PERFORMANCE COMPARISON AND REPEATABILITY EVALUATION OF THE FLEX PLI AND THE TRL PEDESTRIAN LEGFORM IMPACTORS

Lan Xu
Sukhbir Bilkhu[1]
Iskander Farooq
Jeff Hickman
Jack Jensen
Ken McCabe
Guy Nusholtz

The USCAR/OSRP Pedestrian Task Group

United States

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ABSTRACT

The objectives of this study were to compare the response differences of the Flex PLI and TRL legforms under various test conditions and to assess their repeatability. A test fixture with four control factors was designed and fabricated to simulate a generalized front structure of a light truck. Using this fixture, thirty-six impact tests with the Flex PLI and the TRL legforms were performed at an impact speed of 32 km/h.

The responses from the two legform impactors, specifically, moments in the Flex PLI and acceleration in the TRL, MCL elongation in the Flex PLI and bending angle in the TRL, and ACL elongation in the Flex PLI and shear displacement in the TRL were compared. The Taguchi method was applied to compare the responses from these three pairs of measurements. The shape and magnitude of the response time histories were used to evaluate the repeatability of the Flex PLI and TRL legforms.

Some results from this limited study indicate that the two legforms did not consistently respond to the same test conditions in the same way and could potentially drive countermeasures in opposite directions. For example, increasing the protrusion of the lower bumper stiffener relative to the bumper generally resulted in lower moments in the upper tibia with the Flex PLI, but higher accelerations with the TRL legform. However, the MCL from the Flex PLI and bending angle of the TRL legform trended consistently with changes of all four fixture factors, although with differing sensitivity.

A repeatability analysis indicated that most measurement parameters of each legform were repeatable or marginally repeatable across the spectrum of the test conditions. However, the MCL elongation of the Flex PLI and the bending angle of the TRL were non-repeatable in some test conditions.

INTRODUCTION

Currently, two legforms are available for pedestrian impact tests: the TRL Pedestrian Legform Impactor, originally developed by the EEVC (European Enhanced Vehicle Safety Committee) consortium [1] and the Flexible Pedestrian Legform Impactor (Flex PLI) [2]. The TRL Legform was incorporated into the ECE (Economic Commission for Europe) regulations in 2003 [3, 4]. The European New Car Assessment Program (EuroNCAP) has been using the TRL legform since 1997. The Flex PLI was developed by the Japanese Automobile Research Institute (JARI) in the early 2000's and over time, various versions have been evaluated [5]. EuroNCAP included the latest version of the Flex PLI GTR (Global Technical Regulation) in their 2014 vehicle tests [6]. Considering that these two legforms are used for the same type of test, it is important to understand their performance differences.

Various versions of the TRL legform and Flex PLI have been evaluated and compared by a number of organizations under different test conditions. A series of pedestrian impact tests involving five vehicles was performed using both

[1] Retired from Chrysler in 2014

legforms [7]. The major findings from these tests were that the two legforms had marked differences in how they interacted with vehicle front structures. Another series of tests on eight vehicles was performed with both legforms [8]. This work concluded that the TRL legform predicted a higher risk of tibia fracture but a lower risk of knee ligament injury than the Flex PLI. In addition, several bumper designs were tested with both legforms [9]. These results indicated that the bumper system that performed well with the TRL legform did not necessarily perform well with the Flex PLI.

The repeatability of the two legforms has also been studied by different organizations. Most repeatability analyses used the Coefficient of Variance, CV, which was based on the International Organization for Standardization document, ISO/TC22/SC12/WG5 N 751, regarding methods to assess the repeatability and reproducibility [10]. A repeatability and reproducibility study using six TRL legforms in 76 tests was conducted by Siems et al. in 2007 [11]. Repeat tests were performed on each legform with a linearly guided impactor. The CV values calculated from the parameter peaks of the repeat tests were all below 5% which indicated "acceptable" repeatability. Another study by Zander et al. [12] concluded that CV values from certification tests with the Flex PLI demonstrated that all tibia moments had acceptable repeatability while some knee ligament elongations had unacceptable repeatability, with CVs >10%. In the same study, two different locations at the front end of two vehicles were each impacted three times with a Flex PLI. Most of the tibia bending moments were repeatable, with CVs <5%; however, some of the knee elongations (ACL, PCL, and MCL) were non-repeatable with CVs >10%. The repeatability of the Flex PLI was then further assessed by the inverse calibration impact tests. The repeatability for the inverse calibration impact was acceptable since all the CV values were less than 4%. Another repeatability study with a later version of the Flex PLI was conducted [13] using two sedans and one (SUV) Sport Utility Vehicle. For each vehicle, two selected locations were each impacted three times. The CV results indicated that all the tibia moments were either repeatable or marginally repeatable. However, elongations of the knee ligaments did not have acceptable repeatability; their repeatability depended on vehicle front end geometry.

The OSRP (Occupant Safety Research Partnership) of USCAR (United States Council for Automotive Research) evaluated these pedestrian legforms. A unique test fixture was designed and used which allowed understanding of the response differences between the two legforms in this evaluation. The objectives were to compare the performance of the TRL legform and Flex PLI, and to assess the repeatability of some of the responses of the two legforms.

METHODOLOGY

Legform Impactors

The TRL legform consists of two rigid segments covered with foam and neoprene skin (Figure A1 in Appendix A) [1, 14]. The segments represent the lower leg (tibia and foot) and upper leg (femur) of an adult, connected by a simulated knee joint that can rotate and translate. The motion of the knee joint is resisted by two deformable elements (ligaments as shown in Figure A1) which are replaced after each test.

The Flex PLI consists of an upper leg (femur) and lower leg (tibia) composed of fiberglass bone cores and several plastic segments attached to its impact side (Figure A2) [2, 14]. The knee element consists of two complex blocks containing over twenty four springs. The entire assembly is wrapped in a thin rubber and neoprene skin.

The TRL legform and Flex PLI instrumentation locations are shown in Figures A3 and A4, respectively [15, 16]. The standard TRL legform instrumentation includes two transducers to measure the relative rotation (bending angle) and relative translation (shear displacement) between the femur and tibia. There is also an accelerometer fitted to the non-impact side of the tibia, close to the knee joint (66mm below its knee as shown in Figure A3).

The Flex PLI has four strain gauges glued to its fiberglass core to estimate the tibia moments at four different locations. These are labeled Leg-1 through Leg-4 in Figure A4, but identified as Tb1 through Tb4 throughout the text. The standard Flex PLI also includes four string potentiometers in its knee to measure the elongations of the Anterior Cruciate Ligament (ACL), Medial Collateral Ligament (MCL), Posterior Cruciate Ligament (PCL) and Lateral Collateral Ligament (LCL). Although the thigh has instrumentation, the moments in the thigh and the LCL elongation were not measured in this evaluation program.

To minimize the potential damage to the Flex PLI (GT version), the owner of the legform (JARI) advised that the maximum tibia bending moment should not exceed 380Nm during any test. A series of tests was performed using the Flex PLI, starting from a low impact speed which was increased gradually, to determine the impact speed for this test program. An impact speed of 32km/h kept the bending moments less than 380 Nm. Both the TRL and the Flex PLI legforms were tested at this speed.

Test Fixture Design

The test fixture was designed to represent a front end of a generic Light Truck and Van (LTV) and is shown in Figure 1. The fixture had three horizontal components which represented the hood edge, bumper, and lower bumper stiffener (LBS). The LBS was adjustable in both horizontal and vertical directions. The fixture was bolted to a heavy bed plate and secured to the test area floor. The foam placed in front of bumper face was expanded polypropylene (EPP) with a density of 32g/l and a thickness of 75mm. It was replaced for each test.

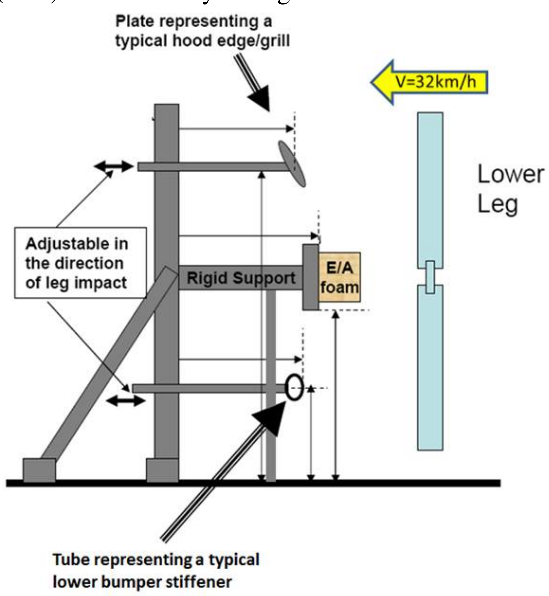

Figure 1. Fixture Design.

Test Matrix Design

Taguchi method A procedure used to analyze the data from this test series was the Taguchi method [17, 18]. The Taguchi method utilizes orthogonal arrays in the design of experiments to significantly reduce the number of experimental configurations compared to a full factorial array. Control factors such as the bumper foam height and LBS position were varied and evaluated.

Test matrix An L9 orthogonal array was used in this study. It had four control factors with 3 different levels. This resulted in 9 tests for each legform. The required number of tests, if a full factorial array were used, would be 162. The factors are given in Table 1. Factor A, the bumper foam section height, was the vertical length of the cross section. Factor B, height of the bumper, was the vertical distance from the ground plane to the bumper lower edge. Factor C, LBS fore/aft position, was its alignment with respect to the bumper contact surface in the horizontal direction. Factor D, the height of LBS, was the vertical distance from the ground plane to the LBS. Photographs of the nine test configurations are shown in Figure B1 (Appendix B). To assess the repeatability of the legforms, two tests were conducted for both legforms in each of the nine configurations.

All four control factors were tested using three levels except for the bumper foam height (Factor A). Only two levels of the bumper foam height were used in the test. The Taguchi method allows for substitution for variables that were not represented in testing. Thus, Level 2 of factor A is the same as Level 1 (A2=A1). A 100 mm bumper section was used in test configurations 1 through 6 in this test series. The factor levels are shown in Table 2.

Table 1.
Test Matrix.

L9 Taguchi Experimental Layout Inner Array - Control Factors and Levels				
*Confg.**	*Bumper Foam Height (z)*	*Bumper Lower Edge From Ground*	*Lower Bumper Stiffener offset to bumper face*	*Lower Bumper Stiffener from ground*
	A	**B**	**C**	**D**
1	**1**	**1**	**1**	**1**
2	**1**	**2**	**2**	**2**
3	**1**	**3**	**3**	**3**
4	**2**	**1**	**2**	**3**
5	**2**	**2**	**3**	**1**
6	**2**	**3**	**1**	**2**
7	**3**	**1**	**3**	**2**
8	**3**	**2**	**1**	**3**
9	**3**	**3**	**2**	**1**

*Confg. = configurations

Table 2.
Factor Levels.

Control Factors and Levels for Taguchi L9			
	Level 1	***Level 2***	***Level 3***
A *Bumper Foam Height (mm)*	100	100	200
B-*Bumper lower edge from Ground (mm)*	350	400	450
C-*Lower Bumper Stiffener Offset to bumper face (mm)*	-50	0	+50*
D-*Lower Bumper Stiffener from ground (mm)*	180	230	280

*Positive is in the legform initial travel direction

Data Processing

For the Flex PLI legform, the directions of the tibia moments (Tb1, Tb2, Tb3 and Tb4) were about the legform X axis. The MCL, PCL, and ACL extension measurements were in the local (dummy) coordinate systems (as opposed to the vehicle coordinate system). For the TRL legform, the directions of tibia acceleration and shear displacement were in the Y-direction (legform travel direction), and the knee bending angle was about the leg's X-axis. Data was recorded at a sample rate of 10,000 samples per second and filtered with a SAE CFC180 filter. Sign conventions, filtering and data processing followed standard industry practices (as described in SAE J211.)

Analysis Method

The measurements from the Flex PLI and TRL legforms that were hypothesized and proposed to assess the same injury type were compared. Moments from the Flex PLI and acceleration from the TRL were hypothesized to assess the risk of bone fracture. MCL elongation in the Flex PLI and bending angle in the TRL were hypothesized to assess the risk of injuries to the collateral ligaments. ACL elongation in Flex PLI and shear displacement in the TRL were hypothesized to assess the risk of injuries to the cruciate ligaments. Since some pairs measured different physical metrics, the trends of both their peak responses and their signal to noise ratios for each control factor were compared.

Factor A in the test fixture, size of the bumper foam, controlled the amount of energy that was absorbed. Factor B, the height of the bumper, controlled the relative height between the bumper and the knee and accelerometer location for the TRL legform, and between the bumper and the Tb1 and Tb2 for the Flex PLI. Factor C, LBS fore/aft position, is the horizontal distance between the contact surfaces of the bumper and LBS. C2 is aligned with the bumper beam, C3 is towards the rear of the fixture (recessed rearward of the bumper surface), and C1 is towards the front of the fixture (protruded forward of the bumper surface). Factor D is the LBS height relative to the ground.

The relationship between moment distribution and loading conditions in a beam is illustrated in Figure C1 of Appendix C. Considering that the shape and construction of the tibia in the Flex PLI is essentially a beam, it is possible to use beam theory for pictorial estimation of the moment distribution in its tibia, as shown by Figure C1. The pictorial estimation indicates that the maximum moments occur near the locations of the reaction forces, which would be the bumper force and LBS force.

The signal to noise (S/N) function used in this analysis is of the smaller-the-better type exhibited in Eq. (1),

$$S/N = -10\,log(\frac{1}{n}\sum_{i=1}^{n} y_i^2) \qquad (1)$$

where y_i are responses and n is the number of repeats from a test configuration. In this study, n=2, y_1 and y_2 are the peaks from the two repeat tests.

Repeatability was assessed by shape and magnitude correlation method. The repeatability between the two signals was measured through the use of cross correlations of the time-histories [19]. The two signals are considered repeatable if both the shape correlation is at least 0.98 and the magnitude correlation is at least 0.95. On the other hand, the two signals are considered not repeatable if either the shape is below 0.92 or the magnitude is below 0.9. In between, the repeatability is marginal. The definition of the shape and magnitude correlations and the repeatability criterions are included in Appendix E. All of the correlations were calculated from 0 to 80 milliseconds.

RESULTS AND DISCUSSION

Peak Response Analysis

The data from the PCL transducer could not be recorded because of faulty instrumentation. Therefore, it was not included in this analysis.

Peak tibia accelerations from the TRL legform and peak moments in the Flex PLI from all the tests are presented in Figures 2 and 3 (t1= test 1, t2=test 2) below and Figure D1 in Appendix D. Among the measured moments at four locations in the Flex PLI, the majority of the maximum moments occurred at Tb1 (at the top location), possibly due to the inertial loading from the knee and its contact with the bumper. Moments in Tb2 were close to Tb1 in configurations 7 and 9. Moments in Tb2 were larger than Tb1 in configurations 4 and 8. Beam theory seems to explain this result: the closer the bumper and LBS reaction points are to the transducer location, the higher the moment. For example, in configuration 4, the bumper was below the Tb1 location and both the bumper and the LBS are nearer to Tb2 than to Tb1; in configuration 8, both the bumper and the LBS are nearer Tb2 again. Therefore, only the Tb1 moments from the Flex PLI are compared to the tibia accelerations from the TRL legform in peak response analysis.

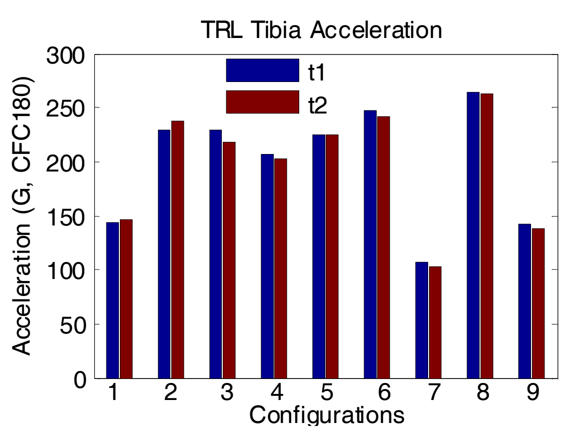

Figure 2. Peak Tibia Accelerations (TRL).

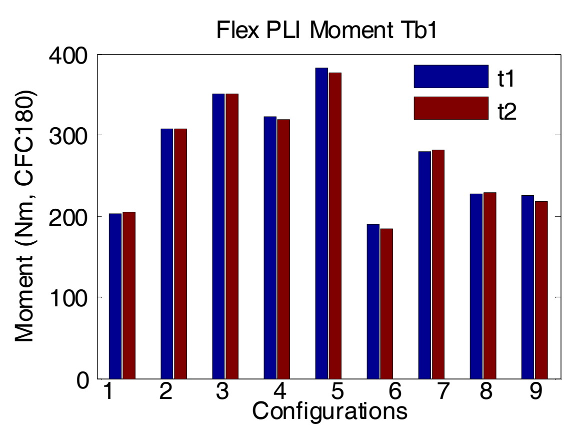

Figure 3. Peak Tb1 Moments (Flex PLI).

The configurations that produced maximum or minimum peaks for the tibia acceleration and Tb1 moment are presented in Table 3. The configurations that resulted in the maximum acceleration from the TRL legform included C1 (protruded LBS), while the configurations that resulted in the maximum Tb1 moment from the Flex PLI included C3 (recessed LBS). C3 created more rotation around the knee (observed from the video) which increased the moments in the tibia. The highest acceleration in the TRL legform occurred when it was impacted at the top quarter of the tibia, but the highest Tb1 in the Flex PLI occurred when both the top quarter and bottom quarter of the tibia were impacted. Similarly, the TRL legform obtained the minimum accelerations in the configuration that included C3, and the Flex PLI Tb1 tended to obtain the minimum in the configurations that included C1.

Table 3.
Maximum or Minimum Peaks in Terms of Configurations.

Variables	Configurations	Comments
Tibia Acc. Max (TRL)	8: A3B2C1D3	contains C1;
	6: A2B3C1D2	contains C1
Tb1 moment Max (Flex PLI)	5: A2B2C3D3	contains C3;
	3: A1B3C3D2	contains C3;
Tibia Acc. Min (TRL)	7: A3B1C3D2	contains C3;
Tb1 moment Min (Flex PLI)	6: A2B3C1D2	contains C1;

Peaks of the bending angle in the TRL legform and the MCL displacement in the Flex PLI are presented in Figures 4 and 5. Both legforms demonstrated considerable similarity in the ranking of the three maximum peaks. This might be due to the similar parameters measured in the two legforms. Bending angle in the TRL legform measures the relative rotation between the femur and the tibia. As the femur rotates with respect to the tibia, the MCL is approximately proportional to the multiplication of the relative rotating angle (similar to bending angle in the TRL legform) and the distance (almost constant) from the pivot point to the location of the measurement device of the elongation. It was observed that C3 is included in the two maximum peak response configurations (3 and 5).

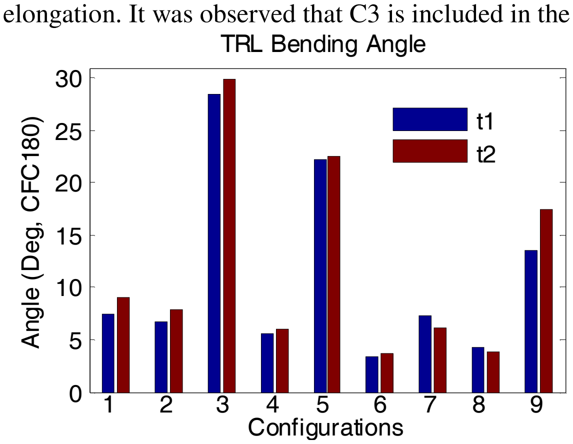

Figure 4. Peak Bending Angles (TRL).

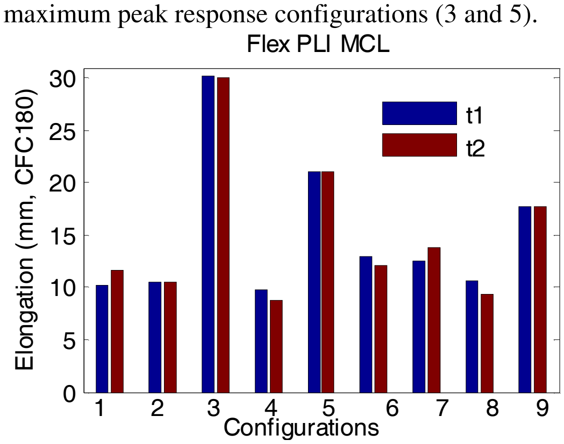

Figure 5. Peak MCL Elongations (Flex PLI).

The peaks of the shear displacement in the TRL legform and the ACL elongation in the Flex PLI are presented in Figures 6 and 7. These two parameters measure the relative translational motion between the femur and tibia. The two legforms responded to most test configurations inconsistently. The trends from one legform could not be predicted from the trends of the other legform. For example, configurations 3 and 9 produced peak shear displacement responses in the low range for the TRL legform, but they produced peak ACL elongation responses in the high range for the Flex PLI. Configuration 4 produced peak responses in the high range for the TRL legform, but it produced the peak responses in the low range for the Flex PLI.

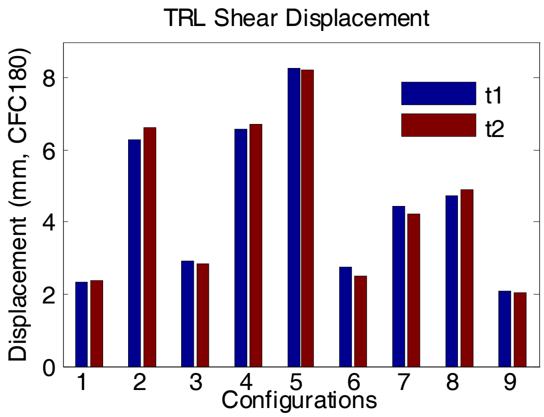

Figure 6. Peak Shear Displacements (TRL).

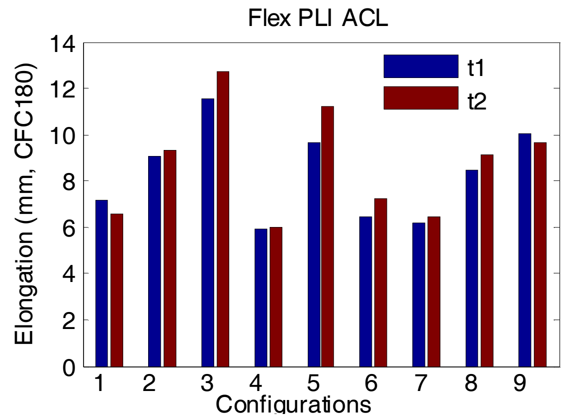

Figure 7. Peak ACL Elongations (Flex PLI).

Control Factor Analysis

The trends and sensitivities of S/Ns (signal to noise ratios) of the two legform responses due to the changes in the levels of the four factors are compared below. S/Ns for tibia acceleration from the TRL legform and Tb1 from the Flex PLI are overlaid in Figure 8. In general, the larger the change in the S/N with respect to an increment in a factor indicates the more sensitive the response is to that factor.

Tibia acceleration and Tb1 moment were affected by Factor A in a similar way, presumably due to the similar transducer locations. Both legform peak responses were influenced by Factor B consistently: there was a bumper position between B1 and B3 that would produce a minimum S/N. However, tibia moment Tb1 peak response in the Flex PLI and the acceleration in the TRL legform were influenced by Factor C in opposite directions. Tibia moment Tb1 peak response in the Flex PLI and the acceleration in the TRL legform were influenced by changing from factor D2 to D3 similarly but with different sensitivities.

The S/Ns for the bending angle from the TRL legform and the MCL elongation from the Flex PLI are presented in Figure 9. All four factors tended to affect the two parameters consistently, but with different sensitivities. The TRL legform was more sensitive to Factors A, C and D than the Flex PLI. The larger bumper section (A3), the lower bumper height (B1), and more forward alignment (protrusion) of LBS (C1) produced less rotation between the femur and tibia. Additionally, it indicates that there was a position between D1 and D3 for the LBS that would produce a maximum S/N.

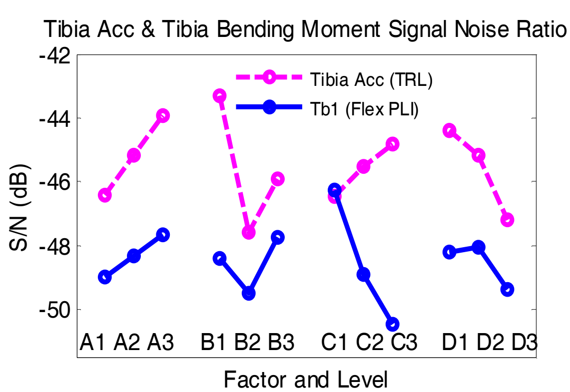

Figure 8. Factor Effects to Tibia Accelerations (TRL) and Tb1 Moments (Flex PLI).

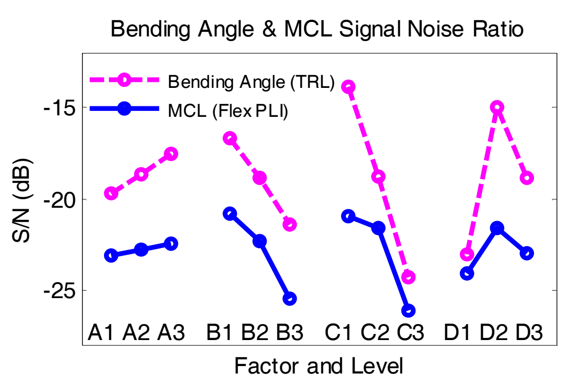

Figure 9. Factor Effects to Bending Angles and MCL Displacements.

The S/Ns for the shear displacement from the TRL legform and ACL elongation from the Flex PLI are presented in Figure 10. The two legforms were inconsistent in their responses to the factors changed in most configurations. With respect to the height of the bumper foam face (Factor A), the Flex PLI ACL was insensitive to the bumper face size. Recall that for control factor A only two values were tested (A1 and A2 were both 100 mm and used for configurations 1 through 6). The differences in S/N ratios between A1 and A2 are attributed to variability in the testing. Because the Taguchi method predicts trends from test outputs and test outputs are affected by test variability and noise factors it is not unusual for an S/N ratio to change for two control factors that are the same. The changes in S/N between A1 and A2 could be considered the limitations of the analysis (at least for control factor A, but not necessarily for the other control factors.) The differences between S/N ratios between A1 and A2 are, however, relatively low, as expected.

Control factor A3 (large bumper face) spans the tibia / femur interface in configuration 9 (see Figure B1). Thus tibia measurement trends would be expected to have discontinuities as the leg is moved up and down with the larger bumper face. This challenges the Taguchi method and trends with respect to control factor A should be interpreted accordingly. However, this geometric configuration is realistic and vehicles could indeed have bumper faces that span this area. As such trends identified in this study (such as the different trends between the two legs) are meaningful.

With respect to the location of the bumper (Factor B), the Flex PLI ACL was insensitive to the bumper height change from B2 (400mm) to B3 (450 mm) above the ground, while the TRL legform shear displacement was significantly sensitive to this change. The trends for both shear displacement and ACL varied differently to the heights of the LBS (Factor D). Only the protrusion of the LBS relative to the bumper (Factor C) affected both legform shear displacement and ACL displacement similarly, however with different sensitivities.

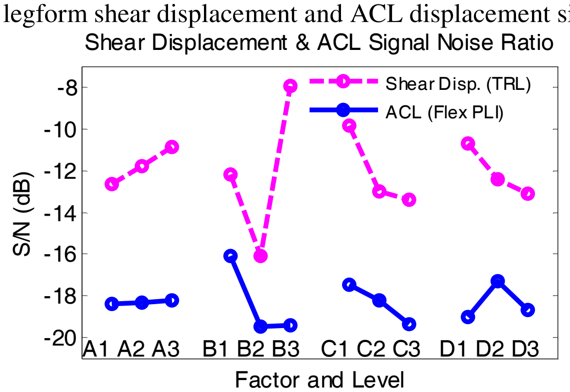

Figure 10. Factor Effects to Shear Displacement and ACL Displacement.

Repeatability Analysis

<u>TRL legform</u> The shape and magnitude correlations for the three parameters from the TRL legform tests are shown in Figures D2 and D3 (Appendix D). The shape and magnitude correlations of the TRL legform measurements are categorized in Table 4. Tibia acceleration of the TRL legform was repeatable in both shape and magnitude for all test configurations. Bending angle was repeatable in both shape and magnitude in only two of the nine test configurations. Shear displacement was repeatable in both shape and magnitude in six of the nine test configurations. Examples of repeatable time-histories for tibia acceleration, bending angle, and shear displacement from test configuration 4 are shown in the subplots of Figure D6, while non-repeatable time-histories for bending angle from test configuration 2 are shown in Figure D7.

Table 4.
Repeatability of TRL Legform Measurements.

Config.	Acc		Bending Angle		Shear Disp.	
	Shp	Mag	Shp	Mag	Shp	Mag
1	Y	Y	Y	N	Y	Y
2	Y	Y	M	N	Y	M
3	Y	Y	Y	M	M	N
4	Y	Y	Y	Y	Y	Y
5	Y	Y	Y	Y	Y	Y
6	Y	Y	Y	N	M	N
7	Y	Y	Y	N	Y	Y
8	Y	Y	Y	M	Y	Y
9	Y	Y	Y	N	Y	Y

Config. = Configuration
Shp=shape; Mag=magnitude;
Y: Repeatable; M: Marginal; N: Non-repeatable;

Flex PLI legform The shape and magnitude correlations from the Flex PLI tests for the six parameters are shown in Figures D4 and D5 (Appendix D). The results of the repeatability level for each parameter from the Flex PLI are categorized in Table5. Tb1, Tb2, Tb3, and ACL were repeatable or marginally repeatable in both shape and magnitude for all test configurations. Tb4 had non-repeatable shape for test configuration 3. It also had non-repeatable magnitudes for test configurations 1 and 7, but they were below the non-repeatable criteria (0.9) with small margin (0.90 and 0.89, respectively). MCL had a non-repeatable magnitude for test configuration 8. It was below the non-repeatable criteria (0.9) with a considerable margin (0.61). As an example, repeatable time-histories for moments Tb1 through Tb4 and MCL and ACL elongations from test configuration 4 are shown in the subplots of Figure D6, while non-repeatable time-histories for MCL from test configuration 8 are shown in Figure D8.

Table 5.
Repeatability of Flex PLI measurements by test Configuration.

Config.	Tb1		Tb2		Tb3		Tb4		MCL		ACL	
	Shp	Mag	Shp	Mag	Shp	Mag	Shp	Mag	Shp	Mag	Shp	Mag
1	M	Y	Y	Y	M	Y	Y	N	Y	M	M	Y
2	Y	Y	Y	Y	Y	Y	Y	M	Y	Y	M	M
3	Y	Y	Y	Y	M	Y	N	M	Y	Y	Y	Y
4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	M	Y
5	Y	Y	Y	Y	Y	Y	Y	Y	Y	M	Y	M
6	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
7	Y	Y	Y	M	Y	M	Y	N	Y	M	Y	M
8	M	M	Y	M	Y	Y	Y	Y	M	N	M	M
9	M	Y	M	Y	M	M	Y	M	Y	Y	Y	Y

Config. = Configurations;
Shp=shape; Mag=magnitude;
Y: Repeatable; M: Marginal; N: Non-repeatable;

Repeatability comparison The mean and standard deviation (Std) for the shape and magnitude repeatability were obtained by combining the 9 shape and magnitude correlations[2]. The mean plus and minus one Std of the correlations for all the parameters in the TRL legform and the Flex PLI are presented in Figures 11 and 12. In terms

[2] This does not imply that every configuration results in similar measured responses. The correlation coefficient across the two repeat tests for one configuration was then combined with the correlation coefficients from the other 8 configurations.

of the means of shape correlations and magnitude correlations, the tibia acceleration from the TRL legform and Tb1, Tb2, Tb3, and ACL from the Flex PLI were repeatable. The magnitude of bending angle in the TRL legform was non-repeatable. The magnitude of shear displacement in the TRL legform and Tb4 and MCL in the Flex PLI were marginally repeatable. However, the magnitude of the MCL in the Flex PLI had large standard deviation (Figure 12) which indicated that its repeatability was dependent on the test configurations: non-repeatable responses might be produced under some test conditions.

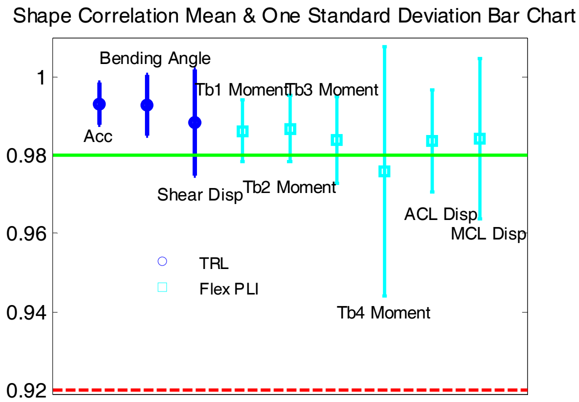

Figure 11. Means and one Std of Shape Correlations.

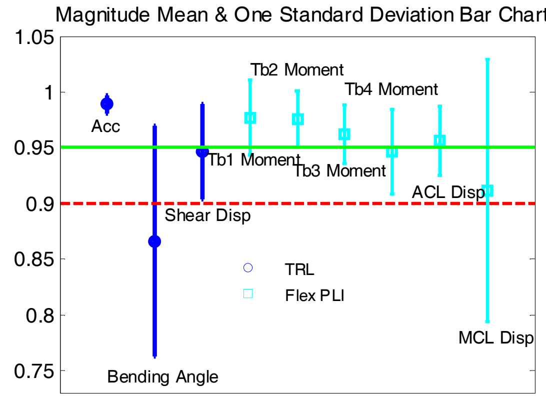

Figure 12. Means and one Std of Magnitude Correlations.

Limitations

The result on the level of the repeatability for these two legforms is limited in this study as there were only two repeat tests in this analysis. More repeat tests should be conducted to confirm the observations of this study.

The control factor analysis provided insights into the trends for the measured parameters with respect to the factor level changes. These trends could be further verified through additional confirmation tests. As an example, the limitation of only 2 repeat tests may have failed to fully quantify the trends associated with bumper foam height. The analysis suggested trends between A1/A2 (which were the same physical dimension) and A3 (which was larger) were insignificant, however more testing repeats may have better quantified the effects of the larger bumper foam height.

All tests were conducted at 32 km/h and neither legform was damaged. Additional tests at 40 km/h or higher should be conducted to confirm the durability of the legforms and if the repeatability changes.

Summary

Tibia acceleration in the TRL legform and tibia Tb1 bending moment in the Flex PLI reached their maximum peaks from different test configurations. The trends from the two legforms were inconsistent (in opposite directions) with respect to the change of LBS alignment with the bumper. This is possibly due to the difference in the mechanisms for producing the force/acceleration and the mechanism for producing the moment. As an example, for producing force/acceleration, the impact to the legform only occurs at one point. However, to produce a significant moment, either two (or more) impact points or one impact point and one (or more) fixed point reactions is required.

Shear displacement in the TRL legform and ACL elongation in the Flex PLI achieved the maximum peaks from different test configurations as well. In addition, to the increments of the four adjustable factors in the fixture, their sensitivities were different and some trends were inconsistent. The inconsistency might be due to the differences in transducer locations and knee designs.

Bending angle in the TRL legform and MCL elongation in the Flex PLI reached the maximum peaks from various configurations consistently, but with different levels of sensitivity.

Observations from the data indicate that the lowest responses (optimal responses) from the instrumentations between two legforms do not occur at the same vehicle front geometries. This could guide the design of the vehicle front structure differently.

Repeatability analysis indicated that across the spectrum of the test conditions in this study, some measured parameters had acceptable repeatability, but others were only marginal. Bending angle in the TRL legform had unacceptable repeatability. The MCL elongation in the Flex PLI is borderline non-repeatable under some test conditions, considering that its mean of overall magnitudes was close to the non-repeatable criteria (magnitude =0.9, Figure 12) and it exhibited a large standard deviation.

CONCLUSIONS

In general, inconsistencies in the responses between the TRL and Flex PLI legforms for the same changes to a generic LTV front geometry are identified in this study. These inconsistencies likely would drive differing vehicle designs depending on what legform was used.

The change to the horizontal alignment between the bumper and the lower bumper stiffener (Control Factor C) affected the "risk of leg bone fracture" assessment values (tibia acceleration in the TRL legform and tibia moments in the Flex PLI) in opposite directions. Contradictory design directions are likely depending on which legform is used.

The "risk of leg ligament tear by bending" assessment values (tibia bending angle in the TRL legform and MCL elongation in the Flex PLI) produced consistent trends but with different sensitivities in most impact configurations.

The "risk of leg ligament tear by shear" assessment values (shear displacement in the TRL legform and ACL elongation in the Flex PLI) produced inconsistent trends in most impact configurations.

Overall, the MCL displacement responses in the Flex PLI were marginally repeatable.

With the TRL legform, the tibia acceleration response was repeatable, but bending angle was not repeatable in some test conditions.

ACKNOWLEDGEMENT

JARI/JAMA loaned their Flex PLI Pedestrian Legform Impactor which made this evaluation program possible.

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APPENDIX A: TWO LEGFORMS

The TRL legform and Flex PLI are illustrated in Figures A1 and A2. The locations of their instrumentations are presented in Figures A3 and A4.

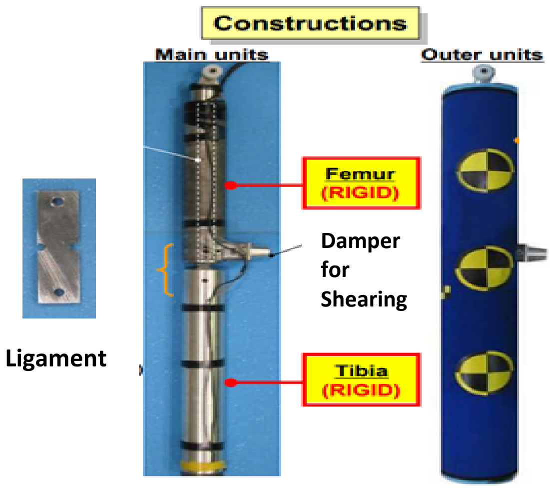

Figure A1. TRL Legform Construction.

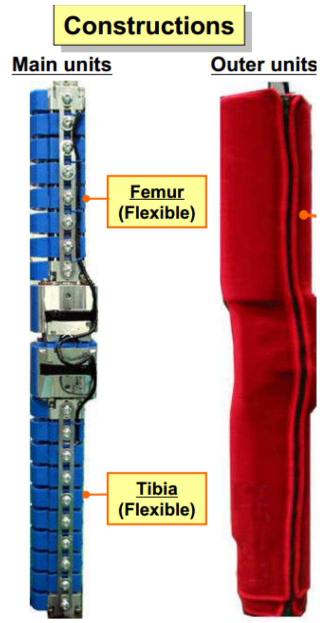

Figure A2. Flex PLI GT Legform Construction.

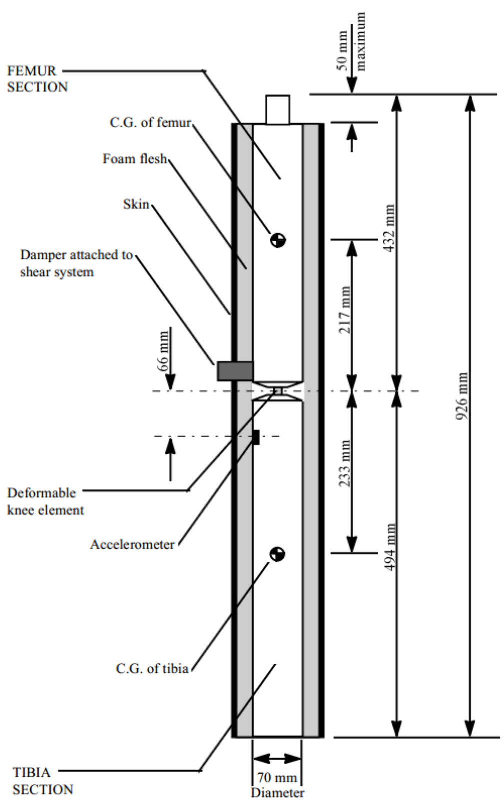

Figure A3. TRL Legform Instrumentation.

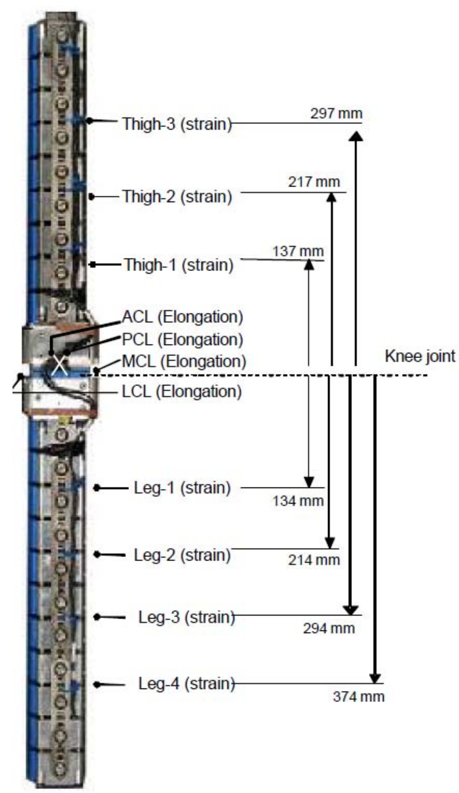

Figure A4. Flex PLI Instrumentation.

APPENDIX B: TEST CONFIGURATIONS

Nine test configurations with the TRL legform and its alignment with the fixture are presented in Figure B1. The configurations with the Flex PLI are similar. The distances from the bottom of the legform to the ground are different for the two legforms: 25mm for the TRL legform and 75mm for the Flex PLI according to the test protocols for the standard tests. With the additional information provided in Tables 1 and 2, as well as in Figures A3 and A4, the positions of the transducers in the legforms with respect to the test fixture can be obtained.

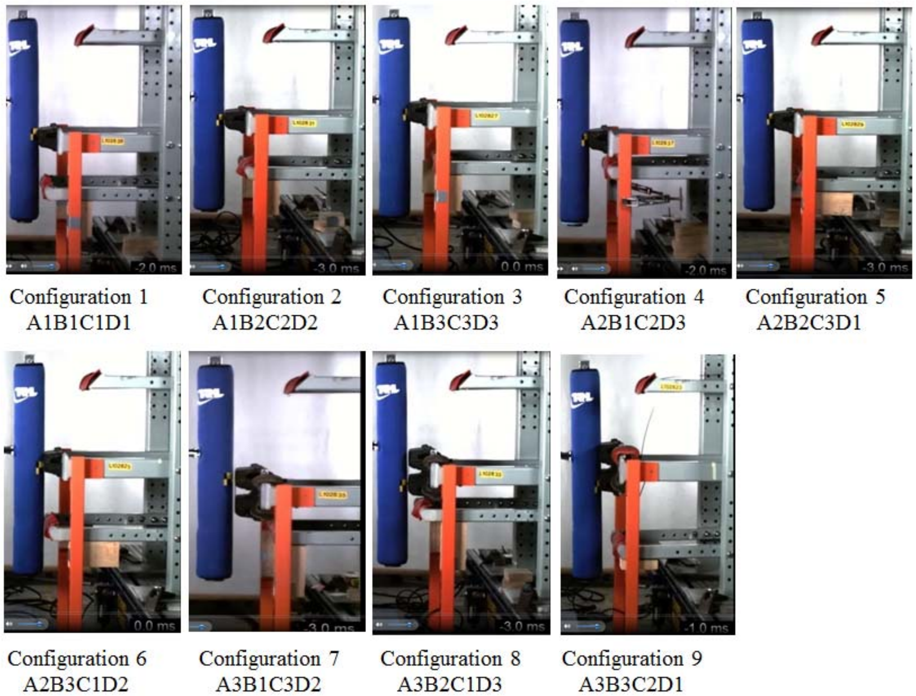

Figure B1. Nine Test Configurations.

APPENDIX C: ILLUSTRATION OF LOAD AND MOMENT TO THE LEGFORM

The moment distribution estimated from elementary linear beam theory for a beam subjected to concentrated and distributed loads is shown in the Figure C1. F_{kn} represents the force from the knee and w_1 and w_2 represent the inertial loading distributions.

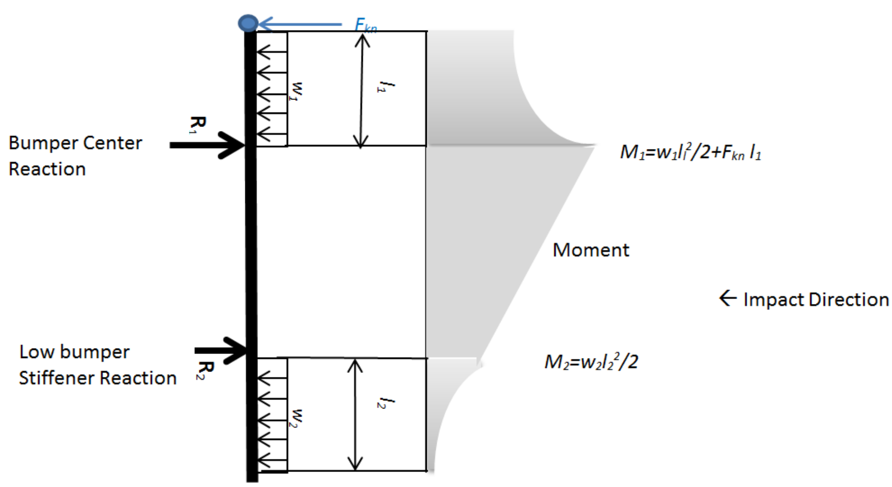

Figure C1. Illustration of Moments in a Beam.

APPENDIX D: TEST RESULTS

Peak Moment Response and Signal to Noise Ratio

Peak responses (absolute peak values) for four tibia moments from the Flex PLI are presented in Figure D1.

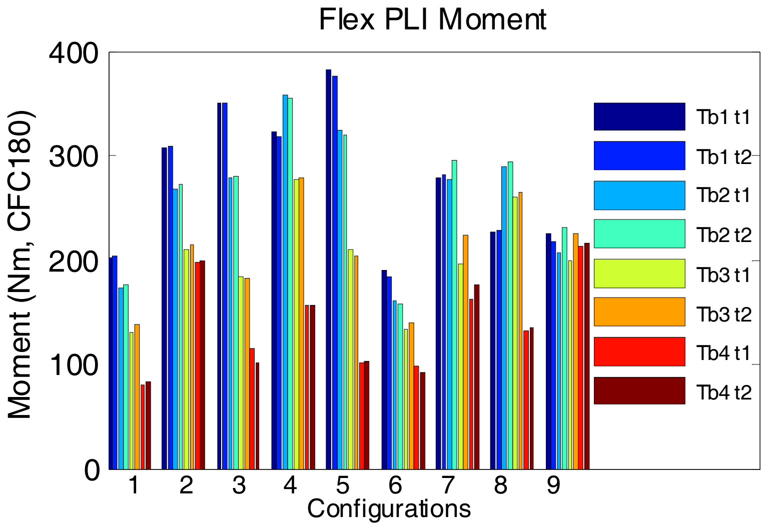

Figure D1. Peak Moments from the Flex PLI.

Signal to noise ratios, S/Ns, are contained in Table D1. The S/Ns for each factor level are in Table D2. The procedure to compute the S/Ns from B1, B2, B3, C1, C2, C3, D1, D2, and D3 are similar: take the S/Ns from the three configurations that include a factor at the same level, and then average them. As an example, when calculating the effect from factor B1 for parameter Tb1 (column 5), the S/N values in Table D1 from configurations 1, 4, and 7 (rows 3, 6, and 9) are used.

There is a slight difference in calculating the effects from factor A, considering A2=A1 in this series of tests. When calculating the effects from A1, the average of six S/N values from six configurations including A1 is the S/N value from A1. The calculation of S/N from A3 is the same as those from the Bs, Cs, and Ds. Once the S/Ns from A1 and A3 were obtained, the S/N from A2 is just the average of the S/Ns from A1 and A3.

Table D1.
Signal Noise Ratios from the TRL and the Flex PLI Legforms.

	Acc	**Angle**	**Shear**	**Tb1**	**Tb2**	**Tb3**	**Tb4**	**MCL**	**ACL**
Configuration									
1 A1B1C1D1	-43.2	-18.3	-7.4	-46.2	-44.8	-42.6	-38.2	-20.8	-16.8
2 A1B2C2D2	-47.4	-17.4	-16.2	-49.8	-48.6	-46.5	-45.9	-20.5	-19.3
3 A1B3C3D3	-47.0	-29.3	-9.2	-50.9	-48.9	-45.3	-40.7	-29.6	-21.7
4 A2B1C2D3	-46.2	-15.2	-16.4	-50.1	-51.0	-48.9	-43.9	-19.4	-15.5
5 A2B2C3D1	-47.0	-27.0	-18.3	-51.6	-50.1	-46.3	-40.2	-26.5	-20.4
6 A2B3C1D2	-47.8	-11.0	-8.4	-45.4	-44.1	-42.7	-39.6	-22.0	-16.7
7 A3B1C3D2	-40.4	-16.6	-12.7	-49.0	-49.1	-46.4	-44.6	-22.4	-16.0
8 A3B2C1D3	-48.4	-12.2	-13.7	-47.1	-49.3	-48.4	-42.5	-20.1	-18.9
9 A3B3C2D1	-43.0	-23.9	-6.3	-46.9	-46.8	-46.6	-46.6	-25.0	-19.9

Table D2.
Signal Noise Ratios Affected by Different Control Factors and Levels.

Factor	Acc	Tb1	Tb2	Tb3	Tb4	Angle	MCL	Shear	ACL
A1	-46.4	-49.0	-47.9	-45.4	-41.4	-19.7	-23.1	-12.7	-18.4
A2	-45.2	-48.3	-48.2	-46.2	-43.0	-18.6	-22.8	-11.8	-18.3
A3	-43.9	-47.7	-48.4	-47.1	-44.6	-17.6	-22.5	-10.9	-18.2
B1	-43.3	-48.4	-48.3	-46.0	-42.2	-16.7	-20.8	-12.2	-16.1
B2	-47.6	-49.5	-49.4	-47.1	-42.9	-18.8	-22.3	-16.1	-19.5
B3	-45.9	-47.7	-46.6	-44.8	-42.3	-21.4	-25.5	-8.0	-19.4
C1	-46.5	-46.3	-46.1	-44.5	-40.1	-13.8	-20.9	-9.8	-17.5
C2	-45.5	-48.9	-48.8	-47.3	-45.5	-18.8	-21.6	-13.0	-18.2
C3	-44.8	-50.5	-49.4	-46.0	-41.8	-24.3	-26.1	-13.4	-19.4
D1	-44.4	-48.2	-47.3	-45.2	-41.7	-23.1	-24.1	-10.7	-19.0
D2	-45.2	-48.1	-47.3	-45.2	-43.4	-15.0	-21.6	-12.4	-17.3
D3	-47.2	-49.4	-49.8	-47.5	-42.4	-18.9	-23.0	-13.1	-18.7

Shape and Magnitude Correlations

The results for shape and magnitude correlations are presented in Figures D2 to D5. The green lines are the repeatable criterions and the red lines are the non-repeatable criterions in those figures (conf.=configurations).

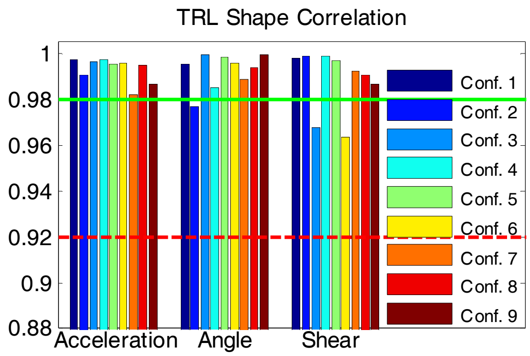

Figure D2. Shape Correlations (TRL).

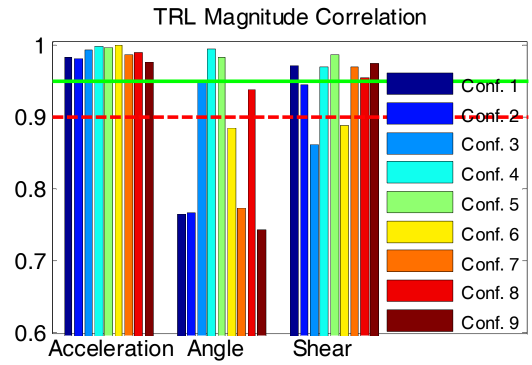

Figure D3. Magnitude Correlations (TRL).

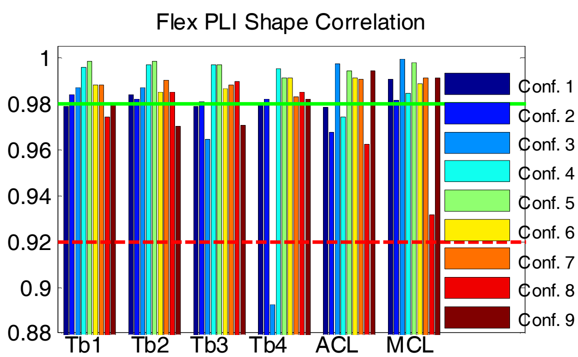

Figure D4. Shape Correlations (Flex PLI).

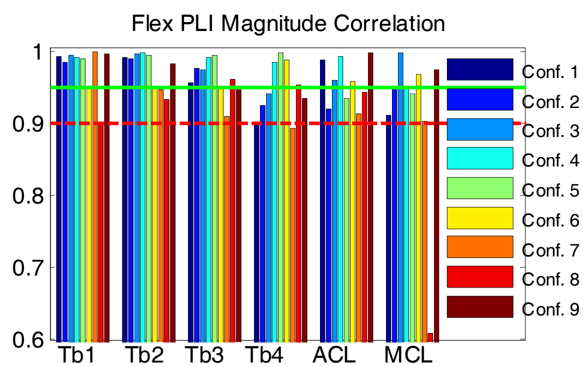

Figure D5. Magnitude Correlations (Flex PLI).

Selected Time Histories

The time histories from test configuration 4 for nine measurements of both legforms are presented in Figure D6 to illustrate the repeatable time-histories. The time histories for the bending angles from test configuration 2 and MCL from test configuration 8 are presented in Figures D7 and D8 to illustrate the non-repeatable time-histories.

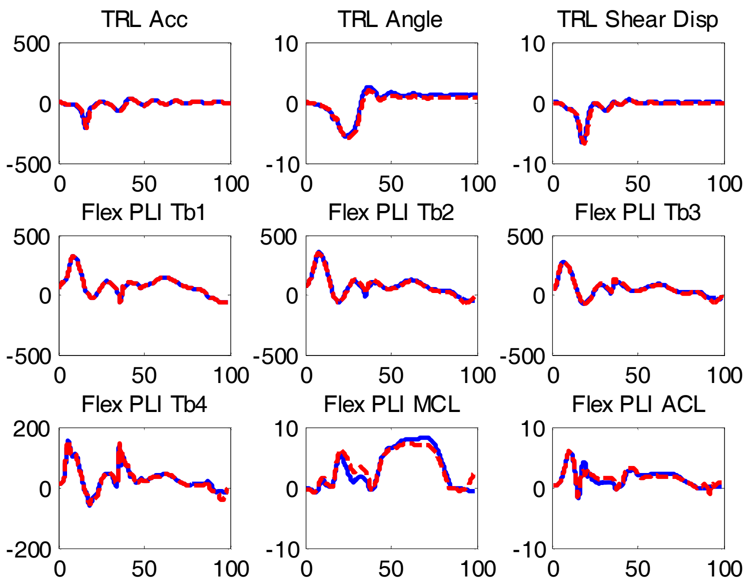

Figure D6. Nine Measurement Response Time-histories from Test Configuration 4.

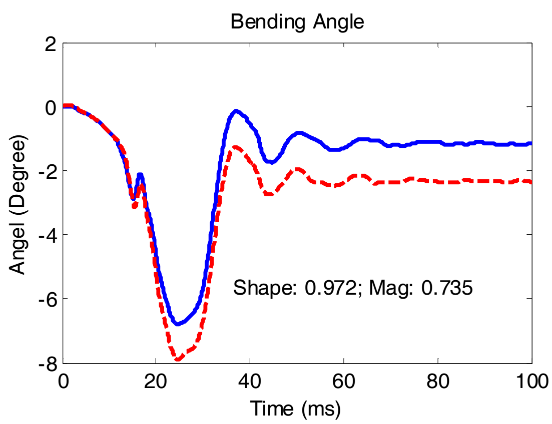

Figure D7. Bending Angles from Test Configuration 2.

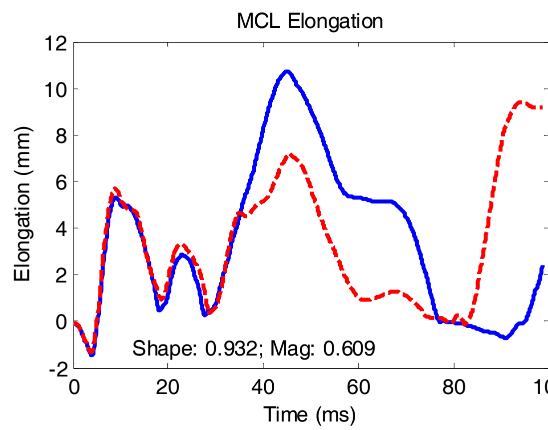

Figure D8. MCLs from Test Configuration 8.

APPENDIX E: SHAPE AND MAGNITUDE CORRELATION METHOD

Definitions

Given two signals denoted as, X: x_i; and Y: y_i. The definitions for the shape correlation and magnitude correlation between X and Y are given in the following.

1. Norm $||X|| = \sqrt{\sum x_i^2}$; $||Y|| = \sqrt{\sum y_i^2}$;
   The average of the two is
   $Mxy = (||X|| + ||Y||)/2;$ (E1)

2. *Shape* correlation:

In general, the shape correlation is defined as
$\max(\sum_j x_i * y_{i+j}/(\|X\| * \|Y\|))$ (E2)

3. Magnitude correlation: $Mx= \|X\| /Mxy;$ $My= \|Y\| /Mxy;$ $Mx+My=2$ (E3)

It should be noted that one of the magnitudes is greater than or equal to one and the other less than or equal to one. Magnitude that is less than or equal to one is used throughout this study.

Repeatability Standards

Two signals with both the shape correlation greater than 0.98 and the magnitude correlation greater than 0.95 are deemed to have acceptable repeatability. Two signals with the shape correlation less than 0.92 or the magnitude correlation less than 0.9 are deemed to have unacceptable repeatability. Two signals with the shape correlation between 0.92 and 0.98 and the magnitude correlation of 0.9 or above, or with the magnitude correlation between 0.9 and 0.95 and the shape correlation of 0.92 or above are deemed to have marginal repeatability.

Figures E1 illustrated the signals that have both repeatable shape and magnitude correlations (shape > 0.98 and magnitude >95) for any set of two curves. Figures E2 illustrated the signals that have both non-repeatable shape and magnitude correlations (shape < 0.92 and magnitude <0.9) for any set of two curves.

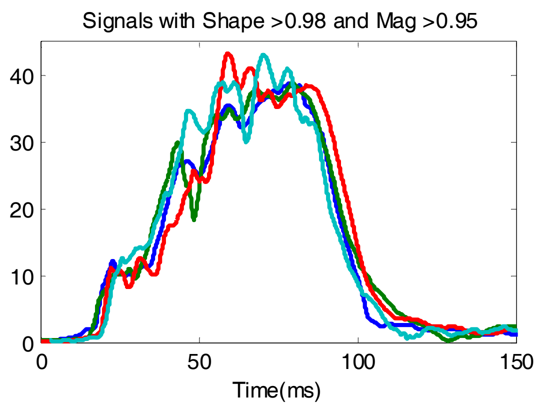

Figure E1. Repeatable Signals.

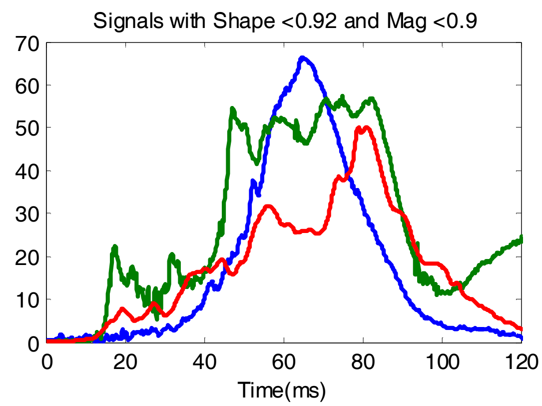

Figure E2. Non-repeatable Signals.