

VALIDATION STUDY

XSENSOR's High Speed Impact Sensor Validation

A study confirming the accuracy and reliability of XSENSOR's High-Speed Impact pressure imaging system.

XSENSOR

Intelligent
Dynamic
Sensing

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Introduction

Pressure imaging has been widely used in the medical and automotive fields to analyze the interaction between individuals and surfaces, such as seats and beds. In the automotive sector, pressure imaging has primarily focused on evaluating seating comfort and design in static and quasi-static conditions.

In 2017, XSENSOR introduced the High-Speed Impact (HSI) pressure imaging system, designed to capture 2D pressure data during dynamic events such as rear-seat impacts, head restraint interactions, and airbag deployments.

Accuracy and repeatability of impact measurements are crucial for several reasons. Namely, to ensure that data collected at test site A will be consistent with data collected at test site B, and also that there is the utmost confidence that identical tests that are repeated days/weeks/months apart will provide the same results. This is important not only in crash testing, but in product design and validation, sports science, and patient safety in medical applications.

XSENSOR's pressure imaging sensors utilize two arrays of conductive elements arranged in a grid. A compressible dielectric material is sandwiched between each grid point, forming an array of capacitors. As pressure is applied, the dielectric compresses proportionally, resulting in a measurable change in voltage. This voltage is then converted into a pressure value by the HSI electronics, generating a 2D pressure map of the interface.

This 2-dimensional pressure map enables us to record the entire interaction between the two surfaces throughout the entire impact, rather than relying on data from a single load cell located at a single point. In the case of a seatbelt, we can visualize how the seatbelt interacts with the Anthropomorphic Test Device (ATD) over the entire torso, which can show areas of localized low pressure indicating perhaps no or poor contact between the seatbelt and ATD, or areas of extremely high pressure (potentially indicating areas of excessive force), which may cause further injury to the occupant.

This study will examine the performance of the HSI sensors and demonstrate the accuracy and repeatability of the sensors in controlled conditions that replicate scenarios that would be experienced in automotive crash testing.

Equipment

Sensor Array

The sensors used for this study were HX210:36.48.05M vest sensors. The sensors have 36 columns and 48 rows, comprising an array of 1728 individual sensing elements (sensels) that are 5 mm x 5 mm in size. The sensors are integrated into a vest that is designed to be worn by the ATD. As each column is energized, all rows are sampled in parallel. When completed, the next column is energized and the process repeated until the entire sensor has been scanned. This constitutes one frame. Three different sensors were used: S0081, S0088, and S0089.

Each sensor is calibrated from 1 to 300 psi (approximately 0.7 – 207 N/cm²) and can record at 3291 complete frames per second – 1728 individual pressure values 3291 times per second.

Pendulum, Instrumentation, & Target

The pendulum consisted of a solid machined aluminum bob with a mass of 20.61 kg. The bob was suspended using 4 steel wires approximately 220 cm long, connected to low-friction pulleys. The end caps were detachable from the central dogbone portion, allowing the weight to be adjusted. A 3D printed cap was fit over the impacting surface with a variable radius of curvature depending on the drop height (381 mm diameter for low severity, 508 mm for high severity). This allowed us to adjust the pressure distribution on the sensor for various impact forces, thereby providing a good spread of pressure values across the calibration range.

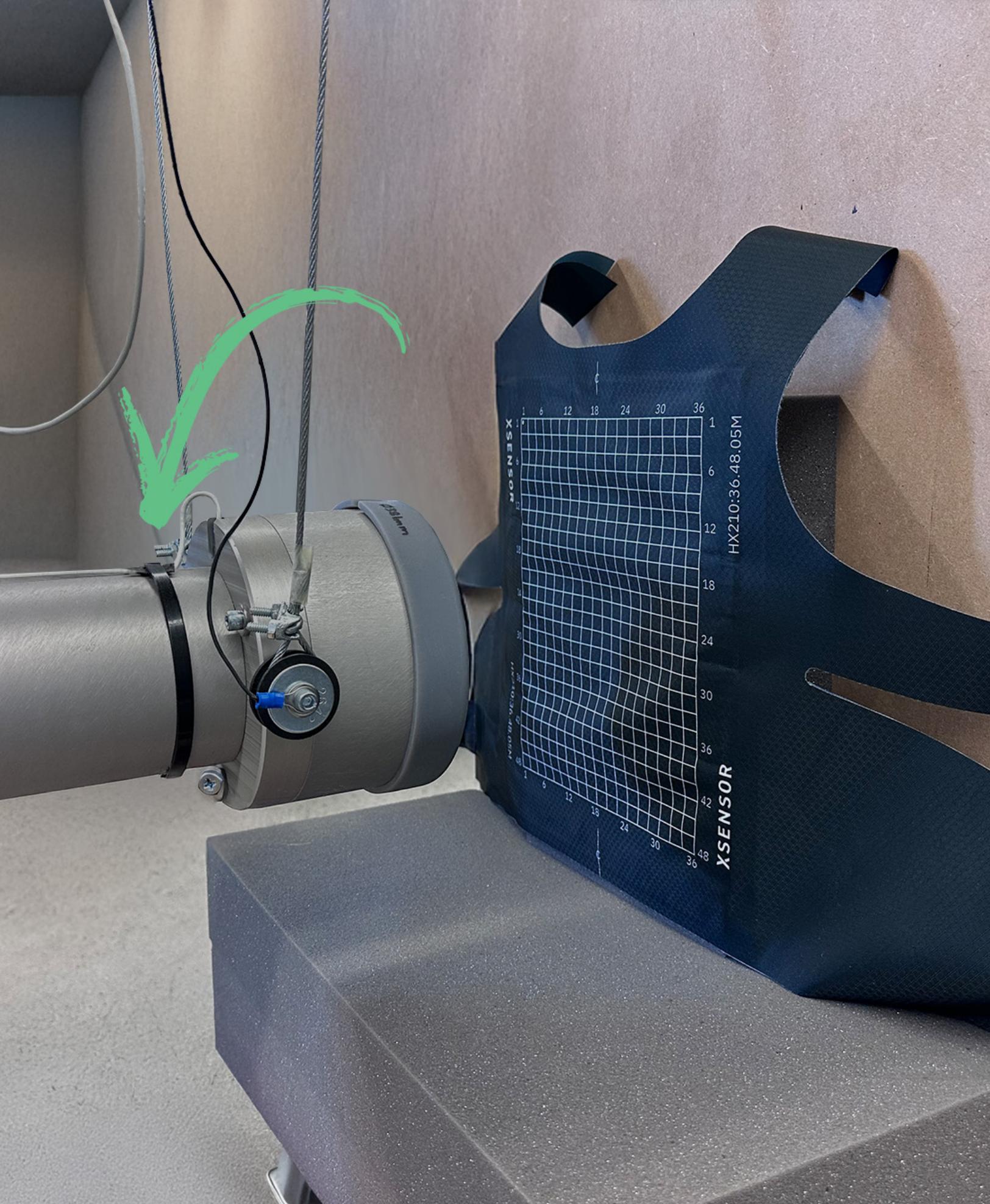
A wood target was constructed, reinforced, and attached to the floor to ensure minimal movement during an impact. A 3" thick high-density foam block (2080BK foam, 1.95-2.05 lbs/cuft, 80+ ILD) was placed on the target, and the sensor was mounted such that the entire sensing area covered the foam. The foam was replaced with a new piece after every high-severity impact. For low-severity impacts, the foam was flipped between tests, and a new region was impacted. The accelerometer (Endevco Model 7264B-2000T) was mounted to the impacting portion, shown in Figure 1 by the green arrow. Data from the accelerometer was recorded by a Keysight DAQ970A Data Acquisition System equipped with a DAQM909A 4 Channel Simultaneous Sampling Module, which had a sampling rate of 50 kHz.

The pendulum was dropped from two different heights to achieve two different severities of impact. The targets were 10-15 g (low) and 45-50 g (high) in order to mimic peak conditions in various types of crash testing. The release mechanism was a manually actuated quick-release cable.

The power for all equipment was supplied from a battery using an onboard inverter to generate AC power. There was some minor noise from the switch-mode converter present in the accelerometer signal, but this was filtered in post-processing.

The pendulum was grounded to an earth ground on an electrical outlet via a wire.

Anti-static spray was applied to the sensor and pendulum cap as needed.



Data Collection & Processing

A remote pushbutton was used to trigger the recording on both the Keysight and XSENSOR data loggers.

When each test was completed, the data was transferred to a PC and exported into an analysis template in Microsoft Excel. Some minor manual time alignments were required to account for the different sampling speeds between the XSENSOR and Keysight data loggers.

An adjacent averaging smoothing algorithm was used to remove the power supply noise in the accelerometer. Figure 2 shows an example of the raw accelerometer data and the smoothed data (low severity).

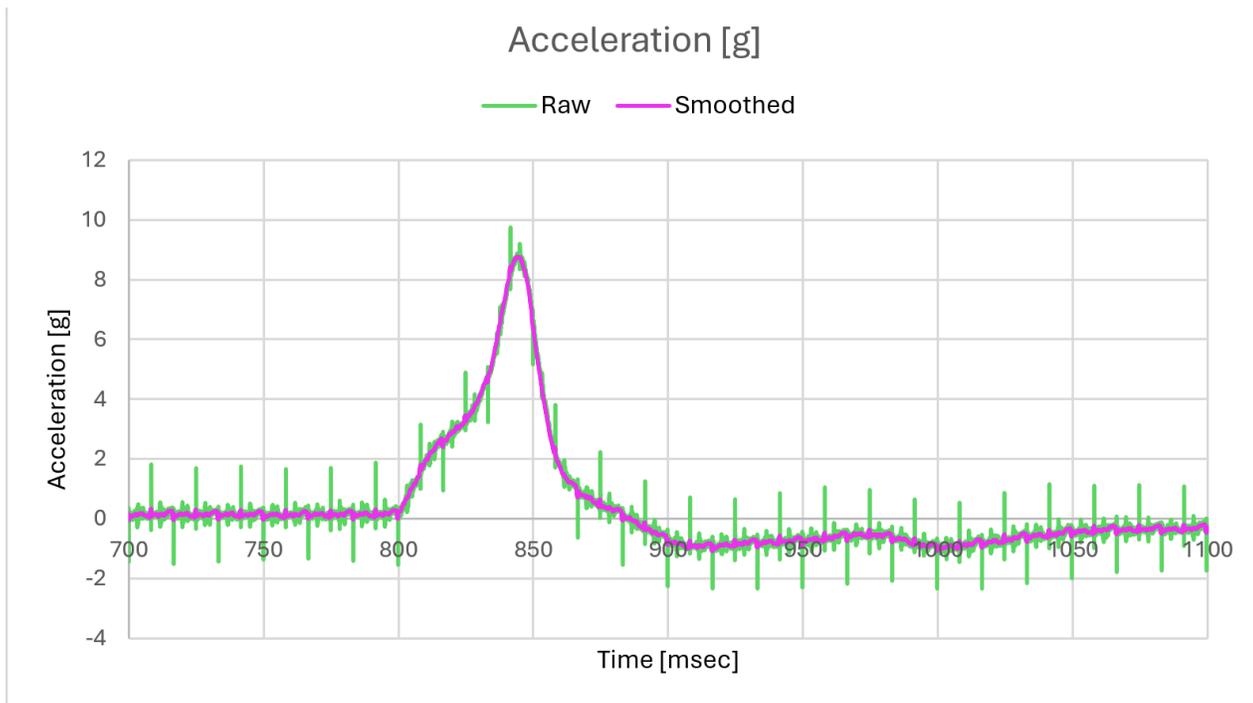


Figure 2 Raw and smoothed accelerometer data.

DATA COLLECTION & PROCESSING

Next, the overlaid force curves from the vest sensor and the accelerometer (high severity, Figure 3):

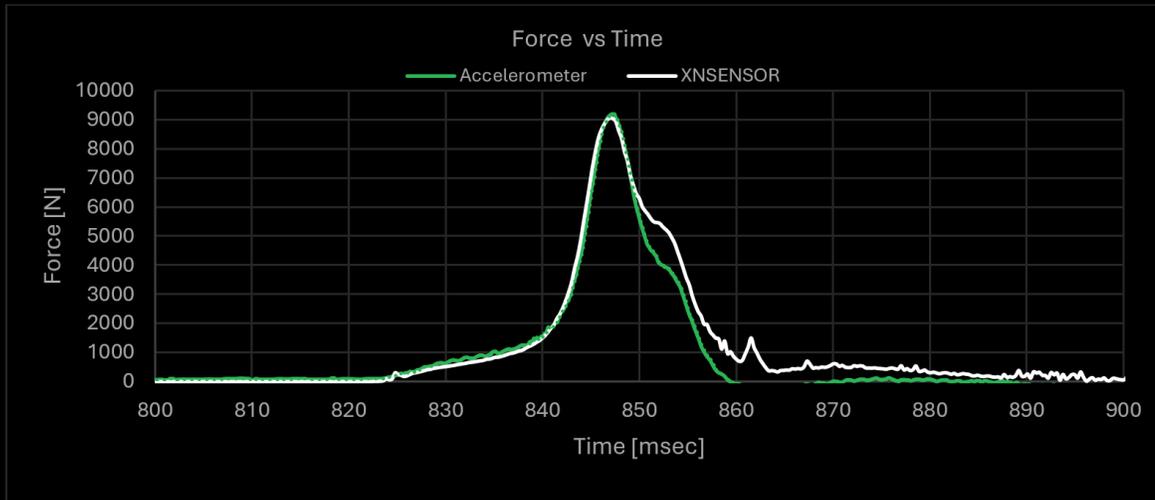


Figure 3 Typical force vs time curves from the accelerometer and Xsensor vest sensor

In most cases, there was an approximate 1.4 msec offset between the original data that needed to be manually corrected. All of the tests had some degree of offset, which needed to be corrected.

When comparing statistics between sessions and sensors, all of the values used for comparison were taken at the peak force moment in time:

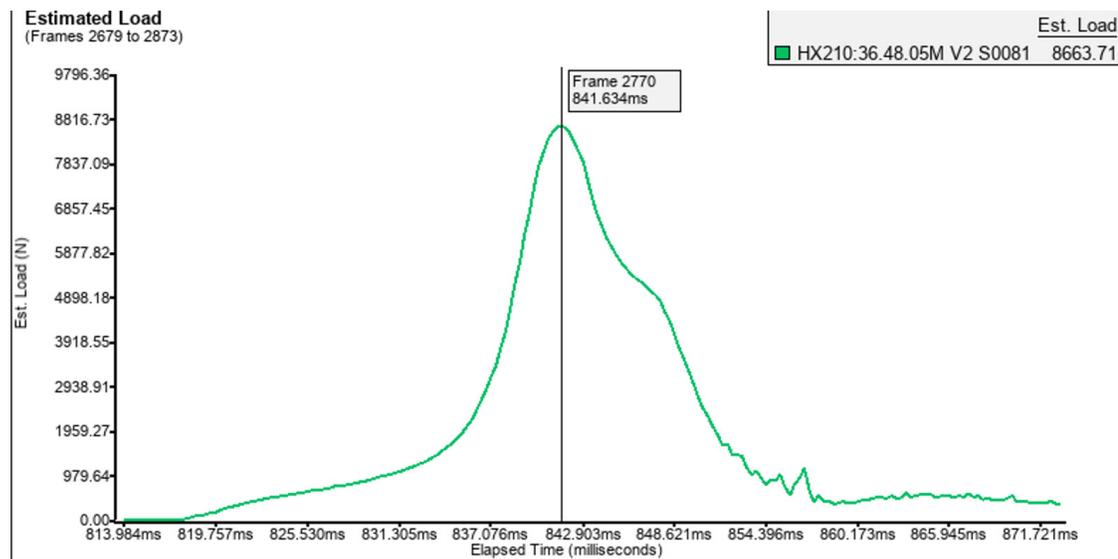


Figure 4 Location where peak average pressure and estimated force were measured and used for comparison between sessions and sensors.

Analysis Methods

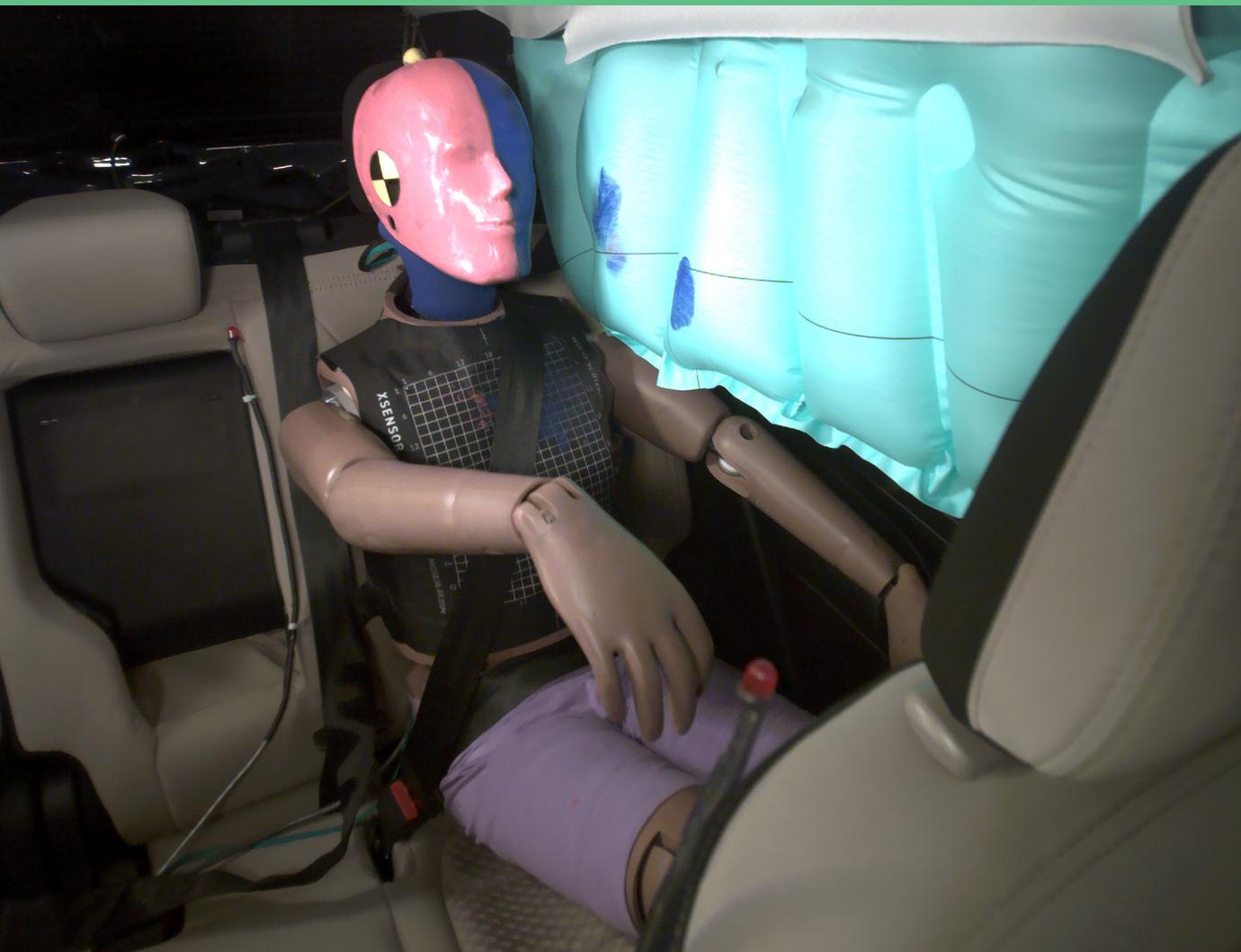
We used several different metrics to quantify the accuracy and repeatability of the experiments.

First, we used the accelerometer force measurements as the reference to compare the estimated load from the XSENSOR vest sensors against. The estimated load is determined by multiplying the pressure for each sensel by the area of the cell and then summing over the entire frame.

For all cases, we used the peak accelerometer force and the peak XSENSOR force and compared these values. Because there was variability in each test (drop height variations, foam variations, etc.), performing a simple standard deviation analysis was not a suitable method to characterize the repeatability of the tests. Instead, we performed a paired t-test, assuming unequal variances between the accelerometer force and the XSENSOR force, to determine if there were statistically significant differences between them at a significance level of 0.05, along with ANOVA analysis on the distributions.

We also calculated the correlation coefficient and r^2 coefficient of determination for each data set. The margin of error for each dataset was also determined at the 99% level.

Image courtesy of Insurance Institute for Highway Safety



Low Severity Data

Overlaying all 90 tests for the low-severity accelerometer force data:

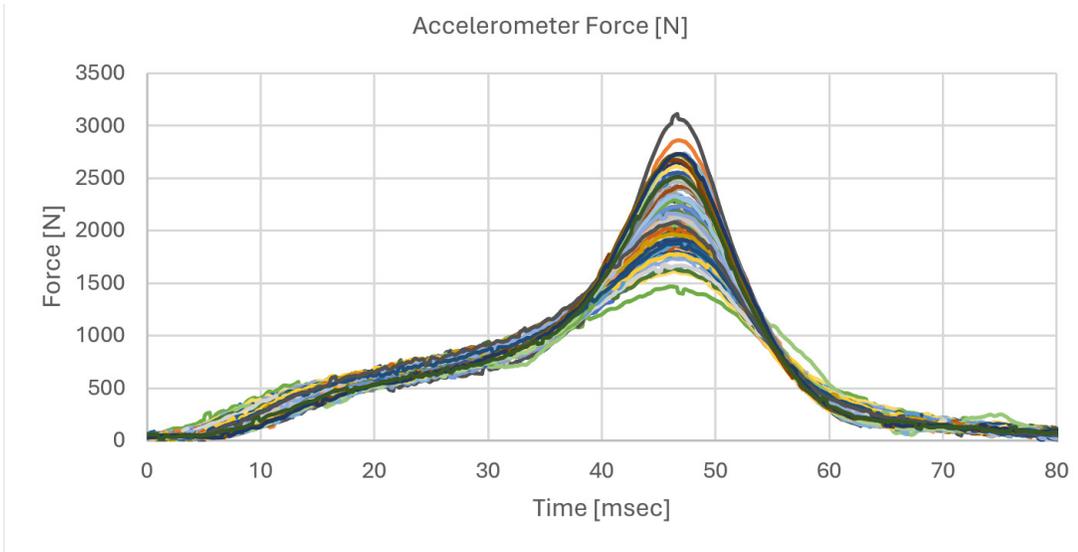


Figure 5 All accelerometer curves (3 sensors, 30 tests each) superimposed.

And from the pressure sensor:

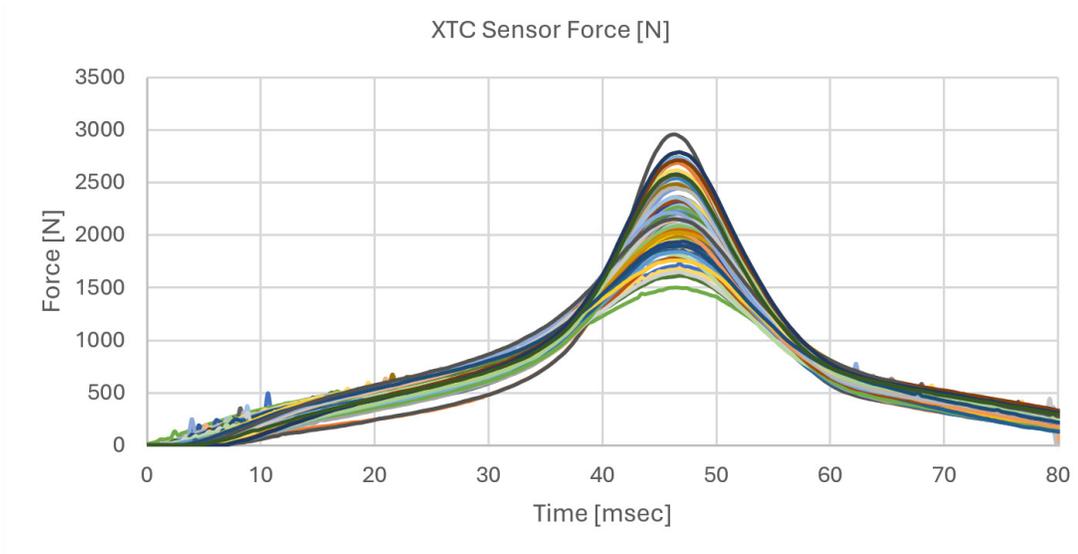


Figure 6 XSENSOR estimated force (3 sensors, 30 tests each) superimposed.

Even though we attempted to drop the pendulum from the same height, there were some variations in the drop height (± 2 cm), which resulted in peak force variation. The variation was also observed in the accelerometer data, and the XSENSOR data tracks the accelerometer data very well.

— LOW SEVERITY DATA

If we average all of the accelerometer curves and overlay them with the averaged XSENSOR curves, we see:

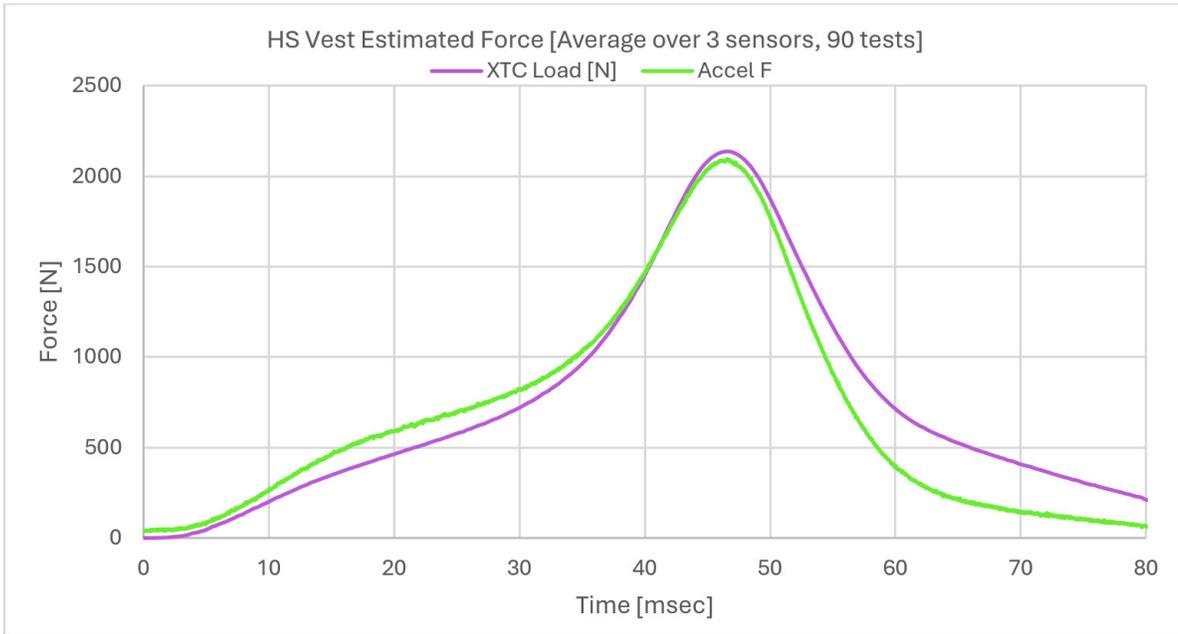


Figure 7 Average curves for accelerometer force and XSENSOR vest force.

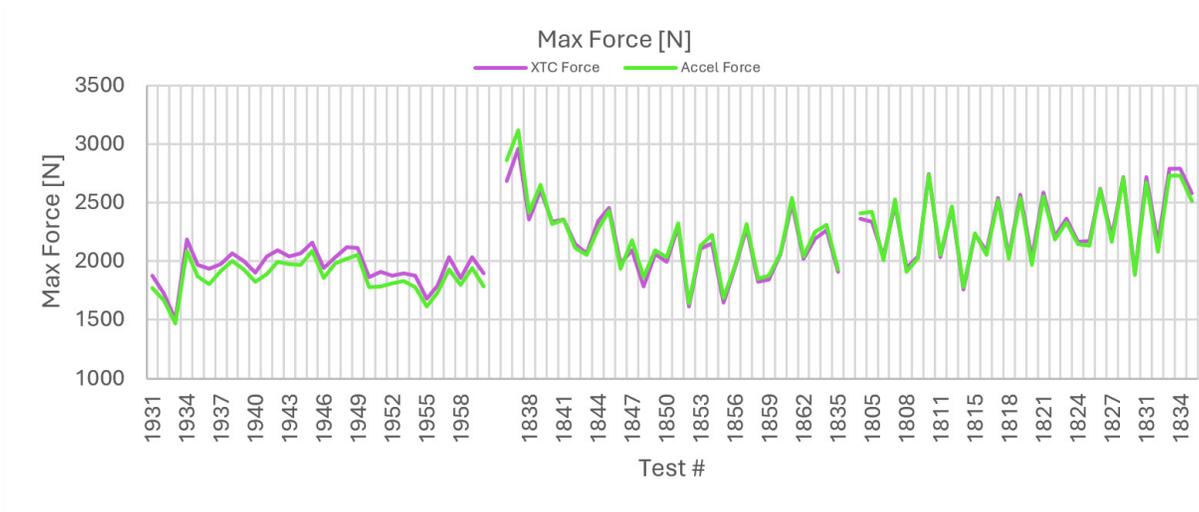


Figure 8 Max force for accelerometer and XSENSOR vest over all tests (low severity)

LOW SEVERITY DATA

Table 1 Statistics for XSENSOR vest and accelerometer impacts for low severity tests.

	XSENSOR		ACCELEROMETER			CI	z*	Margin of error		
	Max psi	XTC Force	Max g	Accel Forc	Facc-Fxtc			F_XTC	F_accel	
avg	12.7	2144.4	10.5	2121.0	54.4	95%	1.96	61.4	66.5	
stdev	1.7	297.4	1.6	321.8	37.4	98%	2.326	72.9	78.9	
2s	3.5	594.8	3.2	643.6	74.8	99%	2.576	80.8	87.4	
2s as %FS	1.2%				3.5%	2s as rel % from accel avg				
2s as rel %		27.7%	30.5%	30.3%	3.5%	2s as rel % from xtc avg				

The XSENSOR averaged peak force is 2144 N, with an 81 N margin of error at 99%.

The accelerometer's averaged peak force is 2121 N, with a 87 N margin of error at 99%.

The average delta between the peak forces is 54 N ± 75 N at k = 2.

We also calculated the correlation coefficient between the accelerometer force and XSENSOR force to be 0.9838, indicating an extremely strong positive correlation, and the coefficient of determination (R²) as 0.9348.

Individually, the estimated load measured by the vest sensor seems to track with the accelerometer force measurements.

t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	Variable 2
Mean	2144.393	2120.985
Variance	88444.34	103565
Observations	90	90
Hypothesized Mean Difference	0	
df	177	
t Stat	0.506798	
P(T<=t) one-tail	0.306464	
t Critical one-tail	1.653508	
P(T<=t) two-tail	0.612927	
t Critical two-tail	1.973457	
Null Hypothesis:		
XTC data is the same as accelerometer data		
Conclusion		
They are statistically the same with 61.3% certainty		

LOW SEVERITY DATA

Examining the histograms in Figures 10 and 11, both are normal-type distributions with a slight right skewness.

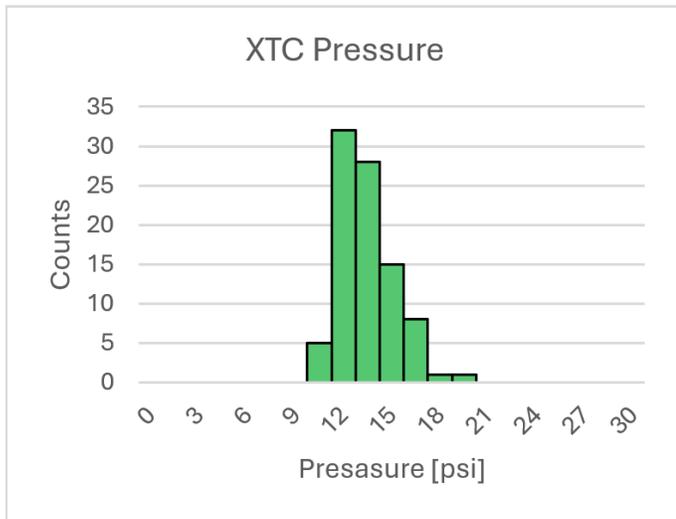


Figure 9 XSNESOR pressure histogram.

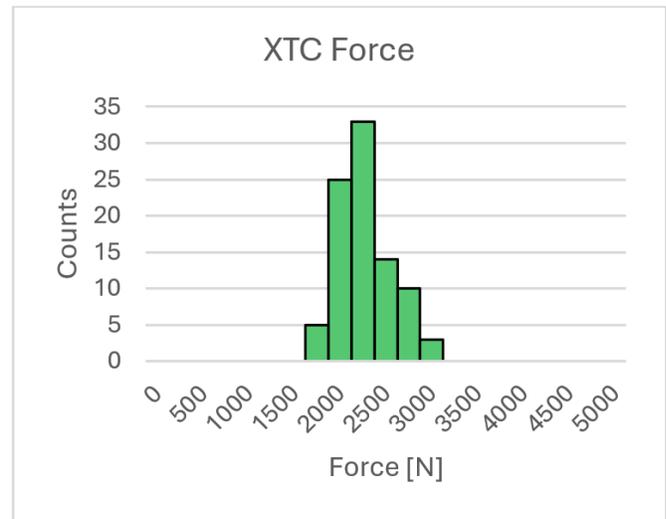


Figure 10 XSENSOR force histogram

From the accelerometer force data:

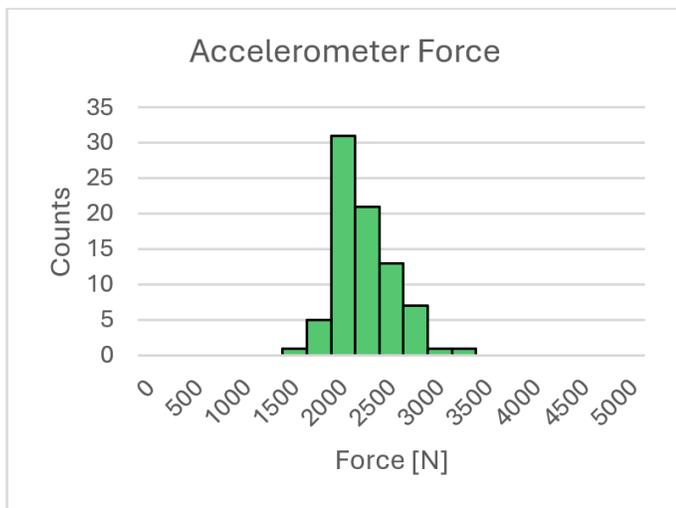


Figure 11 Accelerometer force histogram

LOW SEVERITY DATA

Similar to the XSENSOR data, the distribution is normal with a slight right skew.

We can plot the XSENSOR estimated force as a function of the accelerometer-measured force for all of the high-severity tests:

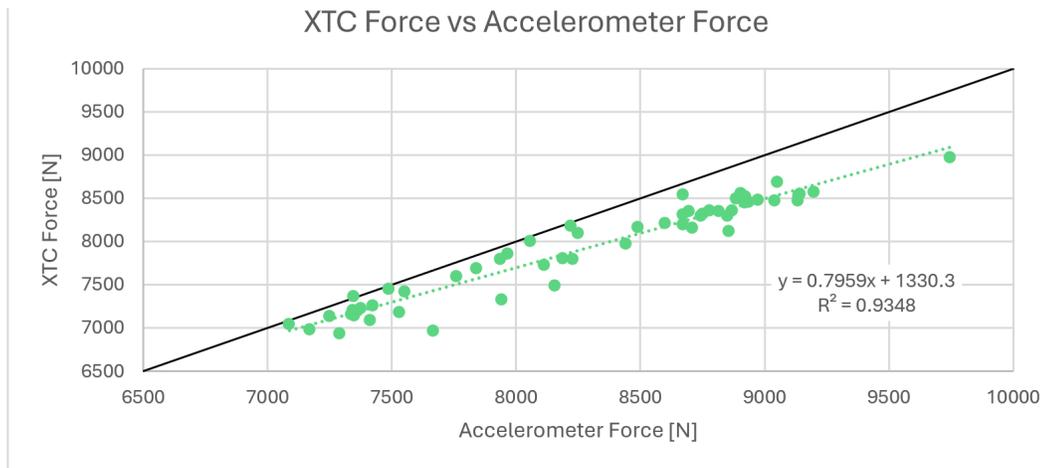


Figure 12 XSENSOR estimated force as a function of the force measured by the accelerometer for all high severity tests. The black line denotes a slope of 1.

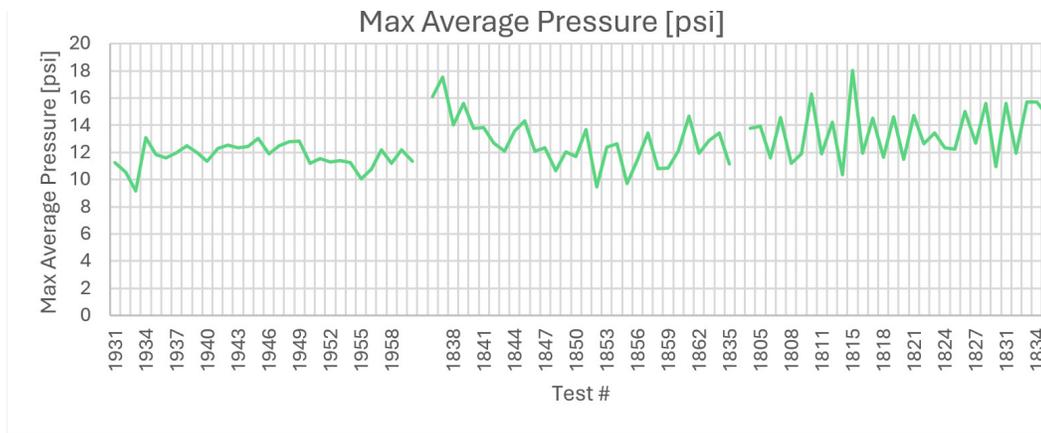


Figure 13 Average pressure of the low severity pendulum impact at the point of maximum force.

We see that the maximum average pressure measured by the sensor is consistent between all sensors. For S0081, the average pressure was 11.7 ± 0.9 psi; for S0088, the average pressure was 12.8 ± 1.8 psi; and for S0089, the average pressure was 13.5 ± 1.9 psi. The specification of the sensor is $\pm 10\%$ full scale, which is ± 30 psi, making all of these measurements within the accuracy specification of the sensor.

LOW SEVERITY DATA

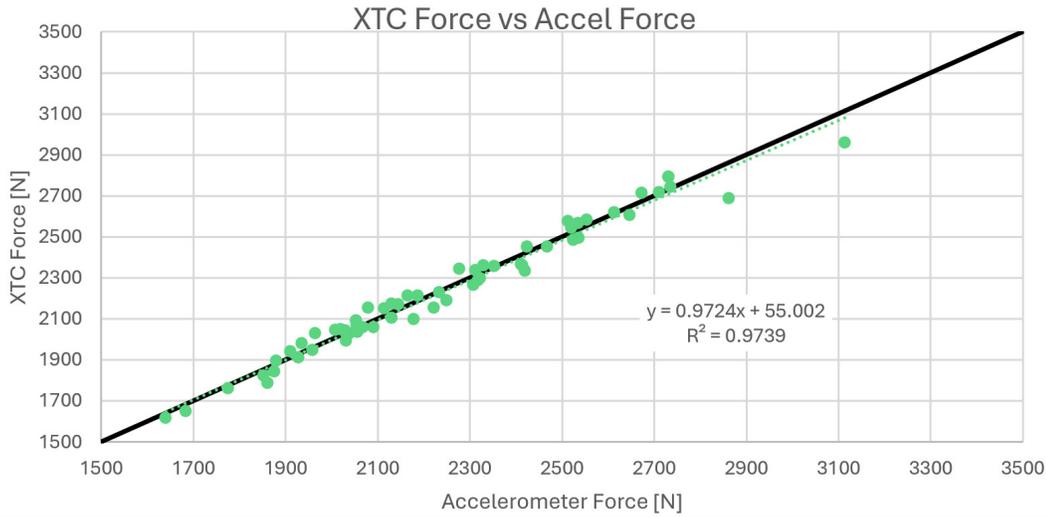


Figure 14 XSENSOR estimated force as a function of accelerometer measured force for all tests. The black line represents a slope of 1.

We can see from Figure 14 that there is essentially a 1:1 correspondence between the accelerometer data and the XSENSOR force data at low severity, with an R^2 of 0.9739.

High Severity Data

For the high-severity testing, we used a single sensor, S0081, repeating 30 impacts. All high-severity force data from the accelerometer, superimposed on the same graph, is shown in Figure 15.

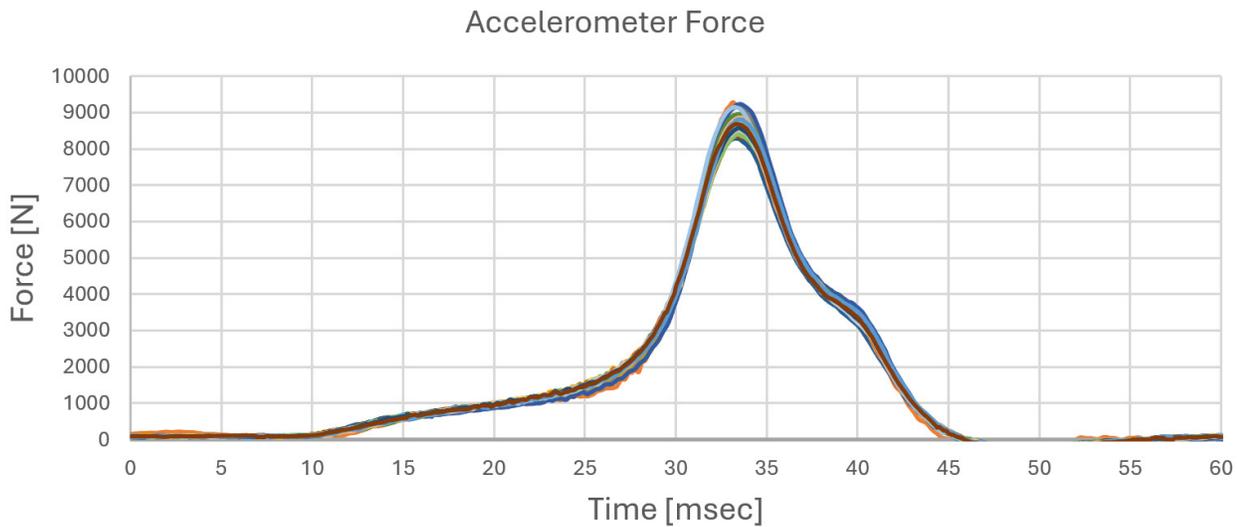


Figure 15 All accelerometer data from 30 tests using sensor s0081.

From the pressure sensor, we observe the force curves in Figure 16.

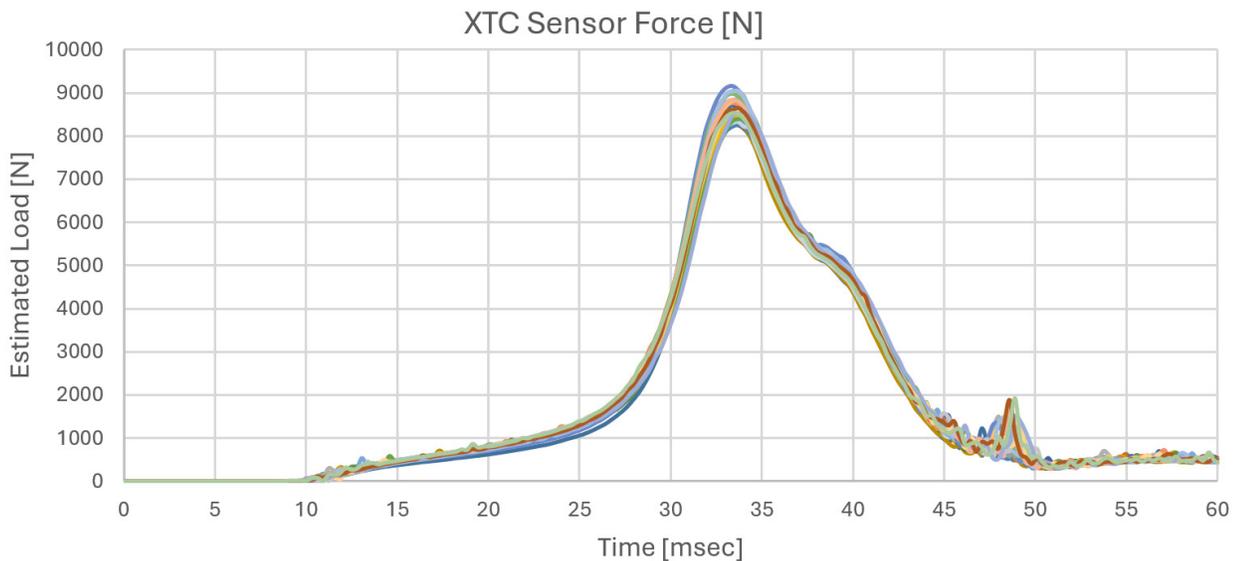


Figure 16 XSENSOR estimated force from 3 sensors, 30 tests each.

HIGH SEVERITY DATA

If we average all 30 of the accelerometer curves and overlay them with the averaged 30 XSENSOR curves, we see the following curves. There is very good time alignment between the accelerometer data and the XSENSOR data. The force data on the increasing portion of the impact from 0 to about 35 msec correlates very well. The recoil data from 35-45 msec show similar characteristics, including the shoulders at approximately 40 msec, but reads slightly higher due to the geometry of the tests, sensor locations, and some hysteresis in the sensor-foam combination.

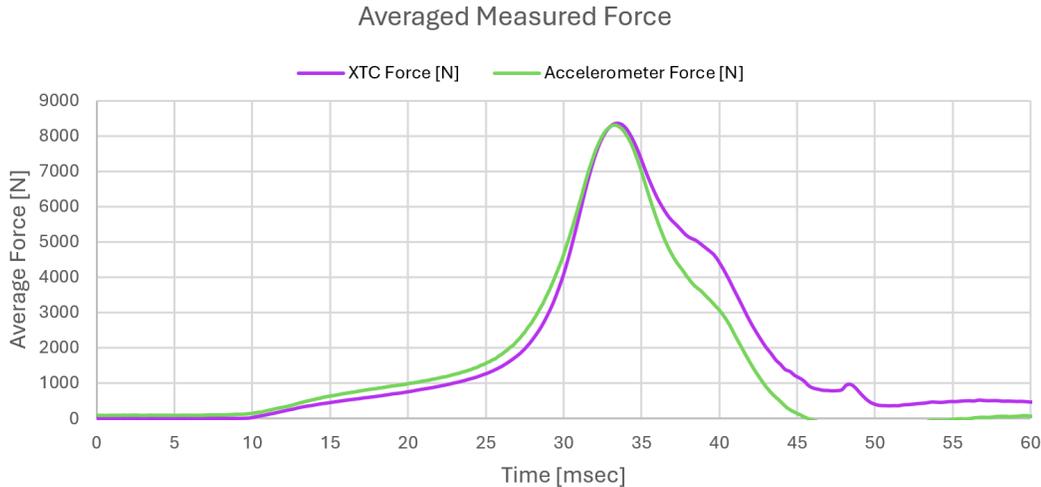


Figure 17 Averaged high severity curves for accelerometer and XSENSOR force data.

	XSENSOR		ACCELEROMETER			CI	z*	Margin of error	
	Max psi	XTC Force	Max g	Accel Forc	Facc-Fxtc			F_XTC	F_accel
avg	50.9	8639.5	43.0	8682.0	66.9	95%	1.96	80	88.2
stdev	1.3	223.7	1.2	246.4	64.6	98%	2.326	95	104.7
2s	2.5	447.3	2.4	492.9	129.3	99%	2.576	105.2	115.9
2s as %FS	0.8%				1.5%	2s as a rel % from accel avg			
2s as rel %		5.2%	5.6%	5.7%	1.5%	2s as a rel % from xtc avg			

The XSENSOR averaged peak force is 8640 N, with a margin of error of 105 N at 99%.
 The accelerometer averaged peak force is 8682 N with a margin of error of 116 N at 99%.
 The average delta between the peak forces is 67 N \pm 129 N at k = 2.
 The correlation coefficient is 0.9668.
 The coefficient of determination (r^2) is 0.9346.

HIGH SEVERITY DATA

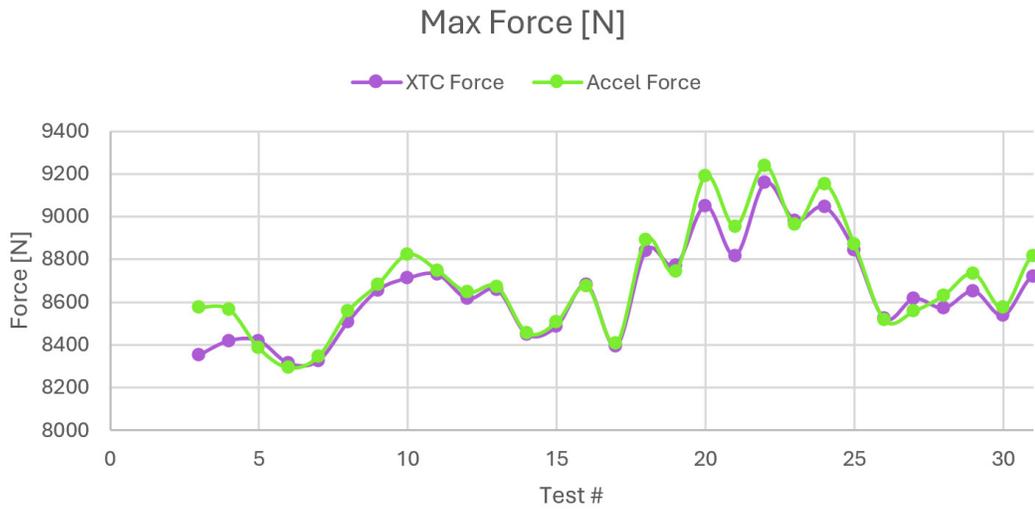


Figure 18 Peak force measured by the accelerometer and XSENSOR vest sensor as a function of test number.

Table 4 shows the t-test results for the data in Figure 18. The results indicate that there is no significant statistical difference between the accelerometer and the XSENSOR vest sensor.

t-Test: Two-Sample Assuming Unequal Variances		
	XTC Force	Accel Force
Mean	8648.862629	8694.708258
Variance	48968.17926	57675.32958
Observations	30	30
Hypothesized Mean Difference	0	
df	58	
t Stat	-0.768938038	
P(T<=t) one-tail	0.222525048	
t Critical one-tail	1.671552762	
P(T<=t) two-tail	0.445050095	
t Critical two-tail	2.001717484	
Null Hypothesis:		
There is no difference in the means		
Conclusion		
They are statistically the same with 44.5% certainty.		

HIGH SEVERITY DATA

Looking at the histogram distributions:

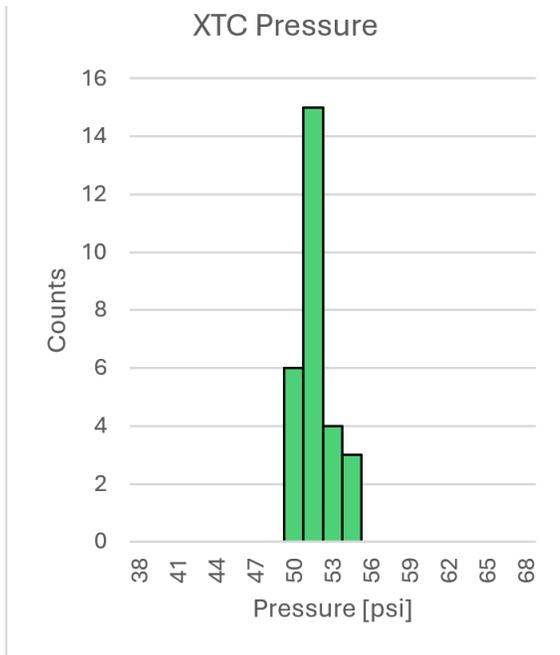


Figure 19 XSENSOR high severity pressure histogram

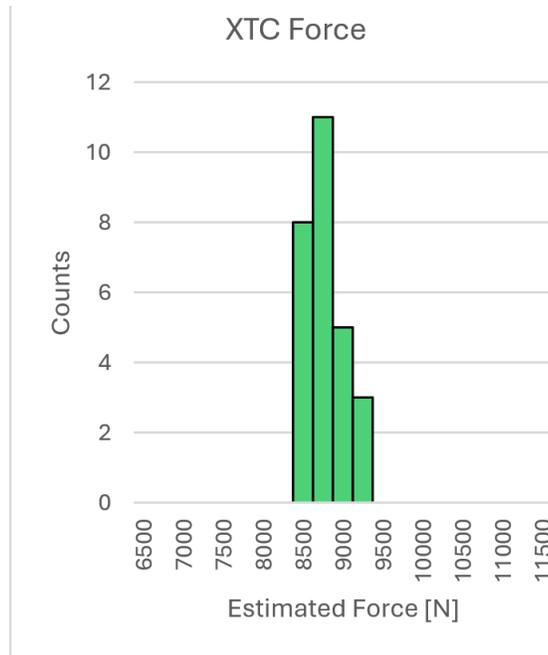


Figure 20 XSENSOR high severity Force histogram

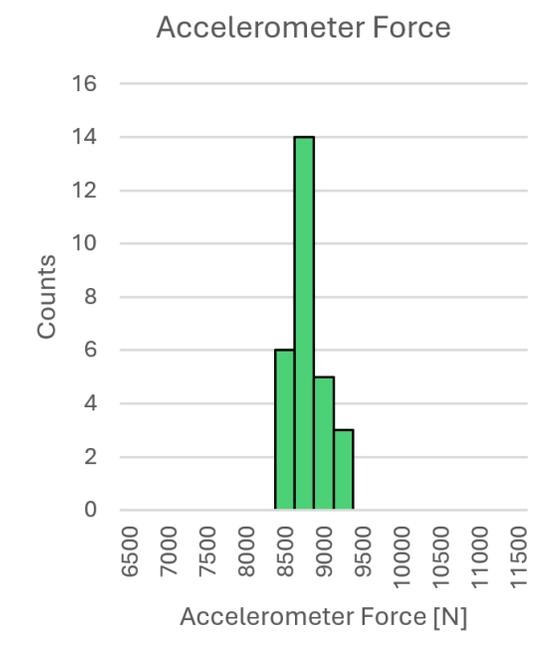


Figure 21 Accelerometer high severity force histogram

The distributions appear to be Gaussian.

HIGH SEVERITY DATA

Plotting the XSENSOR estimated force as a function of the accelerometer measured force:

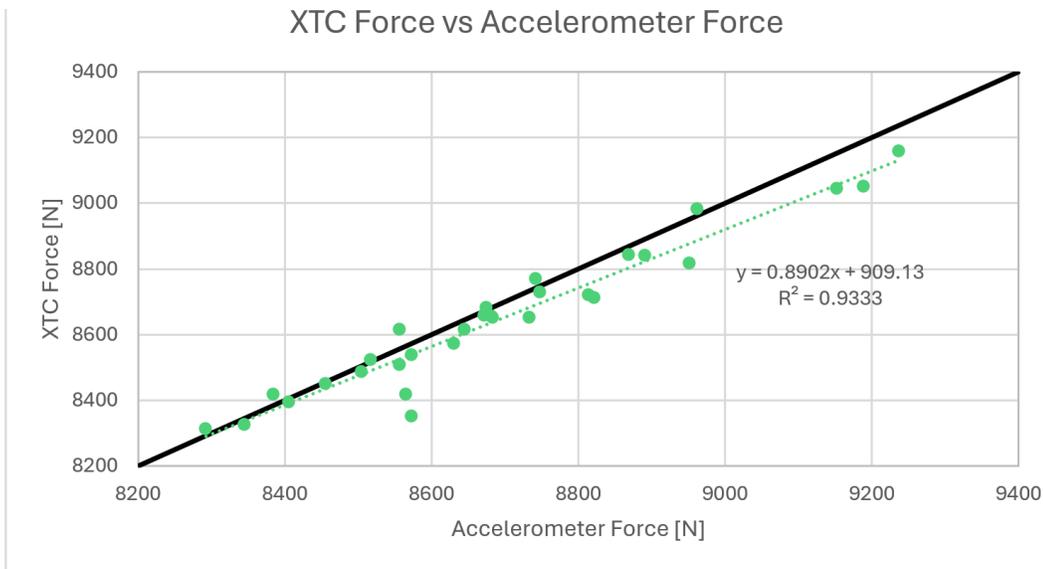


Figure 22 XSENSOR estimated force as a function of the force measured by the accelerometer for all high severity

If we consider the pressure measurements:

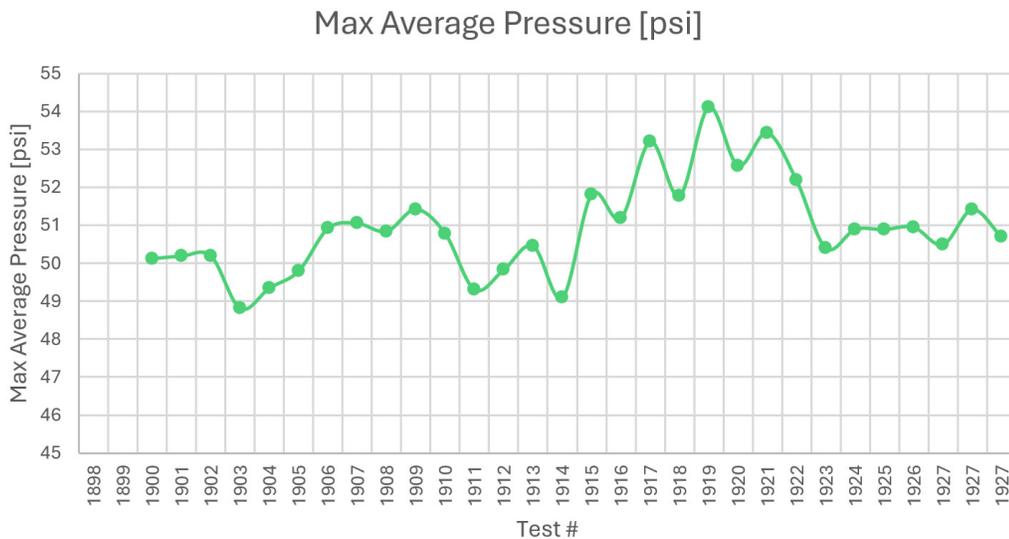


Figure 23 Average pressure of the pendulum impact at the point of maximum force.

For this sensor, the average pressure was 50.9 ± 1.2 psi. The specification of the sensor is $\pm 10\%$ full scale, which is ± 30 psi. Since the force measurement of the pressure sensor is in agreement with the accelerometer force measurement, we can assume that the pressure readings are correct and within specification.

Discussion

For all low-severity impacts, we observed excellent consistency and repeatability, both within individual sensors across multiple tests and between different sensors.

1. Statistical analysis of low-severity impacts revealed no significant difference (61.3% certainty) between the accelerometer measurements and the force data collected from all three pressure sensors.
2. These tests demonstrated a strong, near-perfect correlation between accelerometer-measured force and the force estimated from pressure sensor data.
3. The high-severity tests showed no statistical difference (44.5% certainty) between the accelerometer and the S0081 pressure sensor.

Implications

Our analysis demonstrates that forces calculated from XSENSOR pressure measurements are accurate, repeatable, and align with those measured by accelerometers. This provides end-users with confidence that data collected at the same location will be consistent across multiple tests and that different sensors deployed in various locations will yield comparable results.

XSENSOR's ISO 17025 accreditation ensures calibration traceability and compliance with industry quality standards, further enhancing data reliability.

The XSENSOR pressure imaging system offers several key advantages over traditional point load cells or accelerometers. It provides a comprehensive 2D map of:

- Force distribution across the entire surface.
- Object location and positioning on the surface.
- Interactions between the ATD, seatbelts, airbags, and the seating structure/frame.

Limitations

The most important limitation of this study was ensuring that when the pendulum was released, there was no rotational moment introduced into the pendulum, which would cause the pendulum to twist during the fall and not strike the sensor in the center. This would result in a portion of the pendulum striking outside the sensing area, and thus the sensor would affect the pressure reading and also underestimate the total force.

This study utilized a limited sample size of three sensors. Future research could benefit from a larger sample to enhance the robustness of the findings.

Conclusions

In conclusion, our findings demonstrate excellent consistency and repeatability across both intra-sensor and inter-sensor tests for all low-severity impacts.

For low-severity impacts, no statistically significant difference was observed between the accelerometer and the three pressure sensors (61.3% certainty). A strong, near-perfect correlation was found between the force measured by the accelerometer and the force estimated from pressure sensor data.

For high-severity impacts, no statistically significant difference was observed between the accelerometer and the S0081 pressure sensor (44.5% certainty).

Future research could expand upon this work by incorporating ATDs as targets, providing more realistic and relevant data for real-world applications.

XSENSOR's High Speed Impact Sensor Validation | Validation Study

XSENSOR Technology Corporation

133 12th Avenue SE

Calgary, AB T2G 0Z9

Canada

support@xsensor.com | xsensor.com

+1 (403) 266-6612 | North America Toll-Free: +1 (866) 927-5222

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