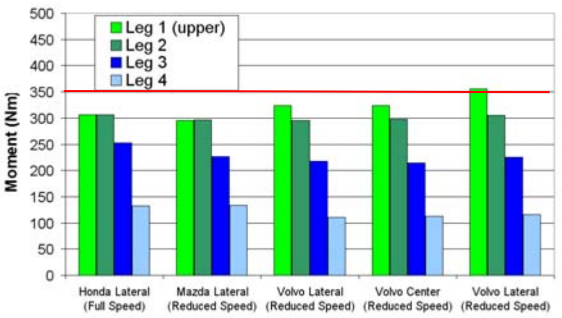


Figure 14. Lower leg moments for all impacts with FlexPLI legform (proposed injury limit of 350 Nm).

Displacements of the potentiometers representing knee ligament extension are shown for the example impact with the Volvo S40 bumper in Figure 15 and compared for all tests in Figure 16. The full-speed Honda Civic test exceeded the proposed injury limits for two of the three ligaments. Among the reduced speed tests, the Mazda Miata exceeded limits for the ACL, and the Volvo S40 exceeded the ACL and MCL limits on all tests.

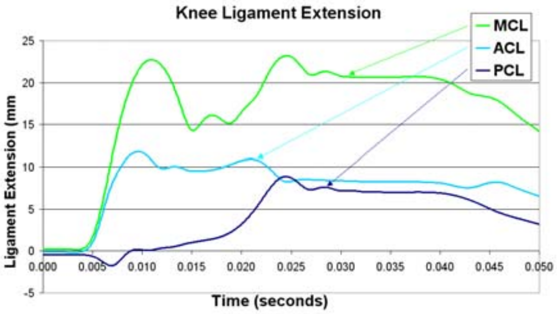


Figure 15. Ligament extension for right lateral impact into Volvo S40 bumper at reduced speed.

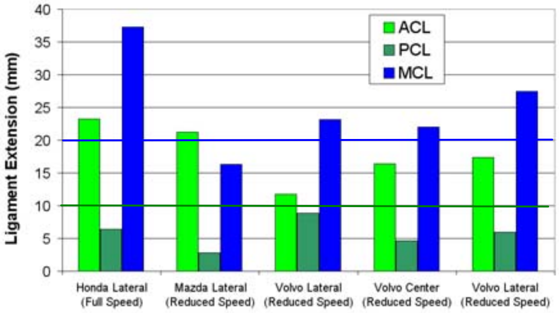


Figure 16. Ligament extensions for all impacts with FlexPLI legform (proposed injury limits of 20 mm for MCL and 10 mm for ACL and PCL).

Upper tibial acceleration is shown for the example impact with the Volvo S40 bumper in Figure 17, and compared for all tests in Figure 18. No injury limits have been proposed for acceleration of the FlexPLI legform.

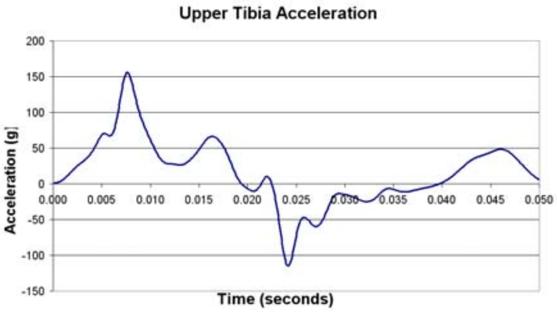


Figure 17. Upper tibia acceleration for right lateral impact into Volvo S40 bumper at reduced speed.

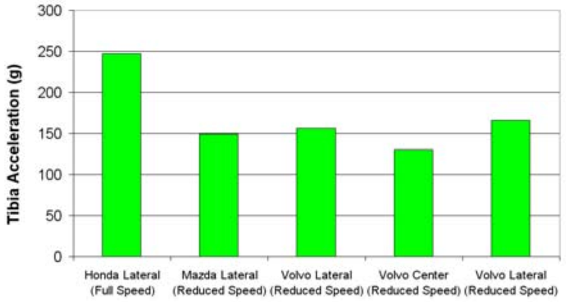


Figure 18. **Upper tibia acceleration for all impacts with FlexPLI legform (no injury limit proposed).**

DISCUSSION

Evaluation of TRL and FlexPLI Legforms

Figures 3 and 10 show the marked difference between how the TRL and FlexPLI legforms interact with the vehicles. The single-jointed TRL bent only at the knee while the FlexPLI's flexible femur and tibial elements allowed it to wrap around the front of the vehicle. This difference in how the legforms conform to the vehicle shape is likely to affect not only the magnitude of bending angle at the knee but all injury measures. Variations in the shape of the bumper, grille, and hood leading-edge structures may have a different effect on injury measures recorded by one legform than they do on the other legform.

The knee shear displacement and knee bending angle calculated using rotary potentiometers by the TRL legform relate directly to physiologic measurements for which known biofidelity corridors exist [11, 12]. These quantities, along with upper tibial acceleration, are the only measurements made by the TRL legform. The simplicity of the instrumentation system contributes to its reliability and the lightness of its wiring umbilical helps to maintain the leg's orientation during free flight.

The instrumentation in the FlexPLI 2004 includes moment measurements along the flexible femur and tibia components as well as injury measurements at the knee joint. This additional information may allow better understanding of how specific structures on the upper or lower vehicle front interact with a pedestrian lower extremity and also offer insight into injury potential of the long-bones rather than just the knee. Although the additional instrumentation in the FlexPLI increases the potential for damage to wiring and loss of data, the pairs of strain gauges mounted to the bone cores allow redundant data to be collected at each level, reducing the risk of lost data as a result of wiring damage. Unfortunately, this built-in redundancy further increases the number of wires in the legform's umbilical and makes it difficult to maintain perfect orientation during free-flight. An onboard data acquisition system may be a useful feature for any free-flight legform.

Both legforms tested in this study were designed outside of North America and had limitations for testing vehicles from the North American market. The FlexPLI legform fractured when used with North American vehicles at 40 km/h or even at a reduced speed of 30 km/h. The bone core elements fractured in three of five tests. The core fractured even before reaching the proposed injury limit for bending moment in two of those three tests that produced fracture.

Although the TRL legform withstood the testing without structural damage, its bending limits were exceeded, restricting measurement of peak values. Peak values of all injury measures were likely affected since this mechanical bending limitation affected the motion of the legform rather than simply its ability to measure the motion.

Comparison of North American and European Bumpers

Comparison of North American and European versions of the specific vehicles tested is possible because the North American vehicles selected for this study corresponded to European vehicles previously tested under EuroNCAP procedures. Although there were minor differences in the launch procedure for the current study from the EuroNCAP procedure, the tests are essentially comparable. The slightly slower than targeted impact speed in the current study makes the comparison conservative in that the current tests were slightly less demanding than the comparison EuroNCAP tests.

The bumpers tested in EuroNCAP procedures were subject to European bumper damage regulations while those tested in the current study were subject to North American bumper standards. However, EuroNCAP results for the European versions of the vehicles tested showed that lower leg pedestrian test performance was not consistently better for the European versions of these same five vehicles. In fact, only the European Honda Civic and Volvo S40 scored any EuroNCAP points in the legform to bumper tests. Table 5 contains peak measurements made for EuroNCAP data for vehicles in the same model year range as the vehicles in this test study

[13]. These peaks are compared to the corresponding peak measurements in the currently reported tests on the North American models in Figures 19 to 21.

Table 5.
Peak Measurements in EuroNCAP testing of European models of test vehicles.

	Test No.	Upper Tibia Accel	Bend Angle	Shear Displ.	Euro NCAP Points
1999	1	536.7	33.3	6.6	0
Ford	2	483.7	34.2	8.0	0
Focus	3	542.7	33.6	5.8	0
2001	1	116.4	7.1	1.9	2
Honda	2	97.7	7.0	2.3	2
Civic	3	189.6	20.7	2.1	1.01
2002	1*				0
Mazda	2	278.1	32.9	4.3	0
MX-5 / Miata	3	351.1	30.6	6.8	0
1999	1	416.0	31.4	7.0	0
VW	2	520.0	29.8	7.4	0
Beetle	3	470.0	27.7	7.0	0
1997	1	231.0	33.7	7.4	0
Volvo	2	220.0	30.5	7.5	1
S40	3	180.0	32.8	7.0	0

* No Mazda impact was performed at site 1 because identical to site 3.

The North American Ford Focus performed better than its European counterpart in terms of shear displacement and tibia acceleration, while the European and North American Ford Focus both exceeded the 30-degree bending angle limit of the TRL legform. The North American Mazda Miata's performance was better than the European model in both bending angle and upper tibial acceleration. Peak measurements made on the North American Volkswagen Beetle and Volvo S40 were comparable to those made in tests of their European models. The European version of the Honda Civic performed dramatically better in lower leg testing than the North American model. In fact, Honda peak injury measurements were lower in every test than in any of the other North American vehicles tested in this study.

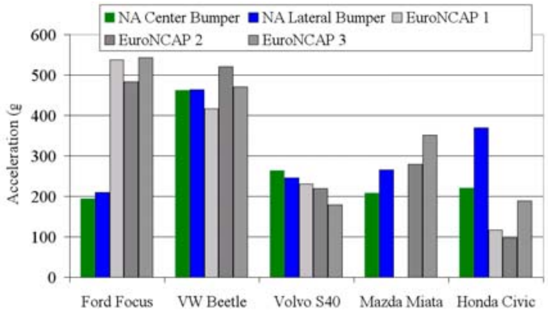


Figure 19. Peak average upper tibia acceleration for North American models compared to European models.

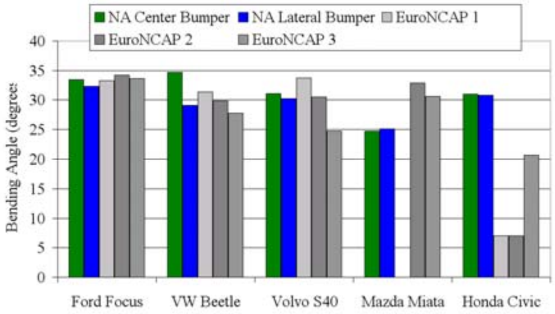


Figure 20. Peak average knee bending angle for North American models compared to European models.

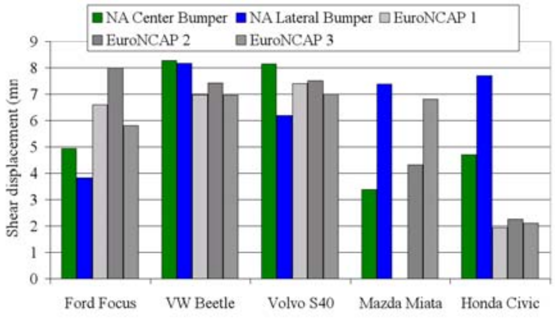


Figure 21. Peak average knee shear displacement for North American models compared to European models.

The similar performance of the Volkswagen and Volvo vehicles compared to European versions suggests that there may not have been significant differences in the international versions of their front bumper systems. The better performance of the North American Ford Focus and Mazda Miata over their European counterparts and the European Honda Civic over its North American counterpart suggests that bumper design differences exist between the international versions of these vehicles.

The European models of the Volvo S40, Volkswagen Beetle, Ford Focus, and Mazda Miata did not appear to offer better pedestrian leg protection than the North American models of those vehicles in spite of the fact that the European vehicles were required to meet different bumper damage requirements than the North American versions. In contrast, the European 2001 Honda Civic showed much improved pedestrian leg protection over the North American Honda Civic in the same year range. Given that the European vehicles tested were not yet required to meet the upcoming European Union pedestrian safety requirements, the better performance of the European 2001 Honda Civic may reflect a trend toward improvement to meet the upcoming pedestrian requirements.

Damageability and Bumper Performance

The relationship between bumper performance in pedestrian lower extremity impacts and bumper damageability was also considered. Damageability testing has been reported for 3 vehicles that are in the same model and year range as the vehicles tested in the current study [14]. Low-speed flat barrier, angled barrier and pole impact tests were performed at 7.96 ± 0.24 km/h [15] on vehicles including the 2000-2005 Ford Focus, 2001-2005 Honda Civic, and the 1998-2005 Volkswagen Beetle. By the IIHS qualitative rating scale, in which the vehicles that sustain the least damage in testing score highest, the Volkswagen Beetle scored Good, the Honda Civic Acceptable, and the Ford Focus Marginal. It was reported that the North American Volkswagen Beetle model tested had indeed been one of the best cars ever tested for bumper performance in the low-speed damage tests and that it performed better in damage tests than the European version of the Volkswagen Beetle [16].

In contrast, the North American Volkswagen Beetle was the worst performer in the current series of pedestrian lower extremity tests, using the modified EuroNCAP point calculation. Next worse of the three vehicles was the Honda Civic lateral bumper tests, both Ford Focus tests, then the Honda Civic center bumper tests. The contrary results of bumper damage tests and pedestrian lower extremity tests illustrate the incompatibility between bumper damage reduction and pedestrian lower extremity safety.

The fact that the more damage-resistant bumpers tended to perform worse in these pedestrian safety tests suggests that structural stiffness of bumper components influences the severity of pedestrian lower extremity injury. However, there were other design elements that appeared from video to have an effect on leg deformation, and therefore loading. These included the depth and angle of the bumper face and the shape of the grille and hood leading edge. Bumpers with a tall, flat face like the Mazda Miata's reduced bending at the knee and below by limiting wrapping of the tibia under the bumper. Similarly, vehicles like the Volvo S40 with upright hood structures above the bumper reduced bending of the knee and upper leg by reducing wraparound onto the hood in this free-flight test.

CONCLUSIONS

The single-jointed TRL legform and the flexible femur and tibia of the FlexPLI legform lead to marked differences in how the two legforms interact with vehicle front structures. Variations in bumper design may have different effects on the injury measures recorded by the two legforms.

Both legforms had limitations in testing North American vehicles in this test series. The FlexPLI 2004 fractured in three tests and the TRL legform was unable to produce reliable peak measurements when bending exceeded thirty degrees.

The North American bumpers tested in this series would not have met European limits set for pedestrian leg loading and repeatedly fractured or exceeded the measurement capabilities of the legforms developed for use in international pedestrian testing. Although four of the five European vehicles tested under comparable conditions also performed inadequately in similar tests, the European version of one vehicle tested showed dramatically improved pedestrian leg protection over its North American counterpart. Although these tests do not establish that the North American bumper standards are the reason for the aggressiveness of North American bumpers, IIHS testing suggests that bumpers that are more robust (i.e., those that score better in their bumper damage tests) may be more aggressive toward pedestrians.

Although this study suggests that less damageable bumpers may be more aggressive toward pedestrians, it does not establish that vehicles meeting North American bumper standards cannot achieve improved pedestrian leg safety. Further work should be done to determine if vehicle front design could be improved to better protect pedestrians while still conforming to current bumper regulations. This work may include both bumper and pedestrian testing of more recent models of the vehicles tested in this study to see how much each of them has changed with new pedestrian regulations on the horizon.

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