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of Transportation

**National Highway  
Traffic Safety  
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DOT HS 813 681

April 2026

# **Development of an Alternative Shoulder For the THOR-50M**

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<b>16. Abstract</b> NHTSA has actively supported development of an advanced frontal anthropomorphic test device (ATD or crash test dummy), the THOR-50M (Test Device for Human Occupant Restraint), incorporating an enhanced shoulder design. This project was to design, manufacture, test, and evaluate an alternative shoulder for the THOR-50M, taking care not to infringe on current U.S. patents or patent applications. The alternative was to include elements ensuring no effective change in fit, function, or range of motion of the shoulder. Two concepts for the alternative were initiated, Option "A" shoulder and Option "B" shoulder. The term "baseline shoulder" refers to the shoulder assembly components described in the THOR-50M September 2018 drawing package, while the term "alternative" shoulder refers to new design components. The baseline shoulder has four key elements as seen in the baseline shoulder patent application by Been and Burleigh in 2014: shoulder pivot, shoulder housing, spring, and adjustable element to adjust the friction of the spring. Significantly changing one or more of these elements should eliminate possible patent infringements. For the two alternatives in this project, the spring and friction adjustment element found in the baseline shoulder were eliminated. A right-side version of the Option "A" shoulder and left-side version of the Option "B" shoulder were fabricated for evaluation.			
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## **Background**

The National Highway Traffic Safety Administration has actively supported the development of an advanced frontal anthropomorphic test device (ATD or crash test dummy), the THOR-50M (Test Device for Human Occupant Restraint) that incorporates an enhanced shoulder design. This project seeks to design an alternative shoulder for the THOR-50M, taking care not to infringe on any current U.S. patents or patent applications.

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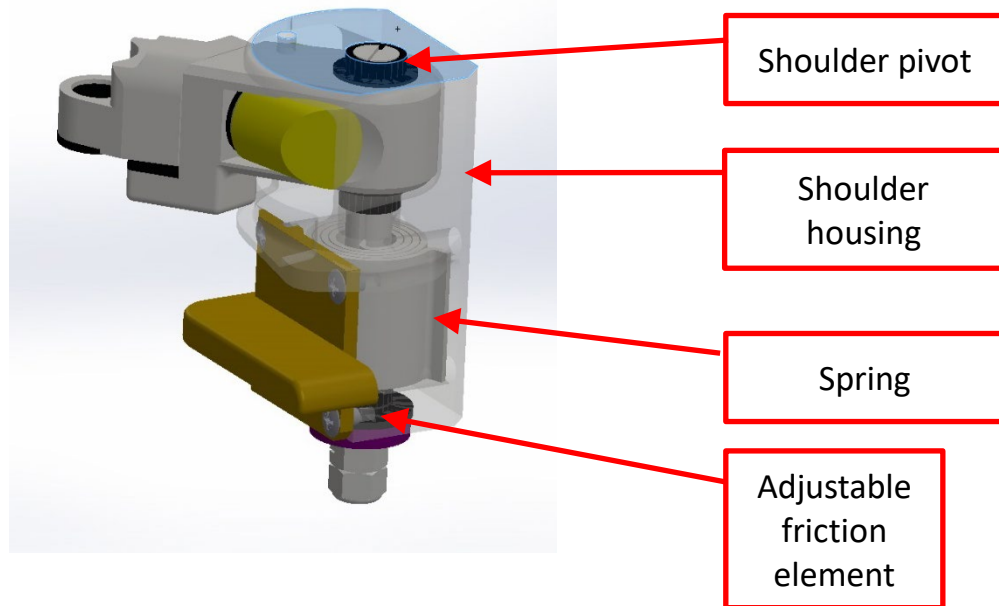
## **Objectives**

The objective of this project was to design, manufacture, test, and evaluate an alternative shoulder design for the THOR-50M ATD. The alternative shoulder design was to include elements that ensured there was no effective change in fit, function, or range of motion of the shoulder. Additionally, the alternative design must not infringe on any existing patents or patent applications.

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## Alternative Shoulder Designs

Two concepts for the alternative shoulder design were initiated (Option “A” shoulder and Option “B” shoulder). For the purposes of this report, the term “baseline shoulder” refers to the shoulder assembly components described in the THOR-50M September 2018 drawing package, while the term “alternative” shoulder refers to alternative design components. The baseline shoulder shown in Figure 1 shows the four key elements of the design as indicated in the baseline shoulder’s patent application (Been & Burleigh, 2014): shoulder pivot, shoulder housing, spring, and adjustable element to adjust the friction of the spring. Significantly changing one or more of these elements should eliminate possible patent infringements. For the two alternatives developed in this project, the spring and friction adjustment element found in the baseline shoulder were eliminated. A right-side version of the Option “A” shoulder and left-side version of the Option “B” shoulder were fabricated for evaluation.



*Figure 1. Baseline shoulder design showing key elements of the design*

The baseline shoulder included 62° of total fore-aft range of motion (49° forward sweep and 13° rearward) (Figure 2). In addition, with the shoulder installed, the torque was approximately 40 in-lb at the maximum forward position. Descriptions of the range of motion and torque measurement techniques are under *Quasi-Static Rotation Test Setup and Conduct*. The torque and the total range of motion were two of the design targets for the alternative shoulders.

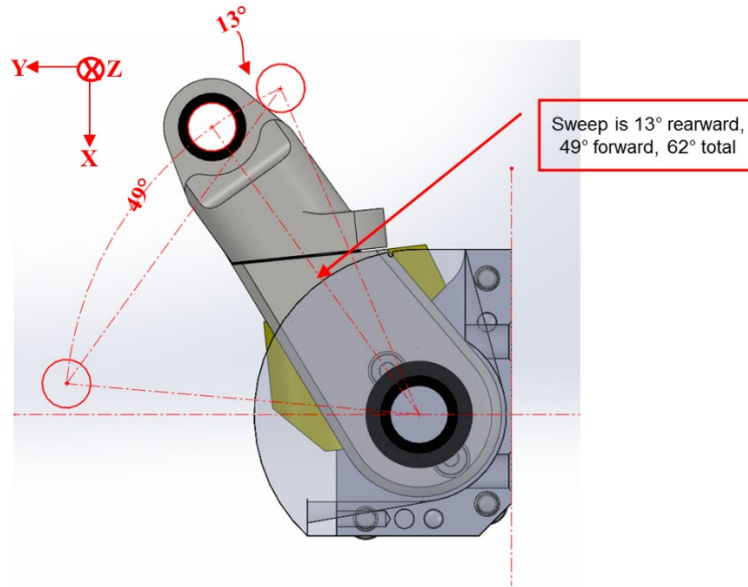


Figure 2. Baseline shoulder (right) indicating range of motion requirements (top view)

### Option “A” Shoulder Design

For the Option “A” shoulder design, the spring and friction adjustment were removed from the baseline shoulder and replaced with a cylindrical molded rubber torque element; to maintain consistency with the part descriptions in the drawing package the element and the surrounding components will maintain the description of “spring” (Figure 3). Spring stiffness can be adjusted by changing the shape or number of voids in the cylinder or by changing the hardness of the rubber compound (Figure 4). A right-side version of the Option “A” shoulder was manufactured for evaluation.

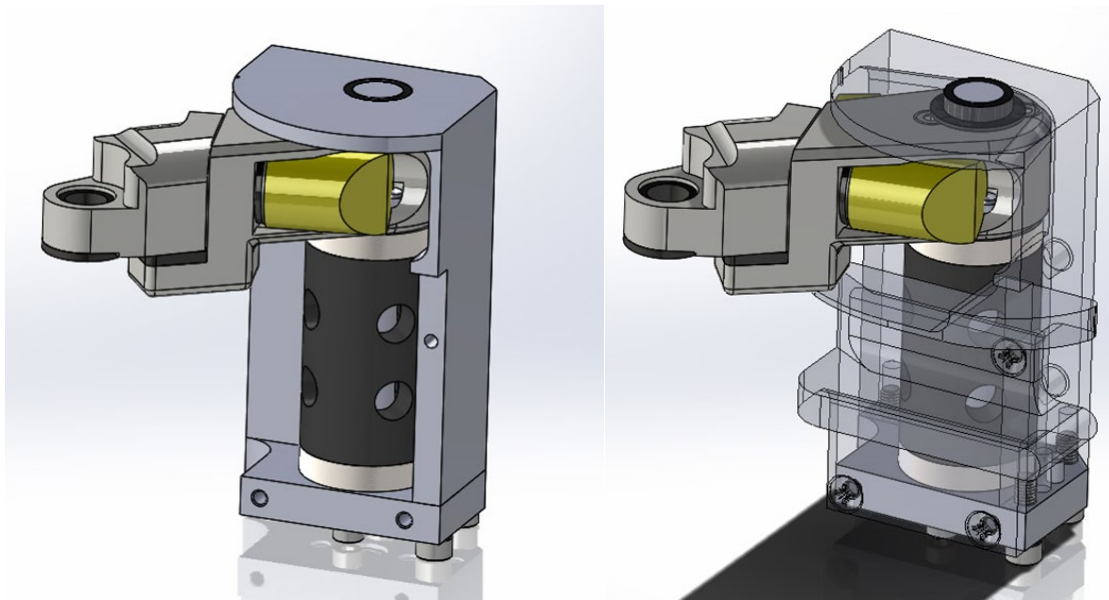


Figure 3. Design Option “A” shoulder concept

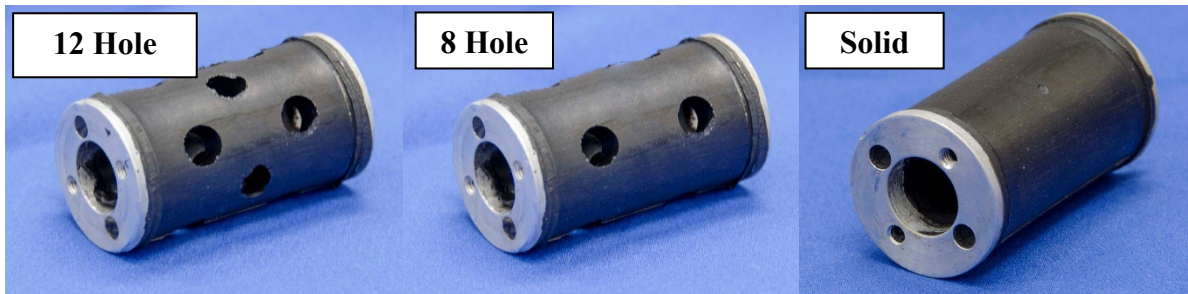


Figure 4. Cylindrical rubber “springs” developed for Option “A” shoulders

### Assembly of the Option “A” Shoulder

The following section describes the assembly of the Option “A” shoulder. Table 1 describes the parts for the Option “A” shoulder illustrated in Figure 5. Option “A” shoulder components are shown in Figure 6 and Figure 7. The assembly process is shown in Figures 3-8 through 3-14

Table 1. Right Side Option “A” Shoulder Assembly Components

Item #	Part Number	Part Description	Quantity
1	472-6812-2	Housing Shoulder, Right	1
2	472-6813-2	Shoulder Support Assembly, Right	1
3	472-6827	Rubber Spring, Molded	1
4	472-6870-2	Plate, Bottom Right	1
5	472-3822	Spring Housing Bushing, Upper	1
6	472-6823	Spring Housing Bushing, Lower	1
7	472-6824	Shaft, Shoulder Pivot	1
8	472-6828-2	Rib Guide, Right	1
9	5000699	Screw, FHCS M4 x 0.4 x 8, Phillips	3
10	5000020	Screw, SHCS M5 x 0.8 x 16	3
11	5000280	Pin, Dowel M5 x 10	2
12	5000461	Screw, SHCS M4 x 0.7 x 25	2
13	5000140	Roll Pin, M3 x 24	1
14	5000151	Screw, SHCS M4 x 0.7 x 10	2

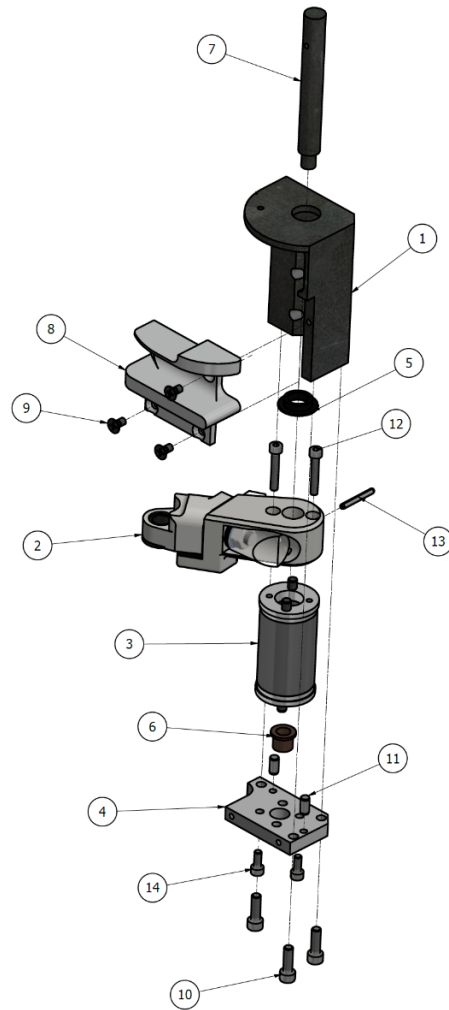


Figure 5. Option "A" shoulder assembly components (right side)

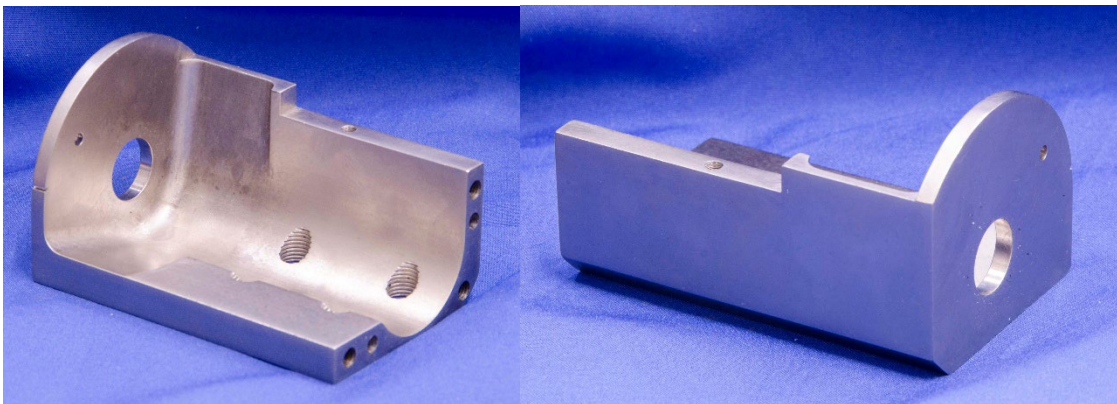


Figure 6. Shoulder housing for the Option "A" shoulder



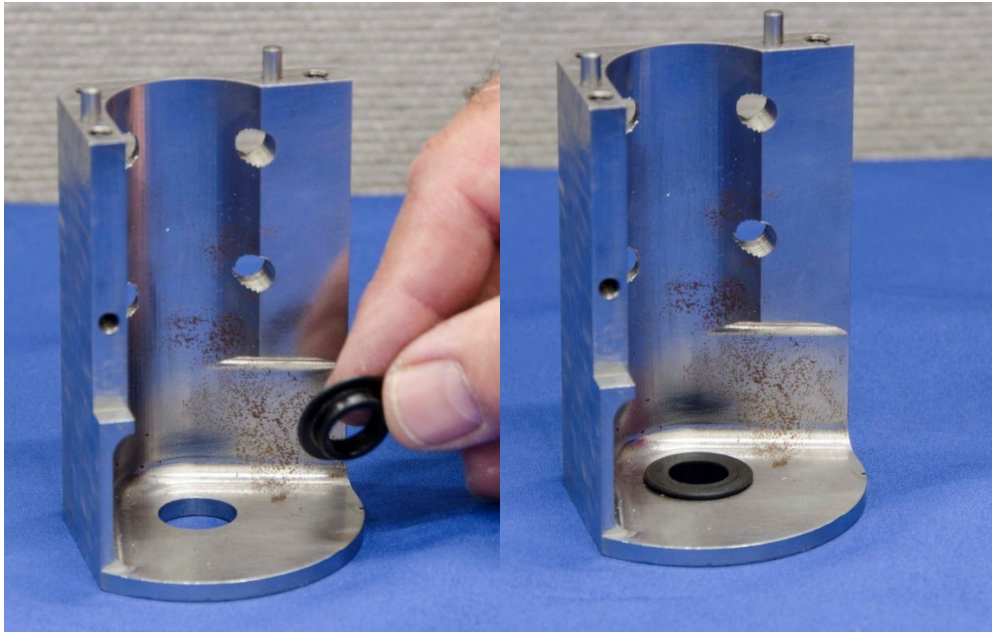
*Figure 7. Shoulder support assembly with shoulder pivot shaft for the Option “A” shoulder*

Insert the shoulder pivot shaft into the molded rubber spring. Install two M4 x 0.7 x 25 SHCS into the end of the shoulder support (Figure 8).



*Figure 8. Install the rubber spring assembly to the shoulder support on the Option “A” shoulder*

Install the upper spring housing bushing into the shoulder housing (Figure 9).



*Figure 9. Install upper spring housing bushing into shoulder housing*

Insert the molded rubber spring assembly into the shoulder housing (Figure 10).



*Figure 10. Install shoulder rubber spring element*

Install the lower spring housing bushing into the bottom plate. Place the bottom plate over the spring shaft, aligning the bottom plate with the dowel pins (Figure 11).

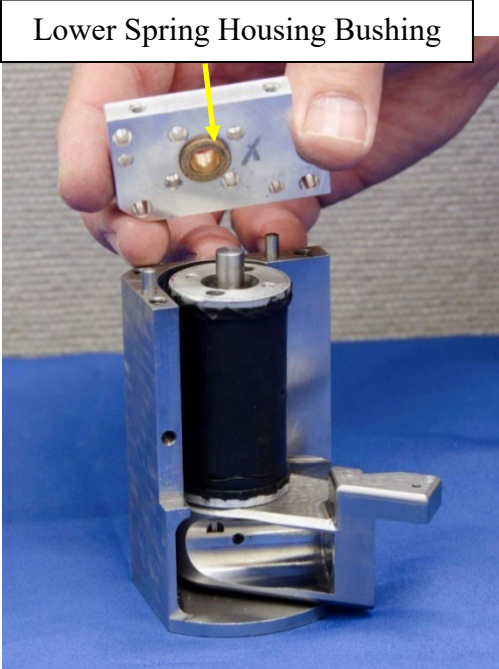


Figure 11. Install bottom plate

Install two M4 x 0.7 x 10 SHCS through the bottom plate and into the rubber spring assembly (Figure 12). Then screw in the three M5 x 0.8 x 16 SHCS on the three corners of the bottom plate.

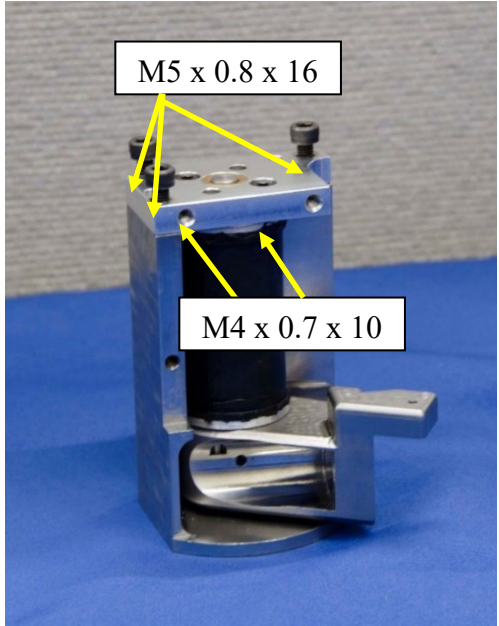
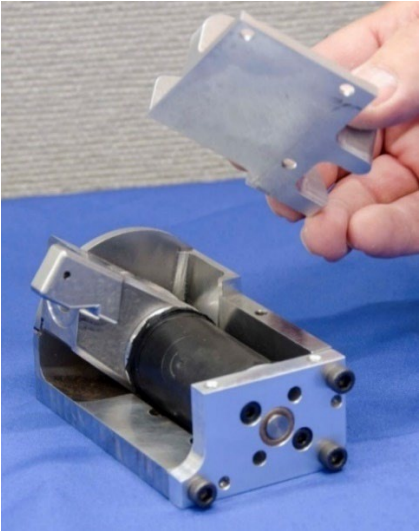
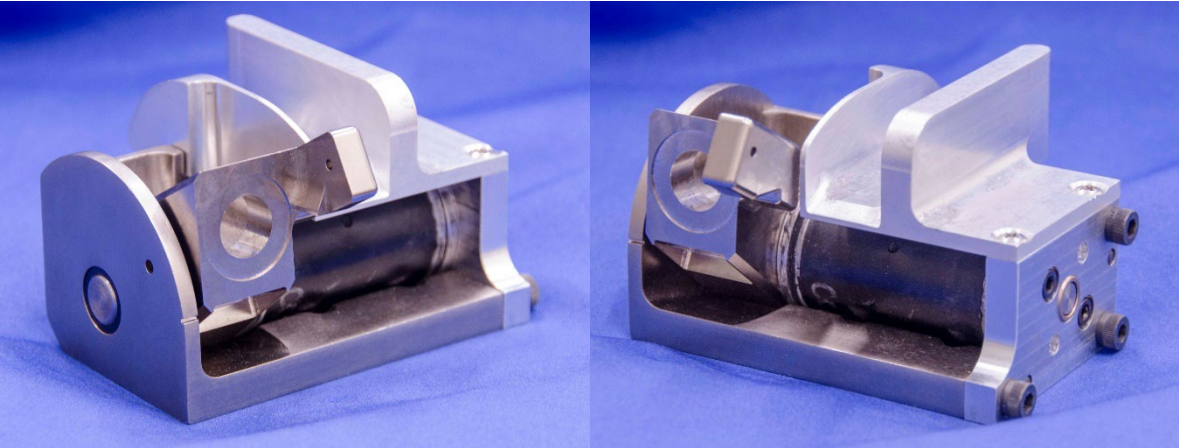


Figure 12. Install screws into bottom plate

Install the rib guide (right side) using three M4 x 0.7 x 8 Phillips screws (Figure 13). The complete Option “A” shoulder assembly is displayed in Figure 14.



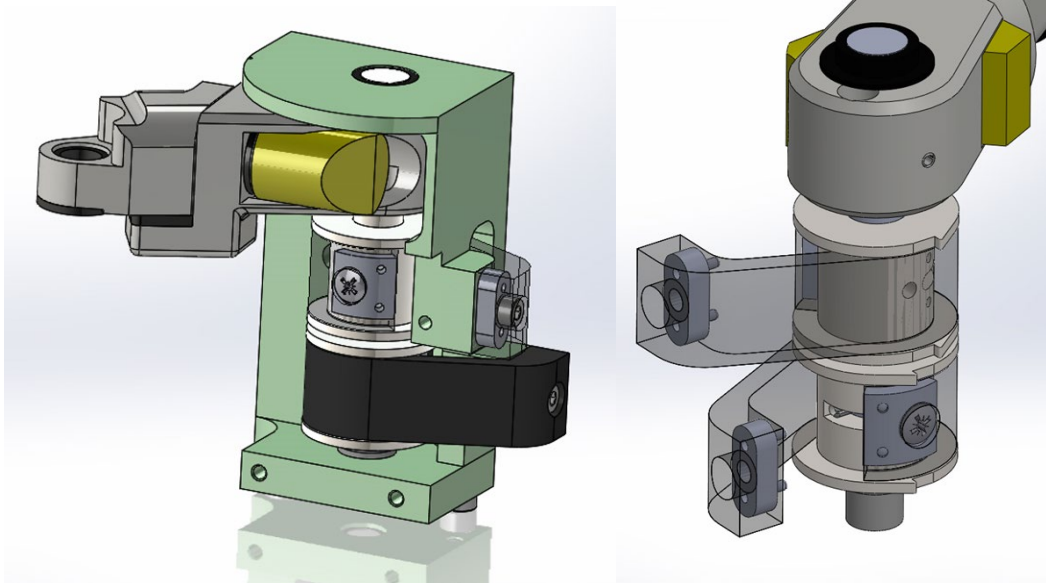
*Figure 13. Install lower rib guide*



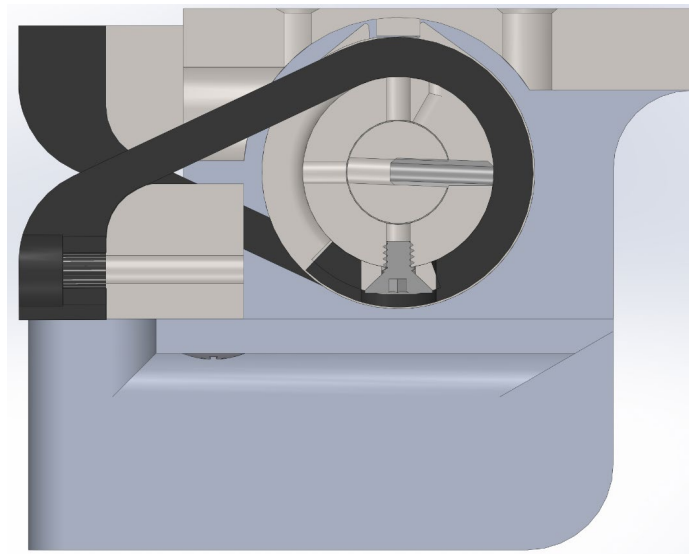
*Figure 14. Option “A” shoulder fully assembled*

## Option “B” Shoulder Design

For the Option “B” shoulder design, the spring and friction adjustment from the baseline shoulder were removed and replaced with molded rubber straps wrapped around spools; to maintain consistency with the part descriptions in the drawing package, the rubber-wrapped spools and the surrounding components will maintain the description of “spring” (Figure 15 and Figure 16). The spring stiffness could be adjusted using variations in hardness of the rubber compound of the straps. This design is more complex than the Option “A” design. As the shoulder rotates, the spools stretch the rubber straps, creating resistance. A left-side version of the Option “B” shoulder was manufactured for evaluation.



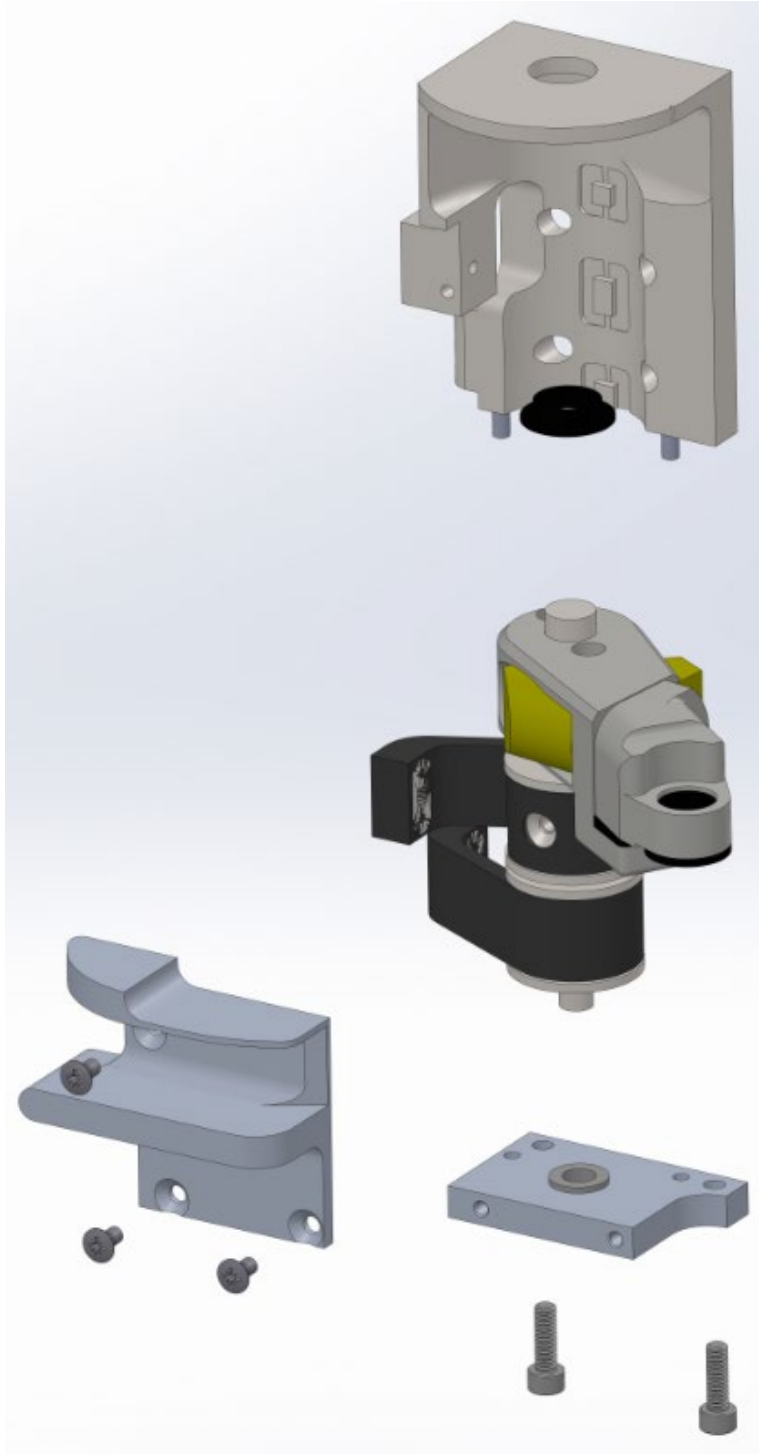
*Figure 15. Design Option “B” concept*



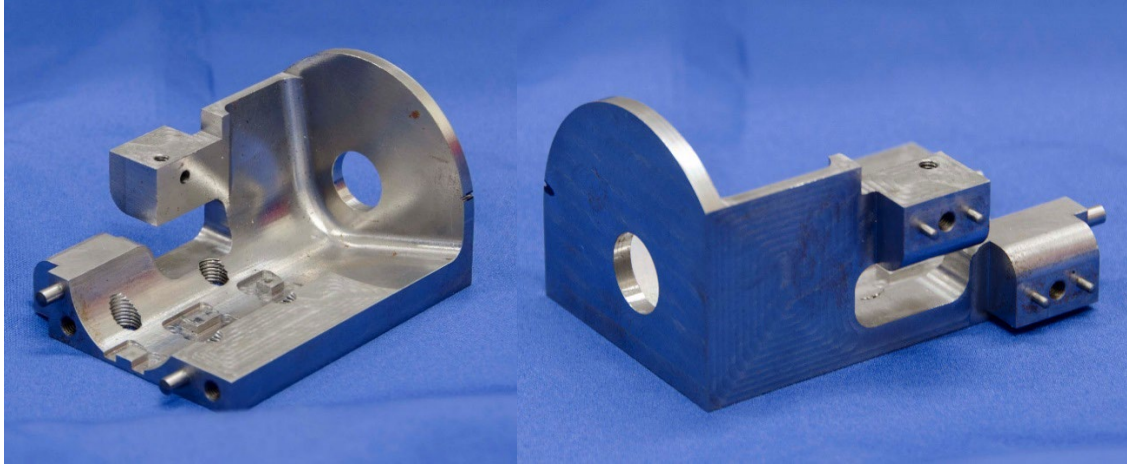
*Figure 16. Option “B” shoulder mechanism for generating torque*

### ***Assembly of the Option “B” Shoulder***

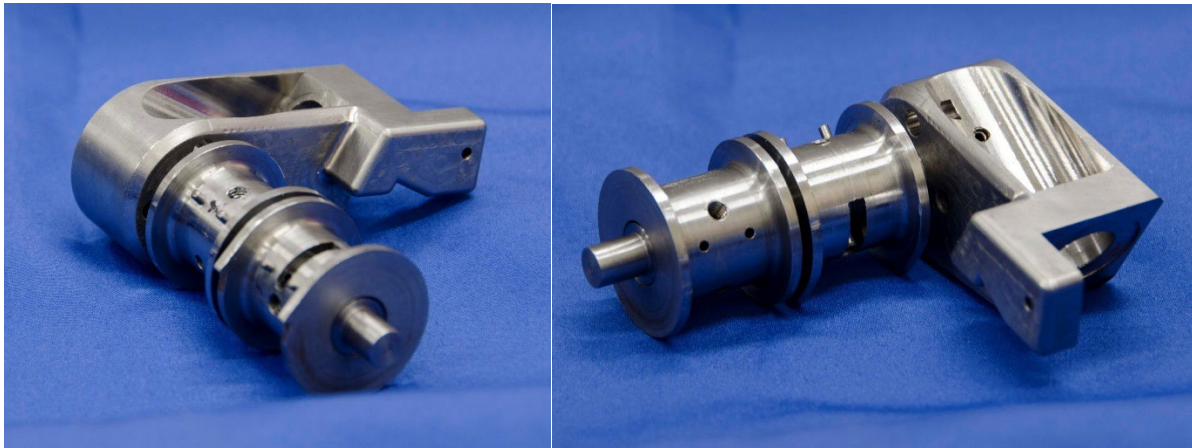
The following section describes the assembly of the Option “B” shoulder (Figure 17). Note that an exploded view of the assembly drawing is not provided since this design was ultimately not selected for further evaluation. Option “B” shoulder components are shown in Figure 18 and Figure 19. The assembly process is shown in Figures 3-20 through 3-26.



*Figure 17. Assembly drawing of the Option “B” shoulder*



*Figure 18. Shoulder housing cover of the Option “B” shoulder*

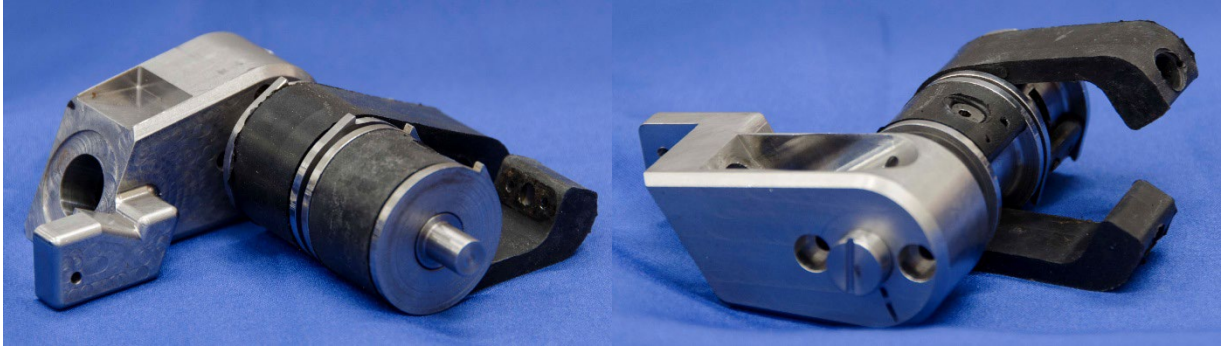


*Figure 19. Spooling components of the Option “B” shoulder*

Install the spring straps to the spools in an opposite facing orientation (Figure 20 and Figure 21).

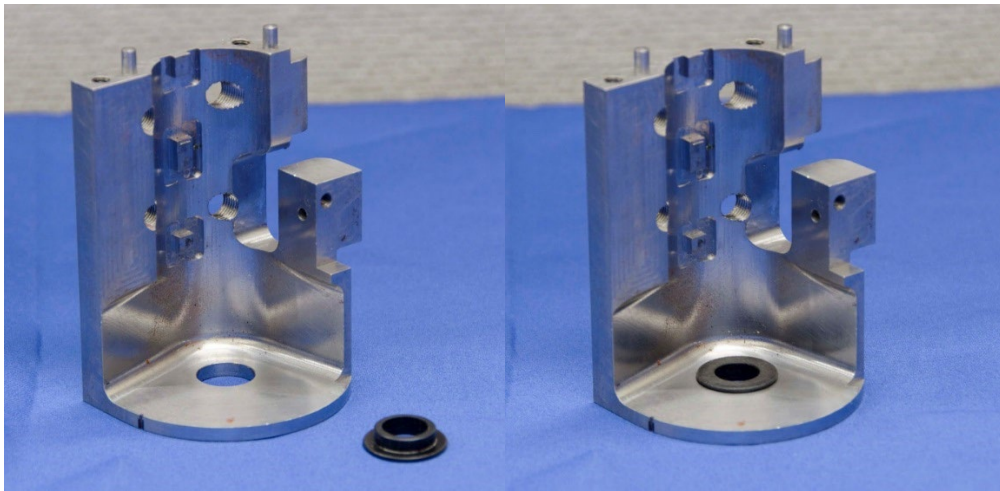


*Figure 20. Install first strap to the spool*



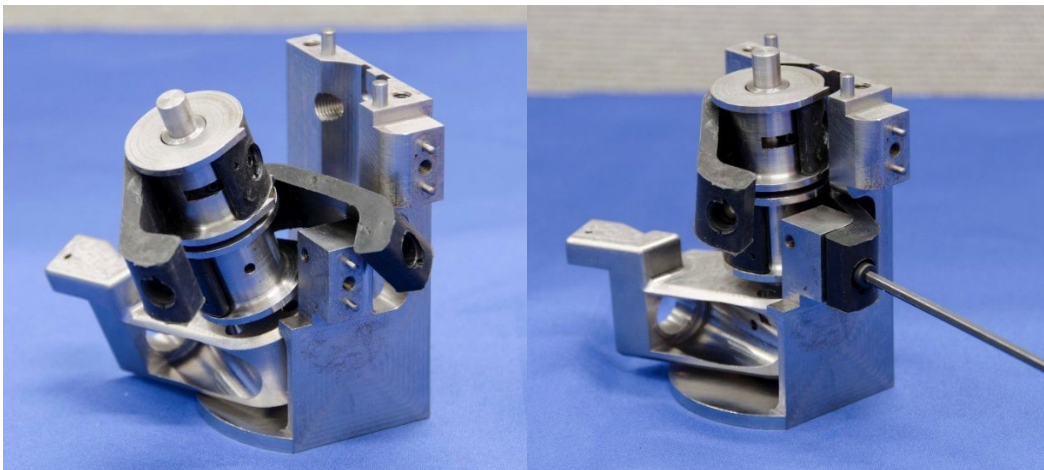
*Figure 21. Install the second spring strap to the spool*

Insert the spool housing bushing into the spool housing cover (Figure 22).



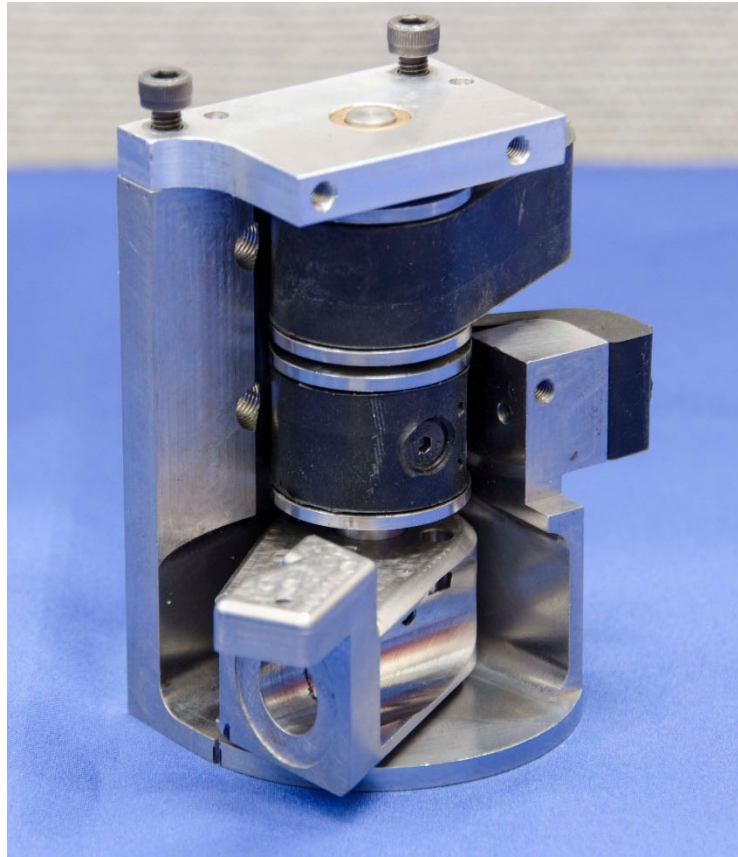
*Figure 22. Install spool housing bushing into the spool housing cover*

Next, install the spool assembly into the spool housing cover (Figure 23). Slide the spring strap into the slot in the housing, install the spring strap over the pins and screw the M4 x 6 FHCS screws into the housing.



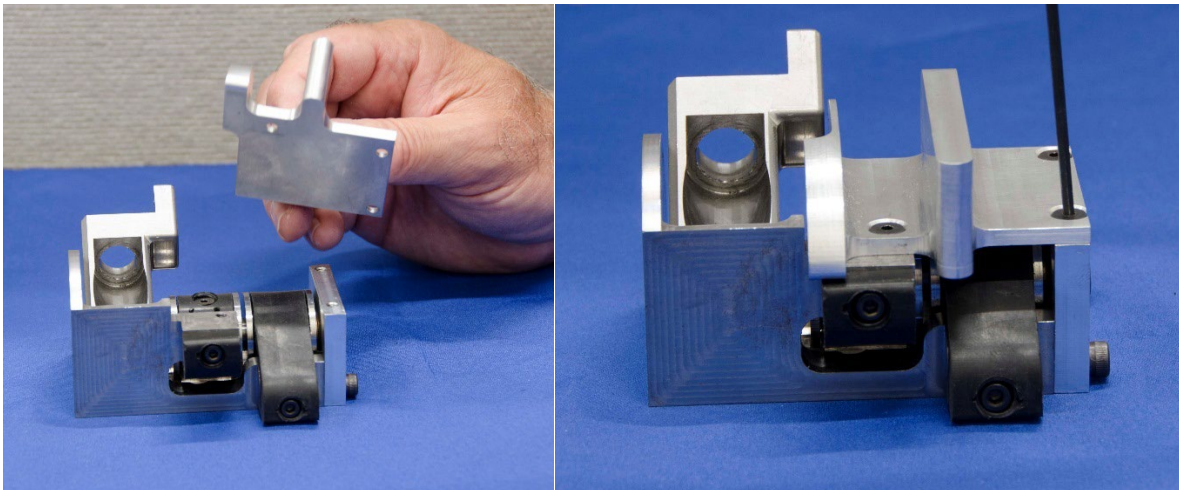
*Figure 23. Install spool assembly into the spool housing cover*

Install the housing end cap using two M5 x 16 SHCS (Figure 24).

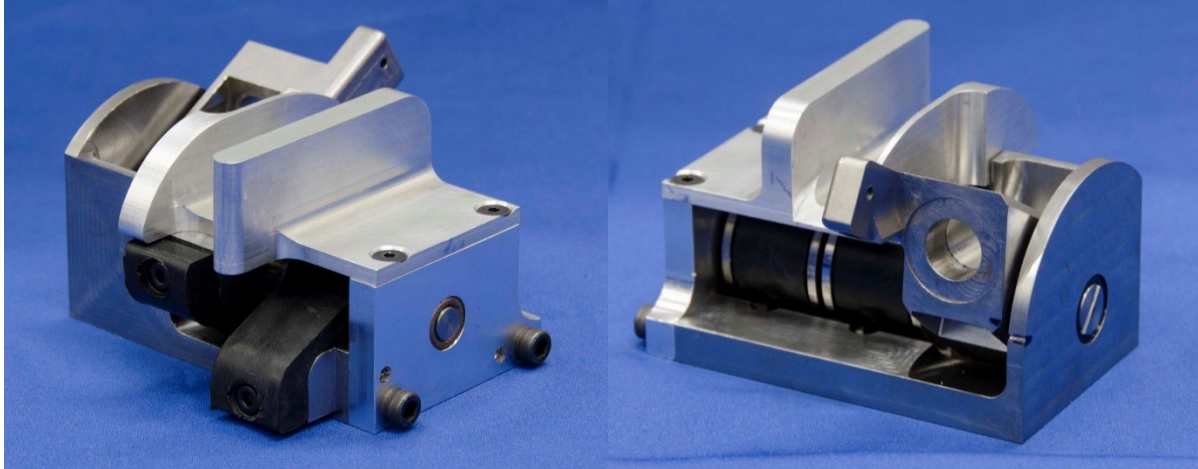


*Figure 24. Install housing end cap*

Attach the rib guide to the housing (Figure 25). The complete Option “B” shoulder assembly is illustrated in Figure 26.



*Figure 25. Rib guide installation*



*Figure 26. Option “B” shoulder complete assembly*

### **Patent Assessment**

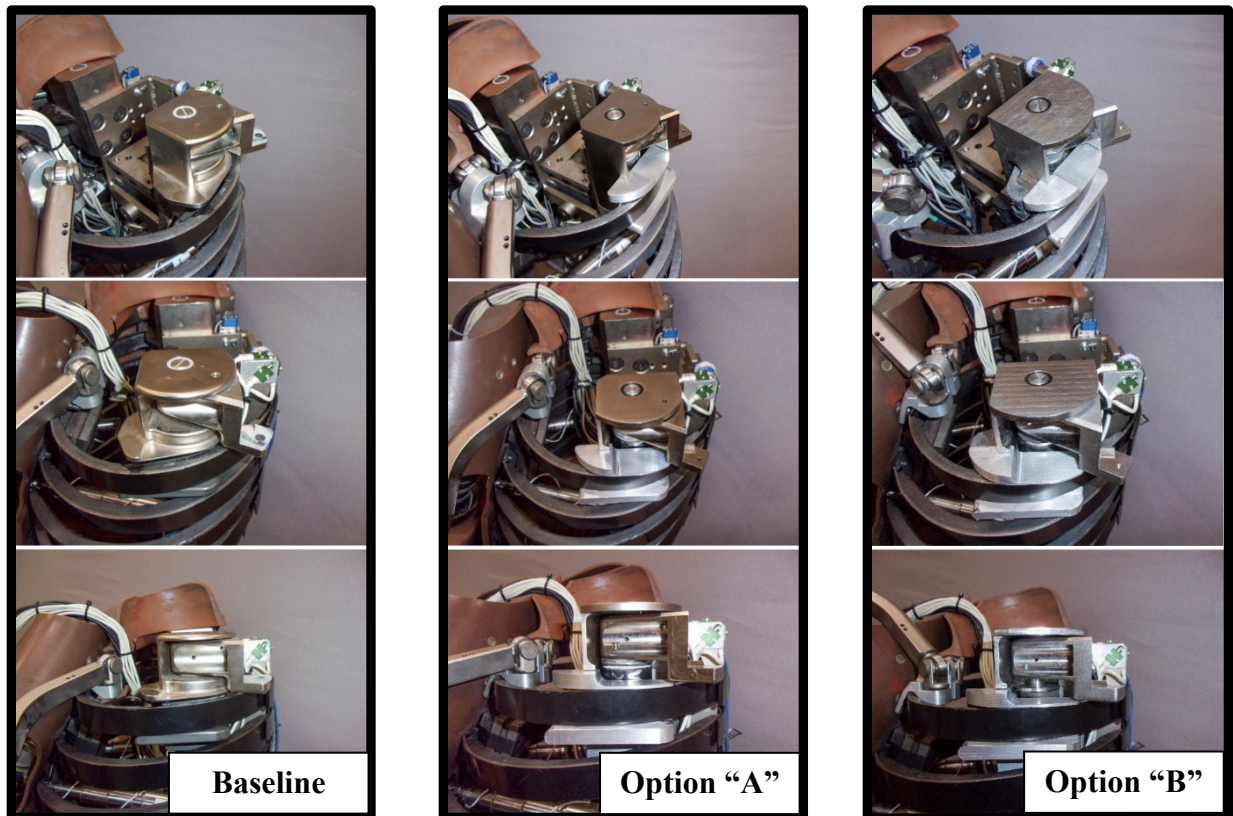
Since the baseline shoulder was patented, the alternative shoulder designs were reviewed to identify potential issues with existing patents. The results of the review, including an evaluation of all claims in the baseline shoulder patent, showed that the alternative shoulder designs did not literally infringe the existing patent. The alternative shoulder designs have no adjustable components of any kind to adjust friction, and neither design has a dampening member like the baseline shoulder. As a result, the alternative shoulders do not include each element of the patent claim as required, so there is no literal infringement. The claims were also examined for doctrine of equivalents infringements and that review also showed that the alternative shoulders do not infringe on any claims for the patent under the doctrine, as there is no friction adjustment feature or equivalent in the alternative shoulder designs. We also note that the patent claims for the baseline shoulder were amended under the patent process that would now prevent the doctrine of equivalents from being applied. Accordingly, the review deemed that neither the Option “A,” nor the Option “B,” shoulders posed any issues with existing patents.

## Evaluation of Alternative Shoulder Designs

Options “A” and “B” alternative shoulder designs were examined to assess any effective changes in fit, function, or range of motion compared to the baseline shoulder design. Fit tests, quasi-static tests, qualification tests, biofidelity tests, and full-scale sled tests were used to evaluate the alternative shoulder designs. The primary design evaluation process focused on matching the quasi-static stiffness rather than qualification test comparisons, since the shoulders are not directly involved in the impact during qualification tests. However, qualification tests and sled tests were performed with the alternate shoulders to be sure they did not change the performance compared to baseline.

### Fit Tests

The baseline, Option “A,” and Option “B” shoulders were independently installed in the THOR-50M to evaluate the fit. All installation points, such as bolt connections, were checked for proper alignment and all components were checked for proper clearances. Figure 27 shows the baseline, Option “A,” and Option “B” shoulders installed in the THOR; for comparison purposes the shoulder installation is shown for all shoulder variations (the right-side images for the Option “A” shoulder were mirrored for comparison purposes). This figure illustrates that all shoulders fit properly when assembled into the THOR.



*Figure 27. Comparison of Baseline (column 1), Option “A” (column 2), and Option “B” (column 3) shoulders installed*

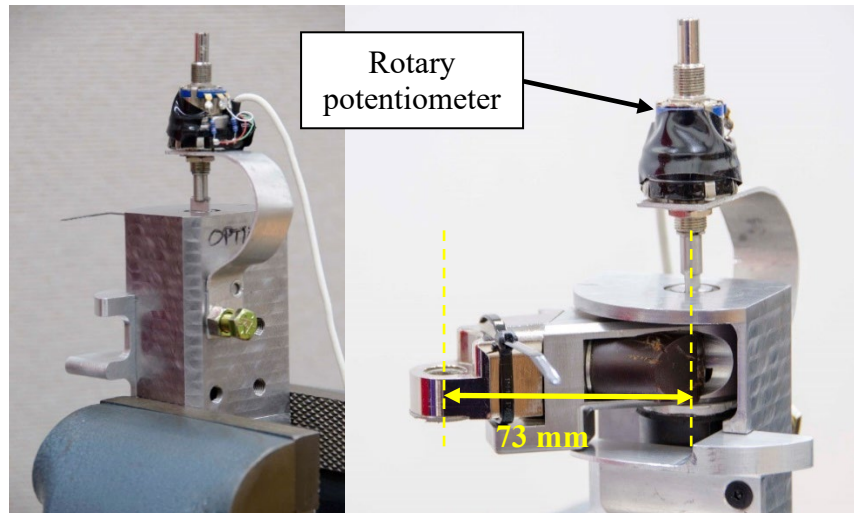
In addition to assembly fit, the shoulders were also moved through their range of motion forward and rearward to check for interference with other parts such as ribs. These tests revealed that both alternative shoulders did not inappropriately interfere with other parts.

### Quasi-Static Rotation Tests

Quasi-static tests were performed to assess range of motion and shoulder stiffness. Tests were conducted with both the baseline shoulder and alternative shoulder designs. The alternative shoulder stiffnesses were then compared to the baseline shoulder to assess suitability for installation in the THOR-50M.

### Test Setup and Conduct

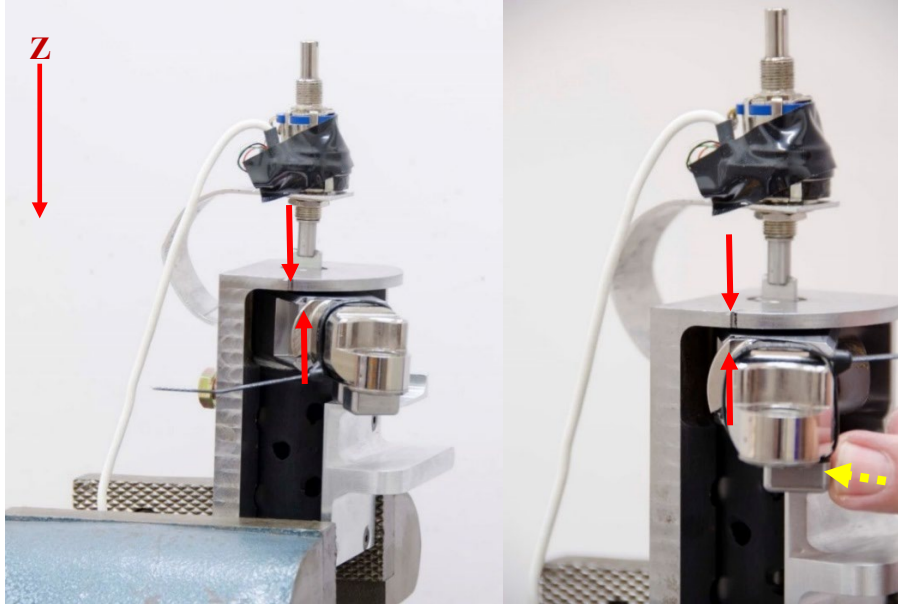
To measure the stiffness forward and rearward, the shoulder assembly was removed from the dummy and clamped in a vice (Figure 28). Once clamped into the vice, a rotary potentiometer was installed into the shoulder shaft. Although only one of the alternative shoulders is pictured in the illustration below, the procedure was the same for all shoulders. Note that the distance from the center of the rotary shaft to the center of the shoulder support shaft hole is 73 mm and is labeled in Figure 28. This measurement is important in the moment calculations explained in the next section.



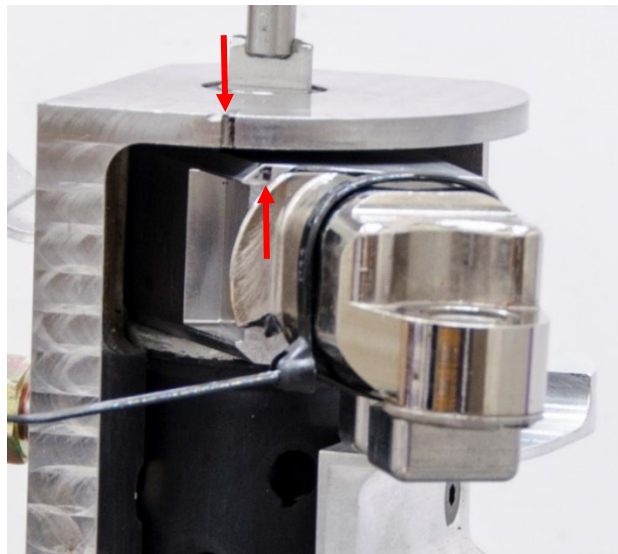
*Figure 28. Moment-angle shoulder test fixture*

Prior to the test, the potentiometer was placed in a “known” position for setting zero. To achieve this, the shoulder was rotated about the Z-axis until the scribe marks on the shoulder and housing were aligned (Figure 29). Alignment of the scribes indicates a “neutral” position, where there is no torque on the shoulder.

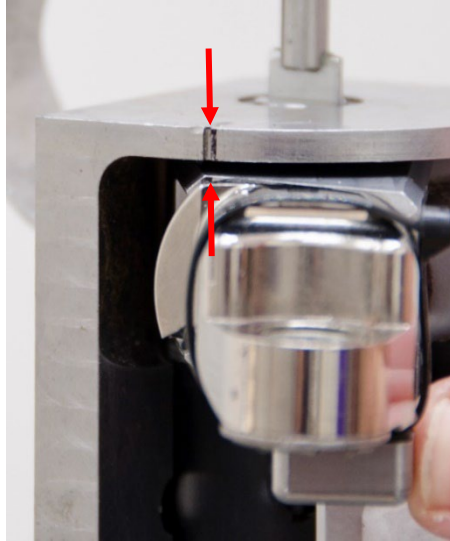
Figure 30 and Figure 31 show detailed views of these marks. Once aligned (Figure 31), the potentiometer was set to zero.



*Figure 29. Align the shoulder alignment mark*

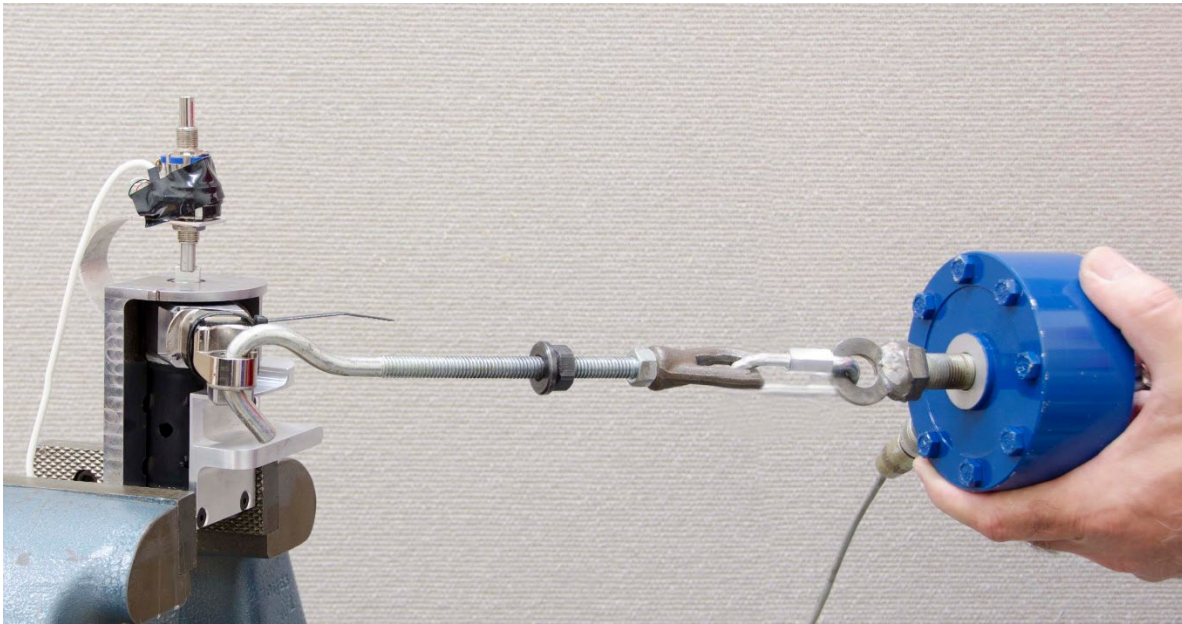


*Figure 30. Detailed view of scribe alignment marks*



*Figure 31. Detailed view illustrating when scribe alignment is achieved*

Using a load cell attached to a pulling mechanism, the shoulder was slowly and steadily pulled forward, assuring that the pull force was perpendicular to the potentiometer shaft (Figure 32). Both the angle from the potentiometer and the force on the load cell were measured. Upon reaching the shoulder stop (about  $49^\circ$  in the forward direction), the pulling mechanism was allowed to go slack, releasing the load.



*Figure 32. Forward pull for the moment-angle evaluation test*

The same procedure was repeated in the rearward direction, where the rearward stop was at approximately  $13^\circ$  of rotation (Figure 33).

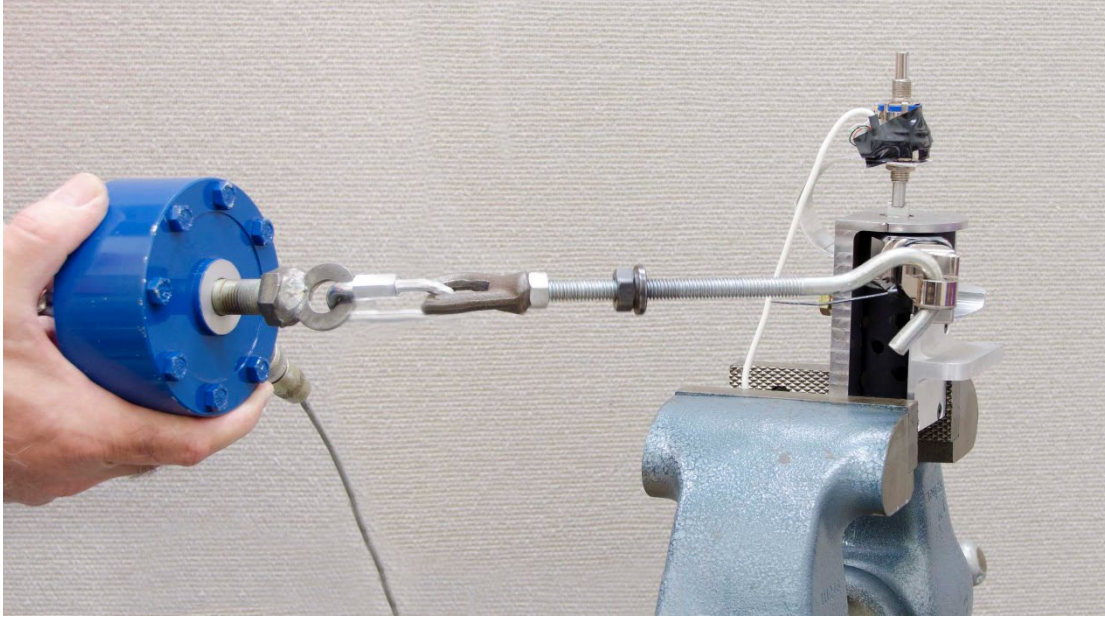


Figure 33. Rearward pull for the moment-angle evaluation test

### Test Results

Quasi-static rotation tests were conducted with three samples of the baseline shoulder, six versions of Option “A” shoulders, and two versions of Option “B” shoulders (Table 2). Option “A” shoulder versions included different material stiffnesses and hole patterns (Figure 4); adding holes through the cylinder decreases the stiffness. Only two versions of Option “B” shoulders were fabricated in different stiffnesses, since the response and tuning of Option “A” shoulders appeared more favorable after initial testing. The test matrix for the quasi-static tests is shown in Table 3. Only the shoulder variants that were at least as stiff as the forward baseline shoulder were tested in the rearward direction.

Table 2. Alternative Shoulder Designs

Shoulder Design	Spring Description	Material
Option “A” Shoulders	Solid cylinder	Nitrile rubber durometer 60A
	Cylinder with 8 holes	Nitrile rubber durometer 60A
	Cylinder with 12 holes	Nitrile rubber durometer 60A
	Solid cylinder	Carboxylated nitrile rubber durometer 90 (XNBR 90)
	Solid cylinder	Neoprene durometer 93A
	Solid cylinder	Carboxylated nitrile rubber durometer 80A (XNBR 80A)
Option “B” Shoulders	Dual straps	Nitrile rubber durometer 50A
	Dual straps	Carboxylated nitrile rubber durometer 82A (XNBR 82A)

Table 3. Test Matrix for Quasi-Static Tests

Shoulder	Shoulder Type/Number	Direction	Test	
Baseline Shoulders	HIS007-R	Forward	S200806-1	
			S200806-2	
			S200806-3	
	HIS007-L		S200804-1	
			S200805-2	
			S200805-3	
	HIS015-L		S200803-2	
			S200803-3	
			S200803-4	
			HIS007-R	S200806-4
	S200806-5			
	S200806-6			
	HIS007-L			S200805-4
				S200805-5
S200805-6				
HIS015-L	S200803-5			
	S200803-6			
	S200803-7			
Option "A" Shoulders	Nitrile 60A 12 Holes	Forward	180627-3	
	Nitrile 60A 8 Holes		180709-1	
	Nitrile 60A Solid Cylinder		180711-4	
	XNBR 90		180719-8	
	Neoprene 93A		190226-5	
	XNBR 80A		200826-8	
	XNBR 90	Rearward	180730-9	
	Neoprene 93A		190226-3	
	XNBR 80A		200820-16	
Option "B" Shoulders	Nitrile 50A	Forward	180627-5	
	XNBR82A		180711-6	

## Baseline Shoulder Quasi-Static Tests

Figure 34 shows the results for the baseline shoulder quasi-static tests. The shoulder quasi-static responses were evaluated and compared using stiffness results (moment versus rotation). For these tests, three repeats were performed in both forward and rearward directions on three baseline shoulder samples, for a total of nine trials in each direction. The adjustable friction element (Figure 1) on each shoulder was set to 1.5 Nm prior to each test. Previously, the z-axis friction adjustment procedure instructed the user to “Adjust the friction for smooth forward and backward motion of the shoulder. The shoulder spring should be able to bring the shoulder back close to its zero position....” Since this was a qualitative, subjective measure, VRTC determined that a setting of 1.5 Nm would achieve this goal and maintain setup consistency among samples, assuring consistent shoulder rotation about the z-axis for quasi-static and all tests conducted in this report. The shoulder moment was calculated by multiplying the 73 mm (.073 m) moment arm (Figure 28) by the force (N) recorded on the load cell. The angle was measured via the rotary potentiometer.

When rotating the baseline shoulder forward and rearward, the moment did not begin increasing for approximately the first 5° of rotation. Since the baseline design has an adjustable friction washer and requires about 5° of rotation before the spring fully engages, the initial (nearly vertical) portion of the curve is a result of overcoming the static friction (break-away force), followed by an approximately horizontal region resulting from dynamic friction. The response becomes linear once the coil spring becomes wound enough to produce sufficient force; this occurs at approximately 5°. In the forward direction, the stiffness was linear from approximately 5° until nearing the forward rotation stop (49°) (Figure 34); the rearward stiffness was also linear from approximately 5° until nearing the rearward rotation stop (13°). The curves in this plot (and others in this Section) were truncated prior to the stop for presentation clarity. To determine the average stiffness of the baseline shoulder response in each direction, a linear portion of the data was selected, taking care to avoid the first 5° and the nonlinear portion where the components engage the shoulder stop. For the forward direction, data points between 20° and 40° were used (Table 4); for rearward, points between 5° and 12° were selected. A linear regression calculation was performed for each test. The stiffness value for each test is shown in Table 4; the %CV (percent coefficient of variation) was calculated by dividing the standard deviation by the average, expressed as a percentage ( $\%CV = STDEV/AVG * 100$ ). The coefficients of determination ( $R^2$ ) for each test were greater than 0.9 in all cases, indicating good linearity in both directions. The average stiffness in each direction (0.1957 Nm/deg forward, 0.1850 Nm/deg rearward) was used as a target for the moment/angle response of the alternative shoulder designs.

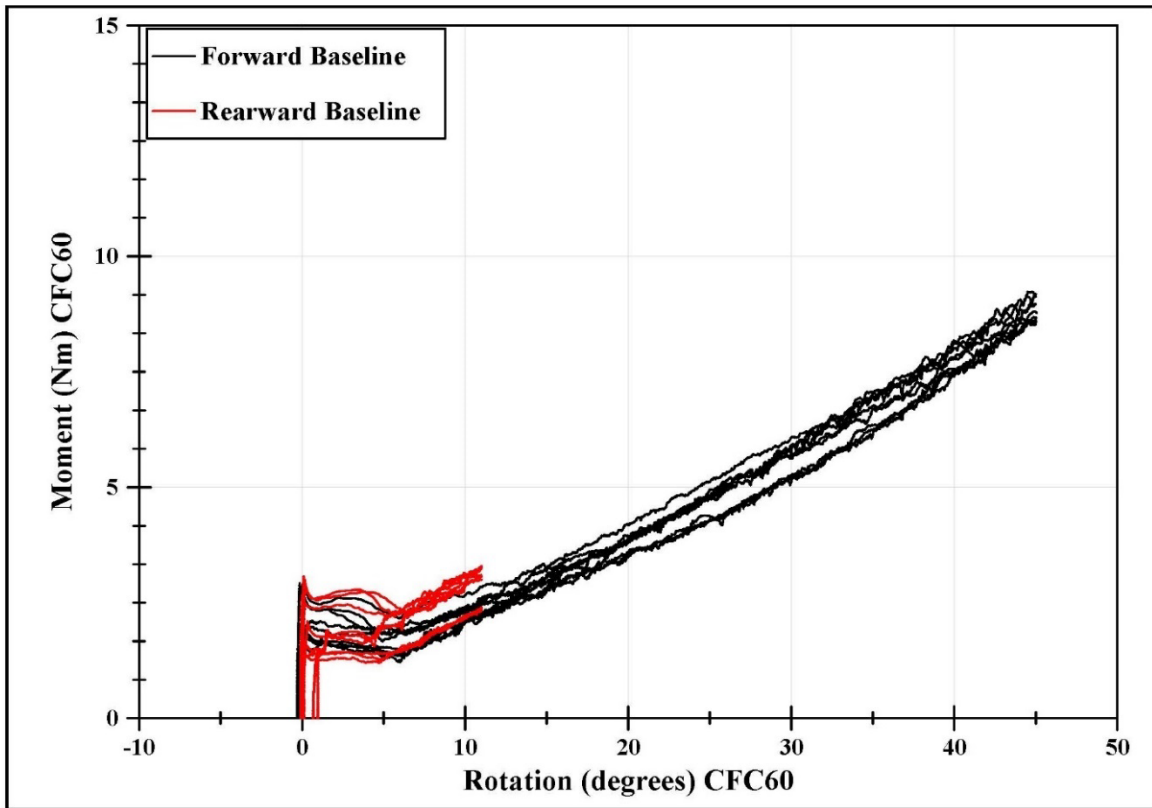


Figure 34. Baseline shoulder moment versus rotation for forward and rearward rotation

Table 4. Linear Regression Results for Baseline Shoulder Tests

Direction	Test	Stiffness (Nm/deg)
Forward	S200806-1	0.2068
	S200806-2	0.2099
	S200806-3	0.2040
	S200804-1	0.1804
	S200805-2	0.1867
	S200805-3	0.1866
	S200803-2	0.1919
	S200803-3	0.1962
	S200803-4	0.1991
	AVG	0.1957
	STDEV	0.0101
	%CV	5.2%

Direction	Test	Stiffness (Nm/deg)
Rearward	S200806-4	0.1923
	S200806-5	0.1788
	S200806-6	0.192
	S200805-4	0.1838
	S200805-5	0.1831
	S200805-6	0.184
	S200803-5	0.1771
	S200803-6	0.1848
	S200803-7	0.1895
	AVG	0.1850
	STDEV	0.0054
	%CV	2.9%

#### Option “A” Shoulder Quasi-Static Tests

The results from forward rotations of six different versions of the Option “A” shoulder versus the baseline shoulder are presented in Figure 35. Table 5 indicates that all the units showed good linearity in the forward direction. Due to the absence of a friction element in the Option “A” shoulder design, there is not a non-linear region like the baseline shoulders prior to 5°. The linear response is due only to the molded rubber springs. When comparing the average baseline shoulder stiffness (0.1957 Nm/deg) to the stiffnesses from various versions of the Option “A” shoulder, the XNBR 80A (highlighted in yellow in Table 5) version was closest to the baseline shoulder with only a 0.4 percent difference in stiffness. The nitrile springs were all too soft while the XNBR 90 and Neoprene 93A versions were too stiff. The XNBR 80A version of the shoulder (test 200826-8) responded closest to the baseline shoulder in the forward pull tests.

For the rearward rotation tests, a comparison between the baseline shoulder and the versions of Option “A,” showed similar trends to the forward rotation tests (Figure 36, note that the XNBR 90 and Neoprene 93A versions were not exercised fully to the stop). When comparing the stiffness of the average baseline shoulder (0.1850 Nm/deg) to the Option “A” shoulder designs, the XNBR 80A (highlighted in yellow in Table 5) springs responded most closely to the baseline shoulder in the rearward tests, with a 2.4 percent difference from baseline shoulder.

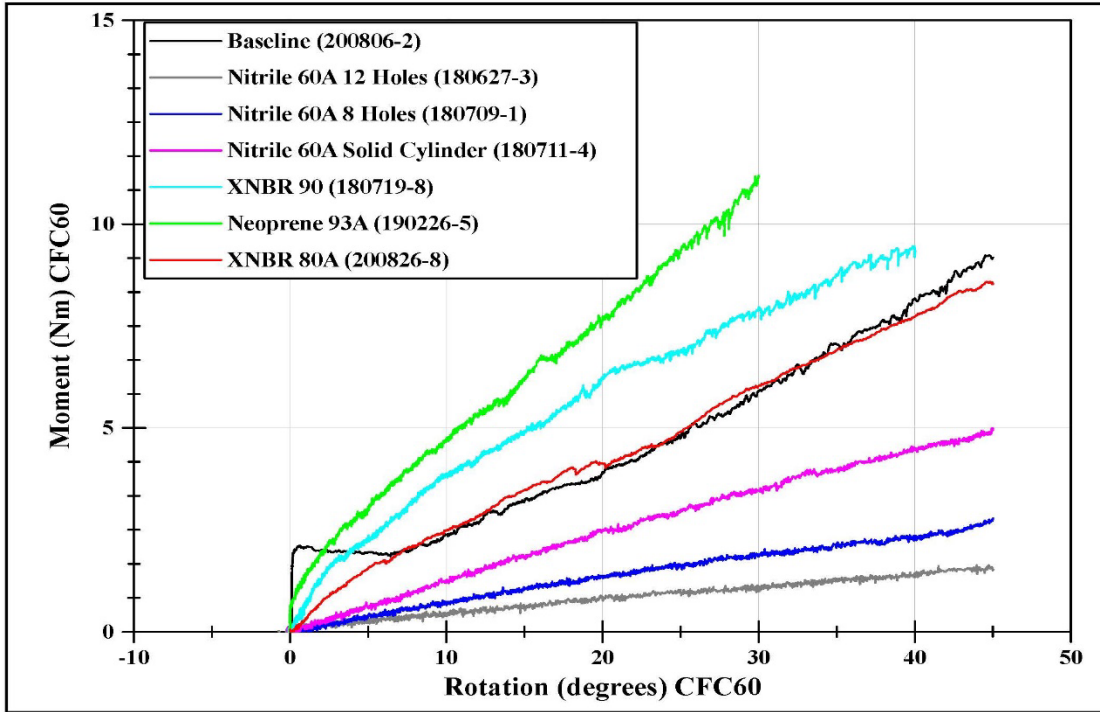


Figure 35. Forward rotation results for variations of the Option “A” shoulder compared to the baseline shoulder

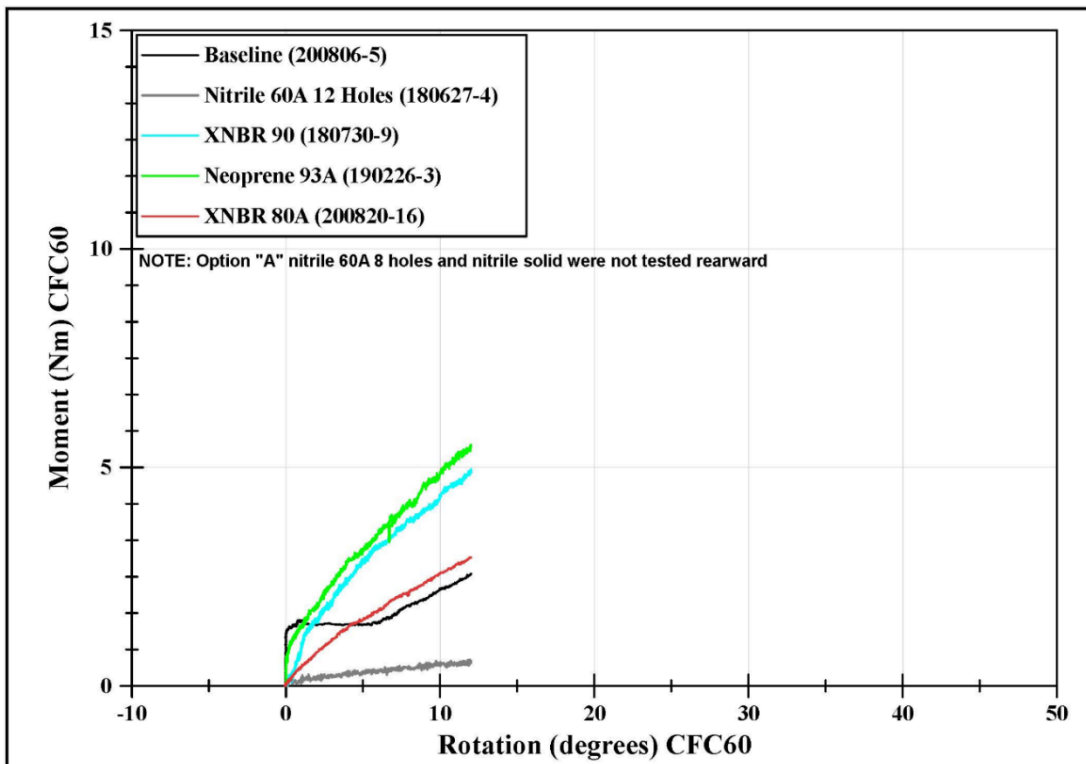


Figure 36. Rearward rotation results for variations of the Option “A” shoulder compared to the baseline shoulder

Table 5. Comparison of Option “A” to Baseline Shoulder Results

Direction	Test	Stiffness (Nm/deg)	% Diff from Baseline Shoulder
<b>Forward</b> (baseline shoulder stiffness = 0.1957)	Nitrile 60A 12 Hole	0.0287	16.7%
	Nitrile 60A 8 Hole	0.0473	14.8%
	Nitrile 60A Solid	0.1037	9.2%
	XNBR90	0.1648	3.1%
	Neoprene 93A	0.3331	13.7%
	XNBR80A	0.1918	0.4%
<b>Rearward</b> (baseline shoulder stiffness = 0.1850)	XNBR90	0.2842	9.9%
	Neoprene 93A	0.3472	16.2%
	XNBR80A	0.2091	2.4%

### Option “B” Shoulder Quasi-Static Tests

The forward rotation results for two different versions of the Option “B” shoulder are shown in Figure 37. Table 6 Shows a comparison of the Option “B” shoulder designs to the baseline shoulder. These results indicate that neither version of the Option “B” shoulder is stiff enough in the forward direction and differ from the baseline shoulder by 15 percent or more. Since these two samples were not as stiff as the baseline shoulder, no rearward results are given. Since the Option “B” shoulder was not stiff enough, and the mechanism was much more complex than Option “A” it was eliminated from further consideration after the simpler design, Option “A,” proved viable. Based on the results from the quasi-static tests, the Option “A” XNBR 80A shoulder, was selected as the most appropriate design version in quasi-static tests.

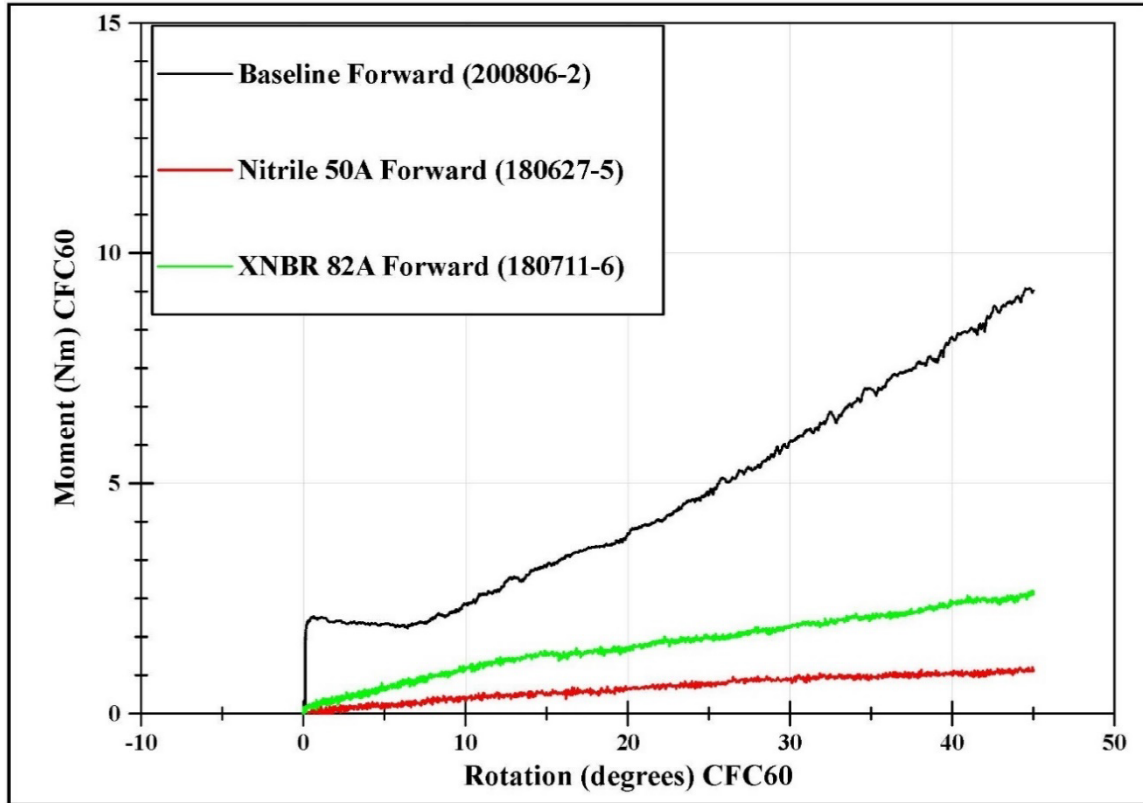


Figure 37. Forward rotation results for variations of the Option “B” shoulder compared to baseline shoulder

Table 6. Comparison of Option “B” Shoulder Results to Baseline Shoulder Tests

Direction	Test	Stiffness (Nm/deg)	R <sup>2</sup>	% Diff from Baseline Shoulder
Forward (baseline shoulder stiffness = 0.1957)	Nitrile 50A	0.0161	0.8652	18.0%
	XNBR82A	0.0451	0.9781	15.1%

### Qualification Tests

Based on the results from the quasi-static tests, it was determined that the three Option “A” shoulders, which were at least as stiff as the baseline, were the most appropriate designs to evaluate in qualification tests; the other rubber molded springs were deemed too soft and would not provide the resistance required to position the arms close to the neutral position. The upper thorax qualification test was selected for comparison since this test would be most likely of all the qualifications to show differences due to the proximity of the impact with the shoulder. Table 7 shows a comparison of upper thorax qualification tests using the baseline shoulder and three different Option “A” shoulder designs: XNBR90, Neoprene 93A, and XNBR 80A. The baseline shoulder and all variants of the Option “A” shoulder versions passed the qualification tests. The test results are shown in Figure 38 to Figure 41.

Table 7. Baseline Shoulder and Option “A” Shoulders Comparison: Upper Thorax Qualification Tests

Parameter	Units	Specification		Baseline Shoulder	Option “A” XNBR 90 Shoulder	Option “A” Neoprene 93A Shoulder	Option “A” XNBR 80A Shoulder
		Min.	Max.	200915-2	180724-2	181030-4	200924-6
Impact Velocity	m/s	4.25	4.35	4.32	4.31	4.34	4.31
Peak Probe Force	N		3039	2633	2853	2661	2630
Peak Upper Left Resultant Deflection	mm	48.3	59.0	51.5	54.2	55.5	50.6
Peak Upper Right Resultant Deflection	mm			53.4	52.6	51.7	55.3
Difference Between Peak Left & Right Resultant Deflections	mm		< 5.0	1.9	1.6	3.8	4.7
Force at Left Peak Resultant Deflection	N	2409	2944	2633	2773	2590	2586
Force at Right Peak Resultant Deflection				2628	2766	2630	2582

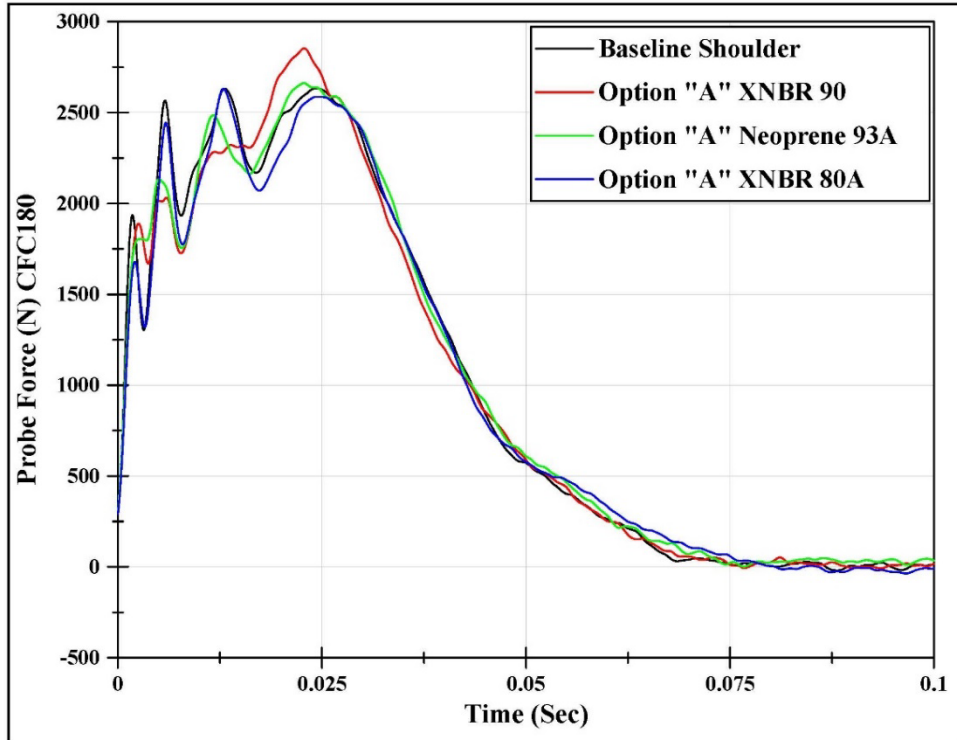


Figure 38. Upper thorax qualification probe force results from Option "A" shoulder and baseline shoulders

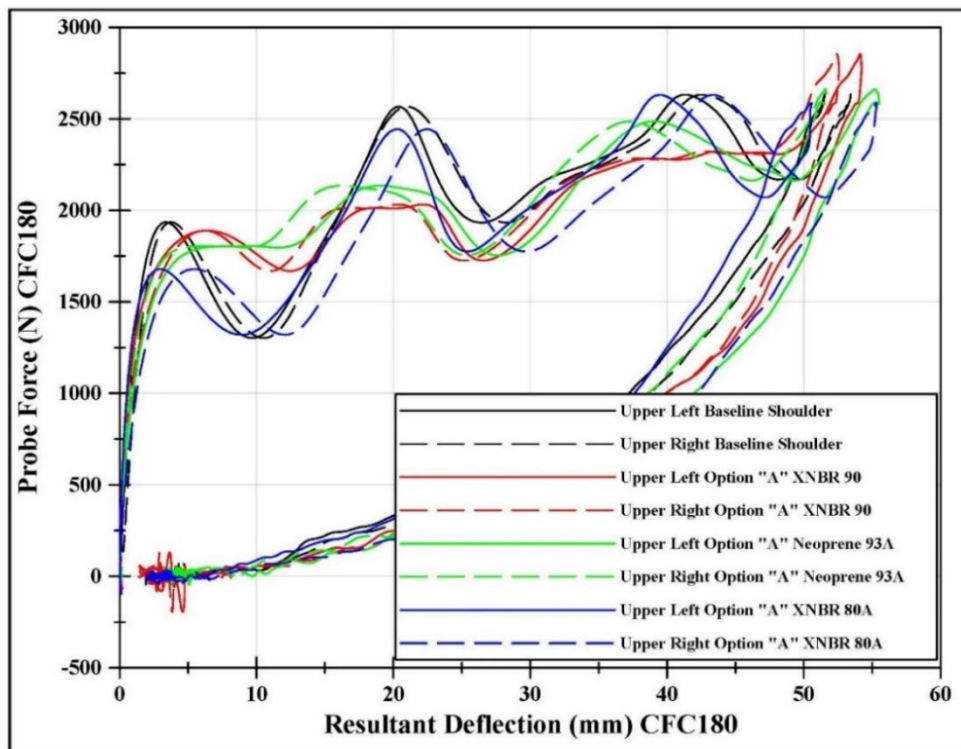


Figure 39. Upper thorax qualification probe force versus resultant deflection from Option "A" shoulder and baseline shoulders

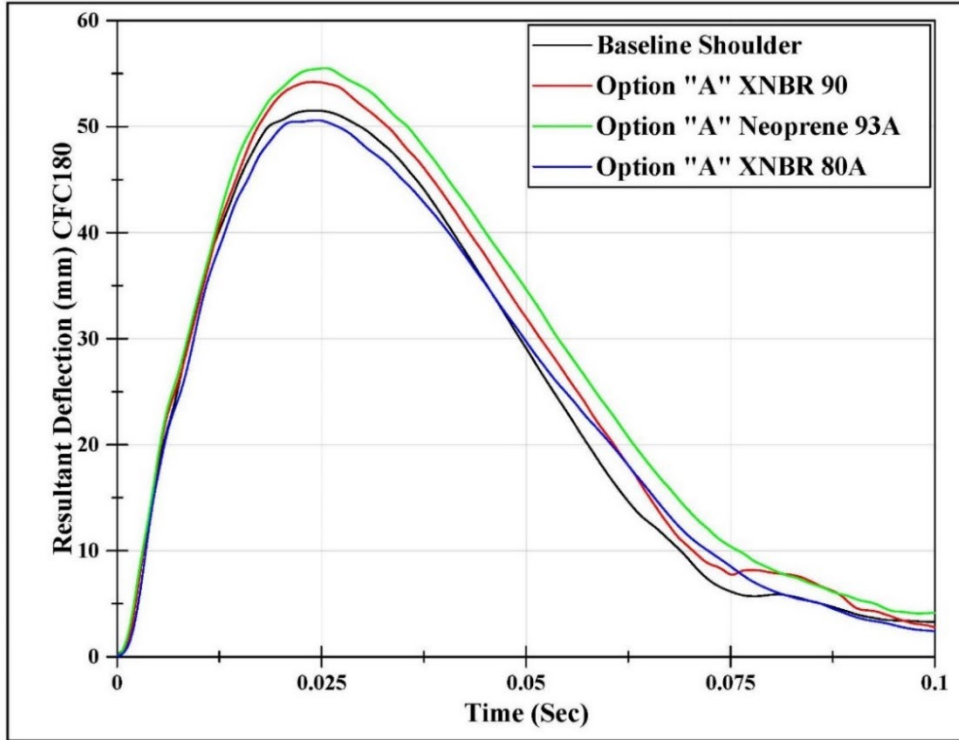


Figure 40. Upper thorax left resultant deflection from Option "A" shoulder and baseline shoulders

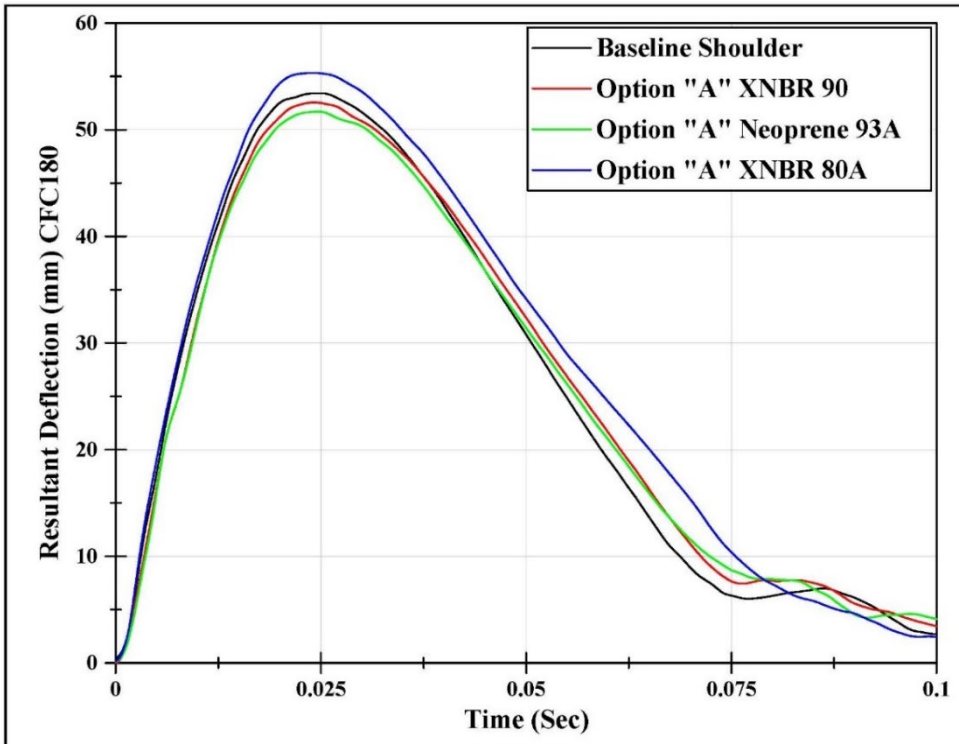


Figure 41. Upper thorax right resultant deflection from Option "A" shoulder and baseline shoulders

In addition to performing the upper thorax tests, the dummy was positioned (but not tested) for lower thorax and abdomen qualification tests with the Option “A” shoulder installed, to assure that the shoulder did not pose any issues with positioning the arms for the tests. With regards to positioning, for all three qualification tests (upper thorax, lower thorax, and abdomen), the THOR-50M was successfully positioned for impact; that is, all setup angles were achievable:

Upper and lower thorax: T6 angle -4.0°, pelvis angle +15.0°

Abdomen: T6 angle -4.0°, pelvis angle +10.0°

In addition to the setup angles, the qualification procedures for the upper thorax, lower thorax, and abdomen qualification tests state that the shoulder is positioned using the alignment marks (see Figure 29). The baseline shoulder allows this alignment, likely because the coil spring permits easier adjustment of the shoulder since it does not produce load immediately, as shown in the quasi-static tests. The Option “A” shoulder aligns with the neutral position mark when it is not installed in the dummy; this was the case in the quasi-static tests (Figure 29). However, when the shoulder is installed into the THOR-50M, the influence of the mass from the arm and clavicle mechanism may load the rubber spring, pulling the shoulder slightly away from the alignment mark; a counteractive force would be necessary to overcome this loading, which is not possible in the setup. The quasi-static tests confirm this theory, revealing that the Option “A” shoulder is linear and produces force immediately upon rotation, which is not the case with the baseline shoulder. However, despite the Option “A” shoulder not being aligned at the marks, the dummy positioning angles were achieved. The test results showed similar responses for the Option “A” shoulder when compared to the baseline shoulder, so the alignment does not appear to influence results (Figure 38 through Figure 41).

### **Repeatability of Upper Thorax Qualification Tests**

Since the Option “A” XNBR 80A shoulder’s quasi-static and qualification tests showed promising responses, this design was selected for additional upper thorax qualification testing to examine repeatability (Table 8). The Option “A” XNBR 80A shoulder with molded rubber spring serial number V005 was installed on the left side, and molded rubber spring serial number V006 was installed on the right side of THOR-50M SN 0015. Three repeat upper thorax qualification tests were performed with the alternative shoulders. Each test passed the specifications, while the combined responses all produced %CV values of 2 percent or lower.

*Table 8. Option “A” XNBR 80A Shoulder Repeatability: Upper Thorax Qualification Tests*

Parameter	Units	Specification		Option “A” XNBR 80A Shoulder					
		Min.	Max.	230404-2	230404-3	230404-4	Avg	Std Dev	%CV
Impact Velocity	m/s	4.25	4.35	4.29	4.30	4.30	4.30	0.01	0%
Peak Probe Force	N		3039	2747	2705	2685	2712	32	1%
Peak Upper Left Resultant Deflection	mm	48.3	59.0	51.4	53.0	53.4	52.6	1.1	2%

Parameter	Units	Specification		Option "A" XNBR 80A Shoulder					
		Min.	Max.	230404-2	230404-3	230404-4	Avg	Std Dev	%CV
Peak Upper Right Resultant Deflection	mm			53.4	53.8	53.9	53.7	0.3	1%
Difference Between Peak Left & Right Resultant Deflections	mm		< 5.0	2.0	0.8	0.6	1.1	0.8	
Force at Left Peak Resultant Deflection	N	2409	2944	2740	2679	2653	2691	45	2%
Force at Right Peak Resultant Deflection				2674	2669	2581	2641	52	2%

For comparison, repeatability tests with the baseline shoulder are presented in Table 9. Like the Option "A" XNBR 80A shoulders, the baseline shoulders also resulted in passing all specifications while also producing %CV values of 2 percent or lower.

*Table 9. Baseline Shoulder Repeatability: Upper Thorax Qualification Tests*

Parameter	Units	Specification		Baseline Shoulder					
		Min.	Max.	230403-1	230403-2	230403-3	Avg	Std Dev	%CV
Impact Velocity	m/s	4.25	4.35	4.30	4.30	4.30	4.30	0.00	0%
Peak Probe Force	N		3039	2737	2662	2682	2693	38	1%
Peak Upper Left Resultant Deflection	mm	48.3	59.0	53.8	52.8	53.3	53.3	0.5	1%
Peak Upper Right Resultant Deflection	mm			54.9	53.6	53.1	53.8	0.9	2%
Difference Between Peak Left & Right Resultant Deflections	mm		< 5.0	1.1	0.8	0.2	0.7	0.5	

Parameter	Units	Specification		Baseline Shoulder					
		Min.	Max.	230403-1	230403-2	230403-3	Avg	Std Dev	%CV
Force at Left Peak Resultant Deflection	N	2409	2944	2655	2574	2543	2591	58	2%
Force at Right Peak Resultant Deflection				2638	2598	2564	2600	37	1%

To assess the equivalence between the two designs, the data was combined in Table 10; since all the %CVs are 2 percent or lower with the combined data, the Option “A” XNBR 80A and baseline shoulders appear to be equivalent. Overlays of all tests are presented in Figure 42 to Figure 45.

*Table 10. Combined Option “A” XNBR 80A Shoulder and Standard Baseline Shoulder Repeatability*

*Upper Thorax Qualification Tests*

Parameter	Units	Specification		Alternative & Baseline Shoulders		
		Min.	Max.	Avg	Std Dev	%CV
Impact Velocity	m/s	4.25	4.35	4.30	0.00	0%
Peak Probe Force	N		3039	2703	33	1%
Peak Upper Left Resultant Deflection	mm	48.3	59.0	52.9	0.8	2%
Peak Upper Right Resultant Deflection	mm			53.8	0.6	1%
Difference Between Peak Left & Right Resultant Deflections	mm		< 5.0	0.9	0.6	
Force at Left Peak Resultant Deflection	N	2409	2944	2641	72	3%
Force at Right Peak Resultant Deflection				2620	46	2%

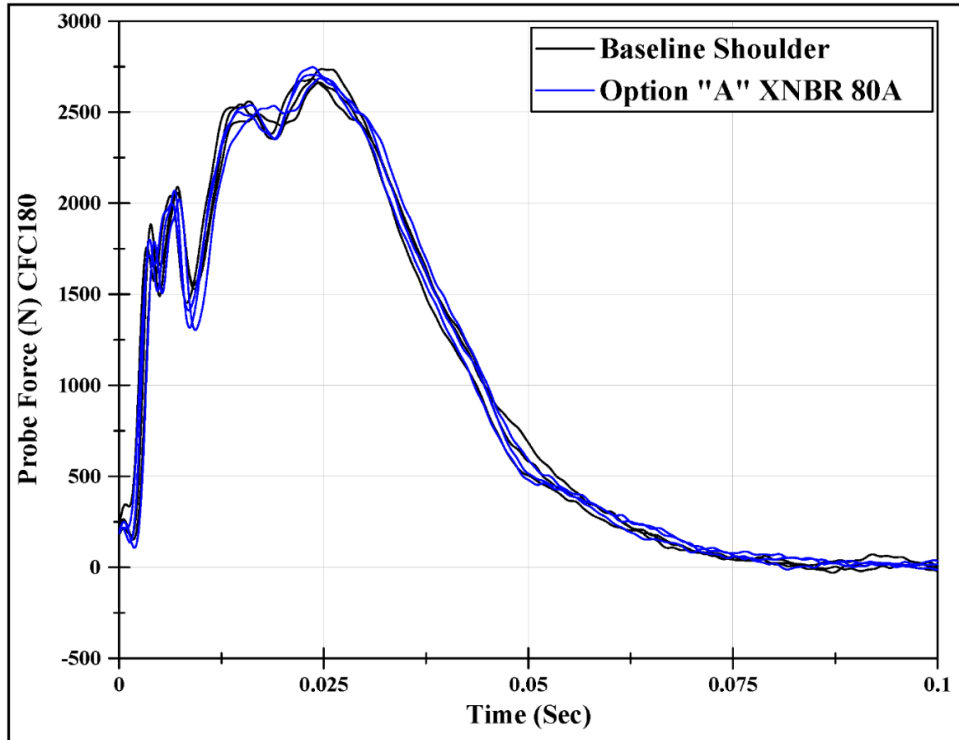


Figure 42. Upper thorax qualification probe force results from Option "A" XNBR 80A and baseline shoulders

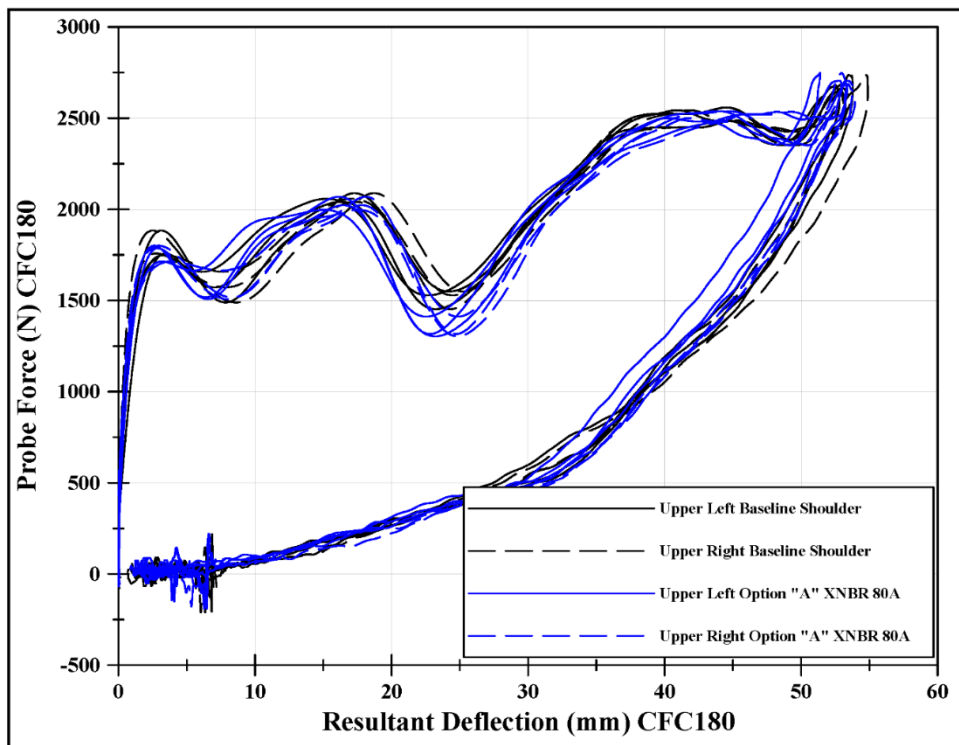


Figure 43. Upper thorax qualification probe force versus resultant deflection from Option "A" XNBR 80A and baseline shoulders

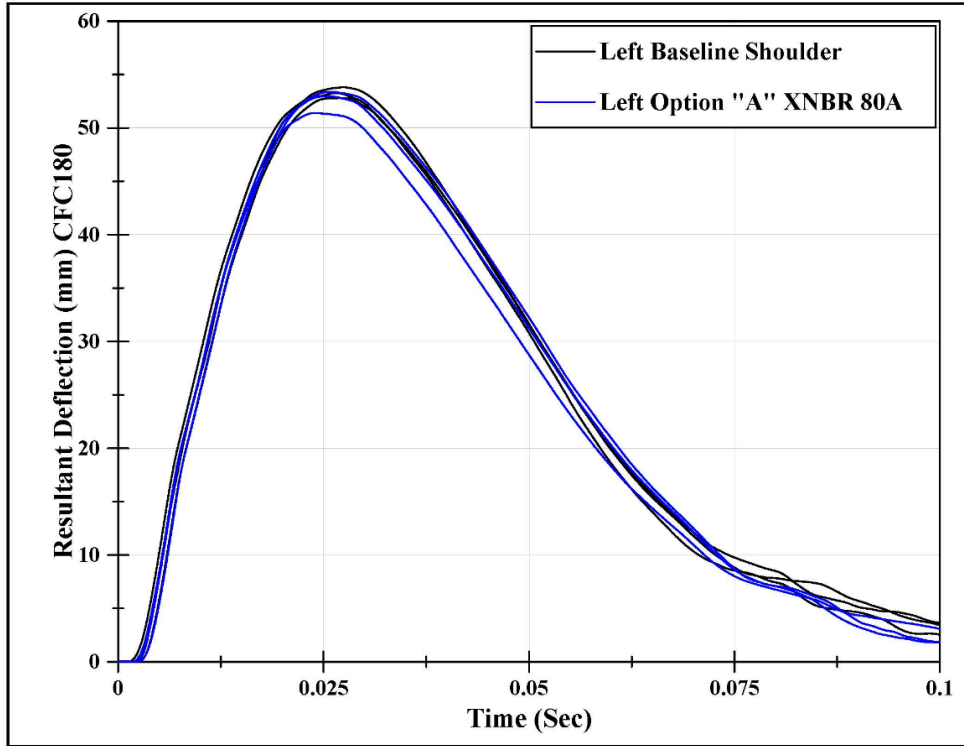


Figure 44. Upper thorax left resultant deflection from Option "A" XNBR 80A and baseline shoulders

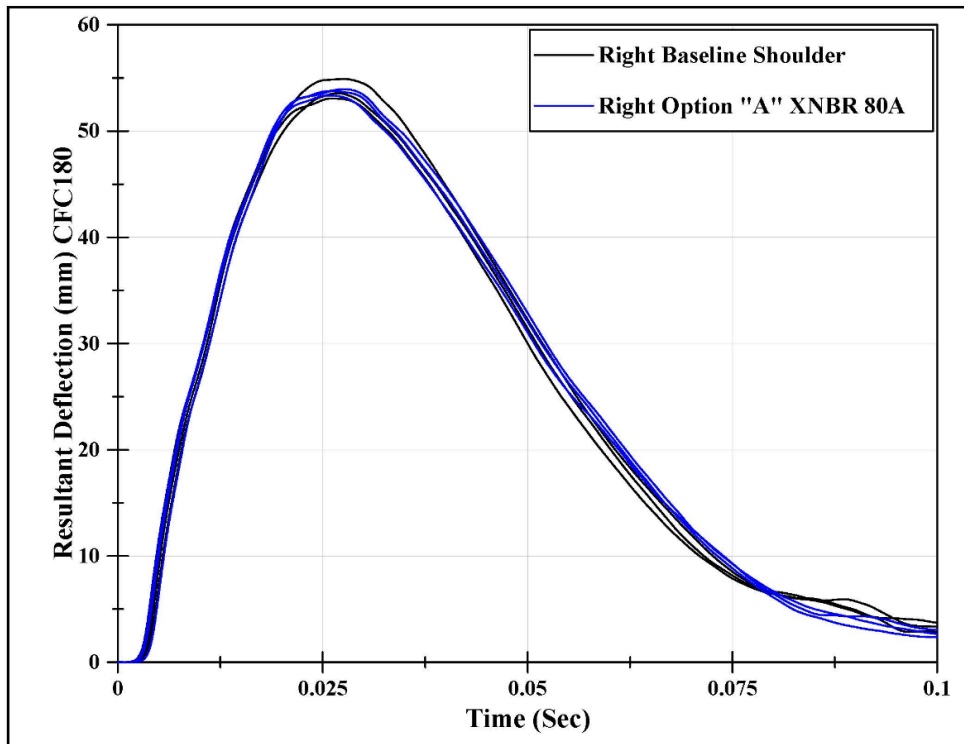


Figure 45. Upper thorax right resultant deflection from Option "A" XNBR 80A shoulder and baseline shoulders

## Sled Tests

Sled tests were performed to compare the THOR-50M Option “A” XNBR 80A shoulder to the baseline shoulder in a dynamic test environment. The Option “A” XNBR 80A shoulders and the baseline shoulders were installed into two THOR-50M ATDs. An evaluation of the responses of the baseline shoulder and Option “A” XNBR 80A shoulder designs in the sled tests included a comparison of kinematics, restraint interaction, chest deflections, and any durability issues which may be attributed to the Option “A” XNBR 80A shoulder.

### ***Test Setup and Conduct***

A 2017 Mazda CX3 sled buck equipped with driver and front passenger seats, air bags, and seat belt pretensioners was used for testing (Figure 46). The buck was reinforced in several areas to improve ATD repeatability between tests. The reinforced areas included the driver and passenger seat mounting brackets, driver footrest, knee bolsters, center console, D-ring and retractor mounting.



*Figure 46. THOR-50M Driver (top) and passenger (bottom) seated for test*

Six tests were conducted in the frontal mode with an average change of velocity ( $\Delta V$ ) of 41.6 mph and average peak acceleration pulse of 38.0 G (Table 11). This pulse approximated the Mazda CX3 frontal NCAP test (#9494). Two different THOR-50M ATDs were used (SN 015 and SN 016). The baseline and alternative shoulders were swapped between the two ATDs after the first three tests were conducted, resulting in each of the two ATDs being configured and tested with both baseline and Option “A” XNBR 80A shoulders. THOR-50M instrumentation included accelerometers and angular rate sensors in the head, upper and lower neck load cells, spine accelerometers (T1, T6, and T12), upper and lower chest IR-TRACCs to measure deflection, pelvis accelerometers, ASIS and acetabulum load cells.

Table 11. Test Matrix for Sled Tests

Test	Velocity (mph)	Acceleration (g)	Driver	Passenger
S201123-1	41.7	38.0	THOR-50M 016 Option “A” XNBR 80A shoulder	THOR-50M 015 baseline shoulder
S201201-1	41.7	38.0		
S201203-1	41.7	38.1		
S201208-1	41.5	37.9	THOR-50M 016 baseline shoulder	THOR-50M 015 Option “A” XNBR 80A shoulder
S201209-1	41.5	38.0		
S201210-1	41.4	38.1		

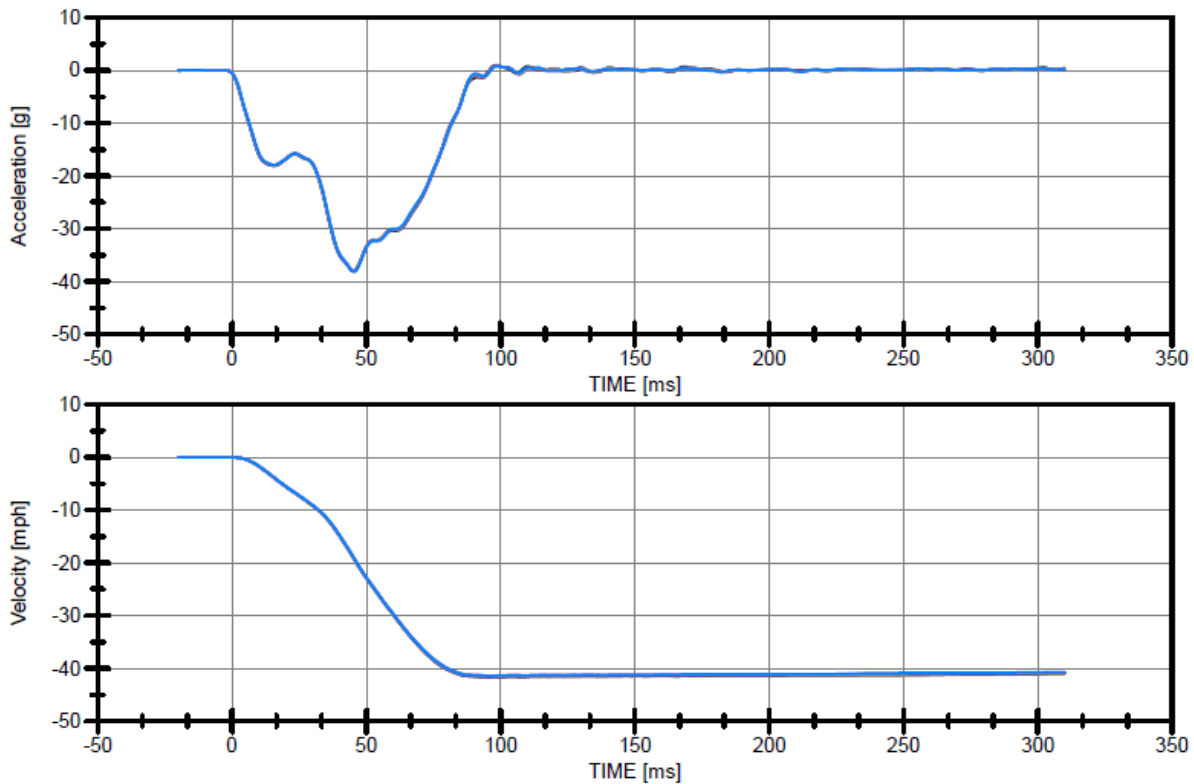


Figure 47. Sled pulse acceleration and velocity

## Test Results

The measurements selected for comparison included those measurements which would have been most influenced by the shoulder, such as peak head excursion and the maximum deflections; these are also the values used to assess potential injuries. The maximum deflections were assessed by selecting the maximum deflection that occurred in a given body region. For the thorax, it was the right upper resultant deflection, and for the abdomen it was the right resultant deflection. To compare any influence of the alternative shoulder on dummy response, the repeatability of both the alternative and baseline shoulders was first examined. If the three repeat tests using the same dummy and same shoulder are repeatable, then the %CVs will be low.

For the driver, Table 12 shows the %CV values from the Option “A” XNBR 80A shoulder are 4 percent or below; the baseline shoulder %CVs were 2 percent or below. Both shoulders are therefore repeatable. The charts in Figure 48 and Figure 49 visually show the repeatability.

Next, the data from the Option “A” XNBR 80A shoulder and the baseline shoulder were combined. These %CV results are also low (4% or below), indicating that the Option “A” XNBR 80A shoulder and baseline shoulders are comparable.

Table 12. Sled Test Results THOR-50M 016 (Driver)

	Test	Head Excursion (mm)	Chest Res. Defl. Upper Right	Right Abdomen Res. Defl.
<b>Option “A” XNBR 80A Shoulder</b>	S201123-1	543	NA	44.4
	S201201-1	548	44.1	45.5
	S201203-1	553	46.4	45.2
	Avg.	548	45.3	45.0
	Std. Dev.	5	1.6	0.6
	%CV	1%	4%	1%
<b>Baseline Shoulder</b>	S201208-1	558	48.7	46.9
	S201209-1	548	49.0	47.6
	S201210-1	545	47.9	48.9
	Avg.	550	48.6	47.8
	Std. Dev.	7	0.6	1.0
	%CV	1%	1%	2%
<b>Both Driver (SN 016) Option “A” XNBR 80A &amp; Baseline Shoulders</b>	Avg.	549	47.2	46.4
	Std. Dev.	5	2.0	1.7
	%CV	1%	4%	4%

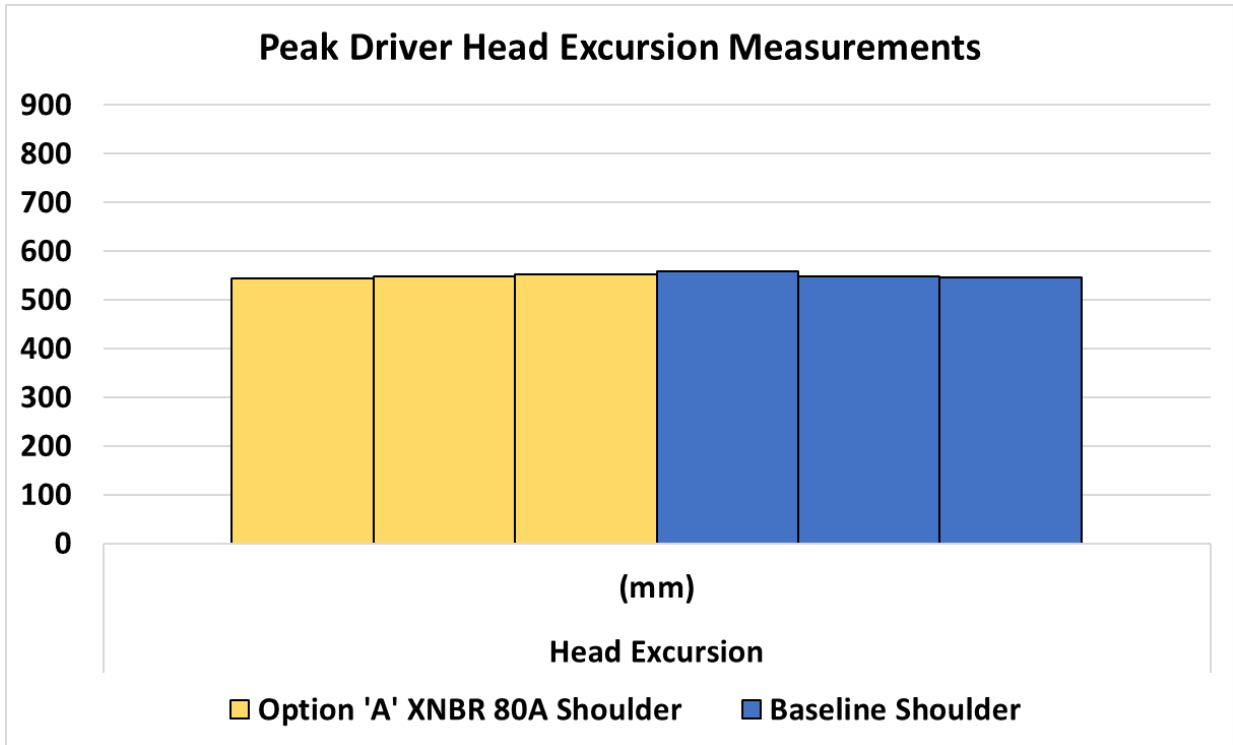


Figure 48. Driver head excursions for Option “A” XNBR 80A and baseline shoulders in sled tests

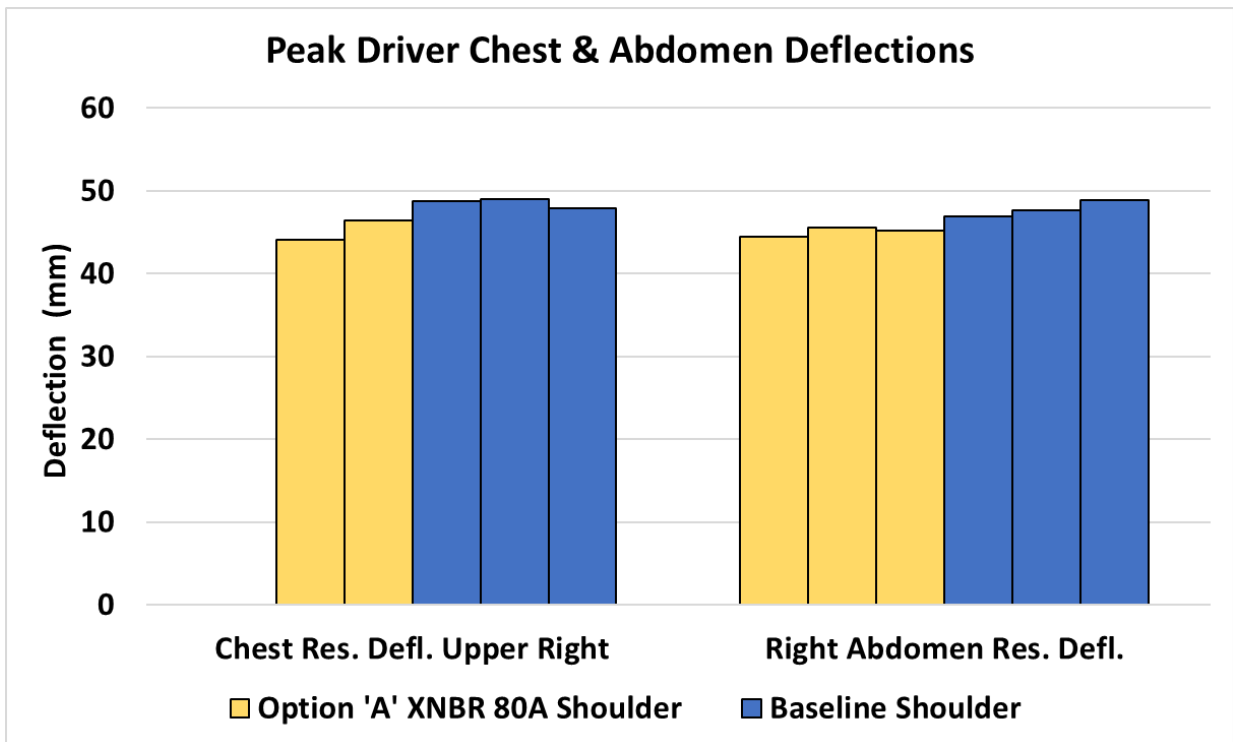


Figure 49. Driver chest and abdomen deflections for Option “A” XNBR 80A and baseline shoulders in sled tests

For the passenger, Table 13 shows the %CV values from the Option “A” XNBR 80A shoulder are 7 percent or below while the baseline shoulder %CVs were 6 percent or below. While the %CVs may seem somewhat elevated for both sets of shoulders, these values are within reason for such a dynamic test environment. Both Option “A” XNBR 80A and baseline shoulders exhibited similar levels of repeatability in the dynamic sled environment. Figure 50 and Figure 51 also show how the measurements compare between the two different shoulders.

When the data from the Option “A” XNBR 80A shoulder and the baseline shoulder tests were combined, the %CV results were 10 percent or below indicating that the Option “A” XNBR 80A and baseline shoulders are comparable.

*Table 13. Sled Test Results THOR-50M 015 (Passenger)*

	<b>Test</b>	<b>Head Excursion (mm)</b>	<b>Chest Res. Defl. Upper Left</b>	<b>Right Abdomen Res. Defl.</b>
<b>Option “A” XNBR 80A Shoulder</b>	S201208-1	700	38.5	39.0
	S201209-1	762	37.1	37.4
	S201210-1	758	42.2	42.0
	Avg.	740	39.3	39.5
	Std. Dev.	35	2.6	2.3
	%CV	5%	7%	6%
<b>Baseline Shoulder</b>	S201123-1	817	48.3	41.3
	S201201-1	762	44.0	38.4
	S201203-1	752	43.1	41.3
	Avg.	777	45.1	40.3
	Std. Dev.	35	2.8	1.7
	%CV	5%	6%	4%
<b>Both Passenger (SN 015) Option “A” XNBR 80A &amp; Baseline Shoulders</b>	Avg.	759	42.2	39.9
	Std. Dev.	37	4.0	1.9
	%CV	5%	10%	5%

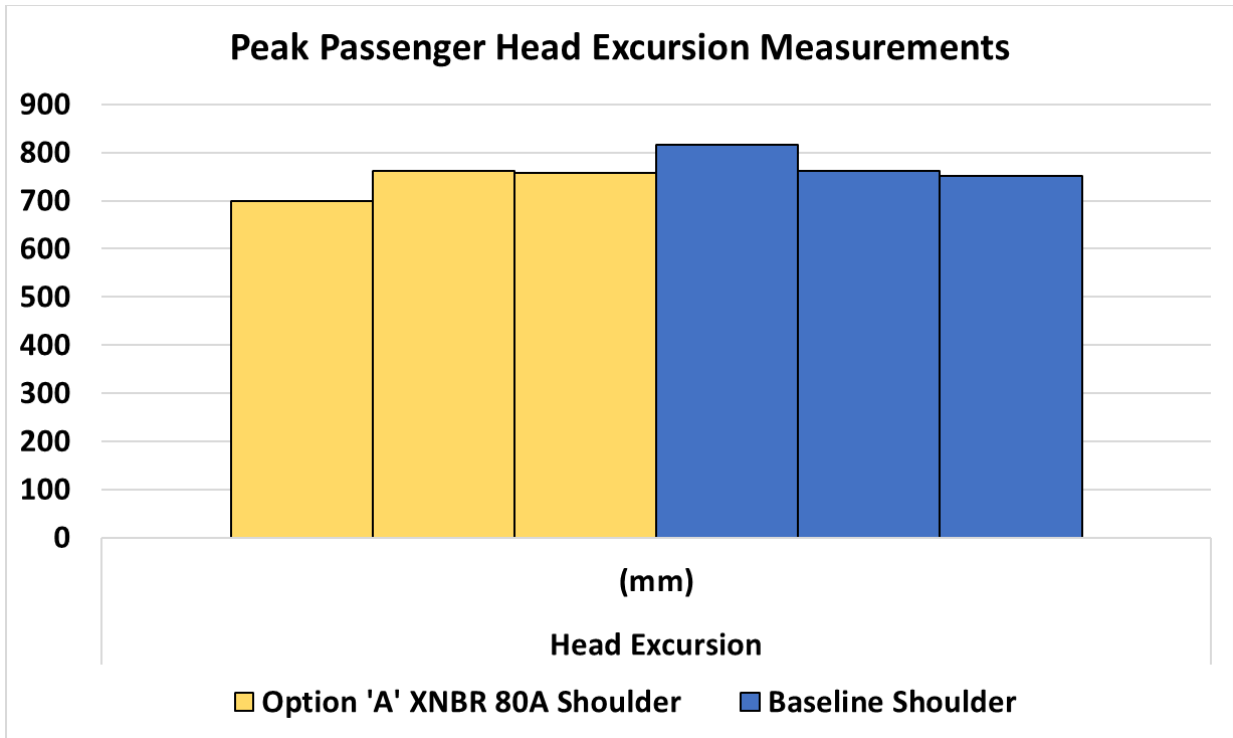


Figure 50. Passenger head excursions for Option “A” XNBR 80A and baseline shoulders in sled tests

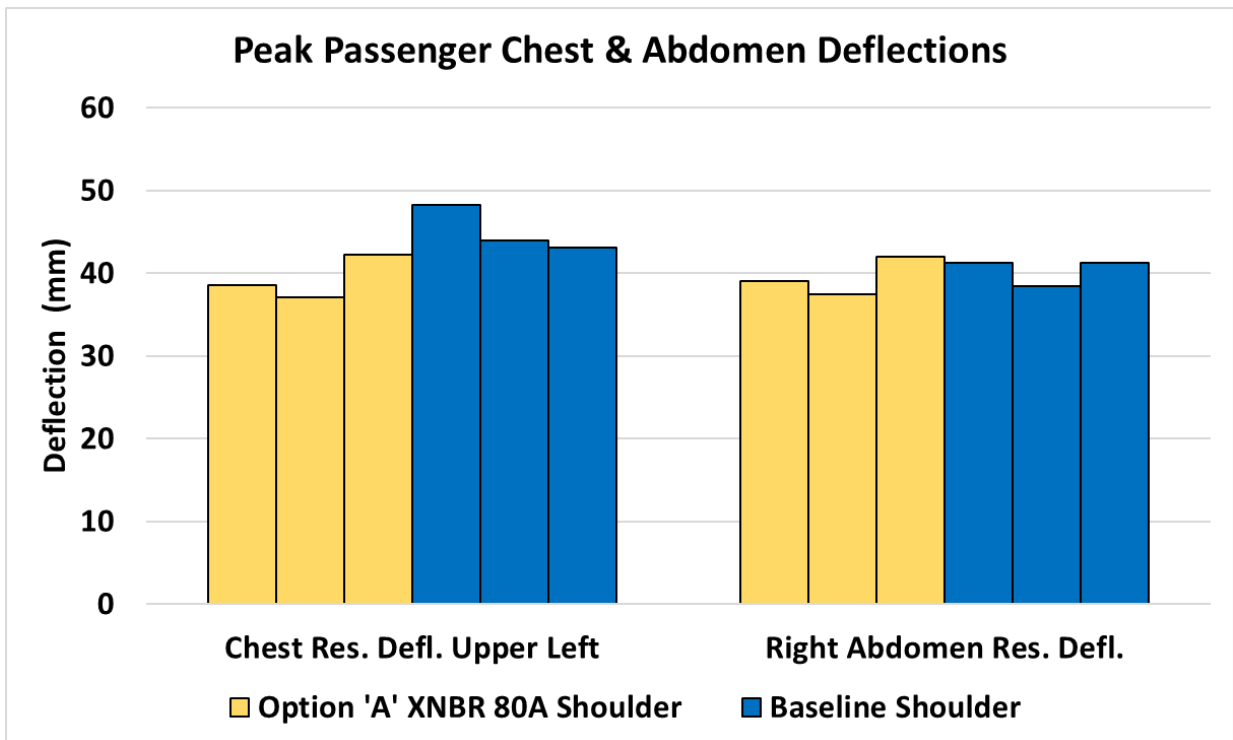


Figure 51. Passenger chest and abdomen deflections for Option “A” XNBR 80A and baseline shoulders in sled tests

## Durability Tests

To examine durability, quasi-static tests were compared on both left and right shoulders before and after sled tests (Table 14). Results indicate that both shoulders perform similar before and after sled tests showing that the design has good durability (Figure 52 and Figure 53).

Table 14. Test Matrix for Quasi-Static Durability Tests

Test	Pre or Post Sled	Rotation Direction	Shoulder Serial Number
S200820-6	Pre-sled	Forward	V005 (Left)
S201117-7	Post-sled		
200820-16	Pre-sled	Rearward	
201118-1	Post-sled		
200826-8	Pre-sled	Forward	V006 (Right)
201118-3	Post-sled		
200826-3	Pre-sled	Rearward	
201118-4	Post-sled		

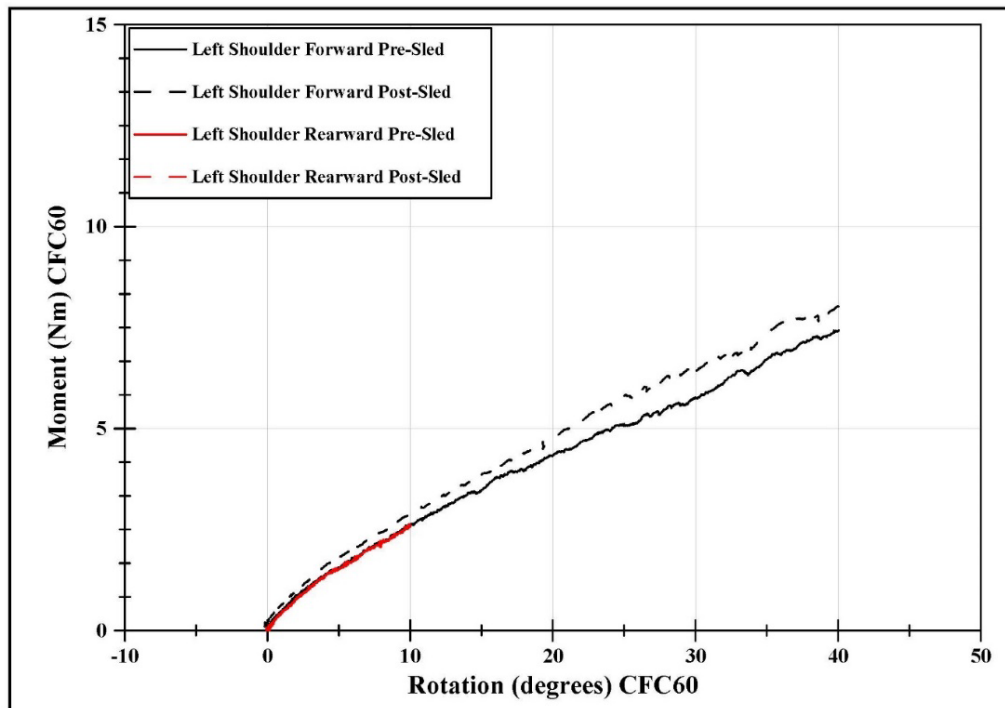


Figure 52. Quasi-static test results for Option “A” XNBR 80A left shoulder (V005) before and after sled tests

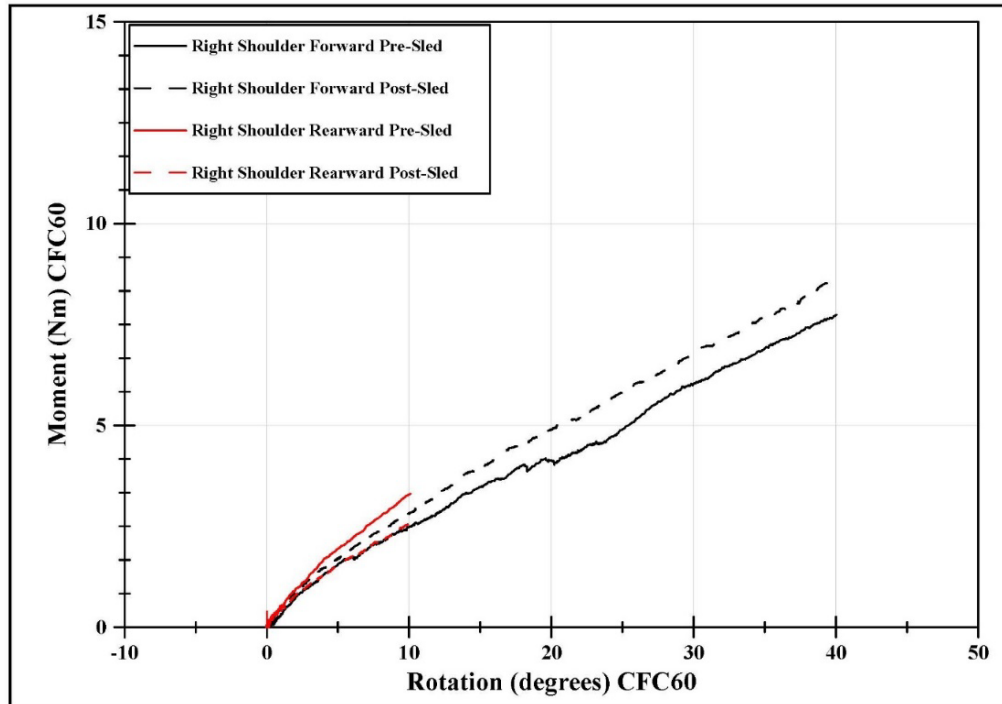


Figure 53. Quasi-static test results for Option “A” XNBR 80A right shoulder (V006) before and after sled tests

## Biofidelity Tests

For the biofidelity tests, to compare shoulder range of motion and stiffness, the THOR-50M ATD arms were statically loaded at three different angles as described in tests conducted by Tornvall et al. (2005). At increasing force level intervals, the position of the shoulder was analyzed using a FARO 3-D location device; this differs from the film analysis performed during the Tornvall study but increases accuracy of the point locations. Since the Option “A” XNBR 80A shoulder in the quasi-static, qualification, and sled tests showed promising responses, this design was selected for biofidelity testing; results were compared between the Option “A” XNBR 80A and baseline shoulders. The Option “A” XNBR 80A shoulder with molded rubber spring serial number V005 was installed on the left side, and molded rubber spring serial number V006 was installed on the right side. These parts were tested quasi-statically and verified to respond as required; Section 0 includes the data from these two molded rubber springs.

## Test Setup and Conduct

For these tests, a fixture was fabricated to load both arms when oriented at three different angles: 90°, 135°, and 170° (relative to vertical) (Figure 54). The THOR was seated in a front-passenger Honda Odyssey seat (2011-2013) in the most upright seat back adjustment position (approximately vertical), with the thorax perpendicular to the lower extremities (as defined by Tornvall et al. 2005). The forearm was removed to aid in pulling at the correct orientations; pull angles were determined by placing an inclinometer at the end of the arm near the elbow joint (Figure 55). Prior to testing, the shoulder was set to “1G” so that the mass of the forearm did not have an adverse effect by counteracting the loading force. A seat belt and a sternum support were used to help hold the THOR-50M in place. The test rig supports the sternum and maintains

positioning while allowing step loading of both arms in 5 kg (~25 N) weight increments up to 40 kg (~400 N), using cables and pulleys (Figure 56). Approximately 400 N was loaded onto a single cable that then split to both arms, simultaneously applying approximately 200 N of force on each arm.

First, the arms were oriented to the pull angle and subjected to the maximum load at the beginning of each test angle to minimize slack in the setup. Next, all mass was removed and the 3-D locations of the shoulders and spine on the THOR-50M were then measured (Figure 57 and Figure 58); Tornvall measured just the shoulder position, but the additional measurement of the spine allows calculation of the movement of the shoulder relative to the spine, in case some unwanted motion of the dummy occurred during loading. Then, mass was added to the hanger in 5 kg increments, to furnish the appropriate pull-force, and the 3-D locations of both shoulders and the spine on the THOR-50M were measured again at each load.

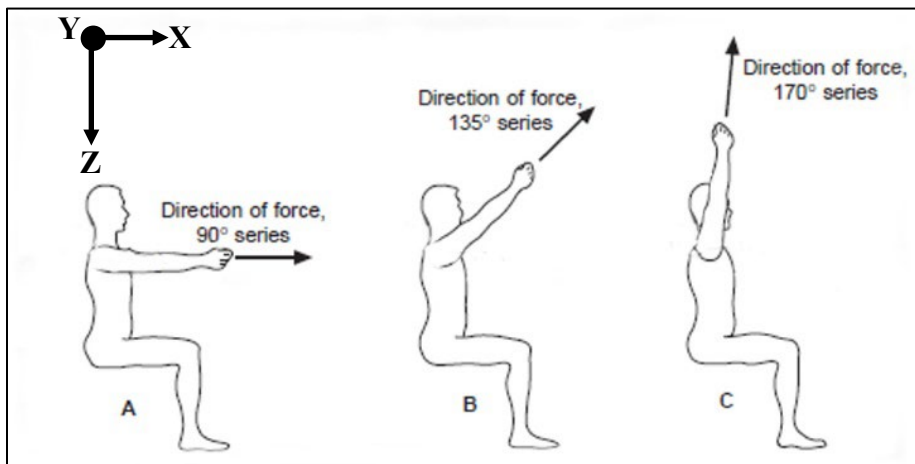


Figure 54. Direction of force for three arm angles tested (Tornvall et. al., 2005 [axes modified to current coordinate system])

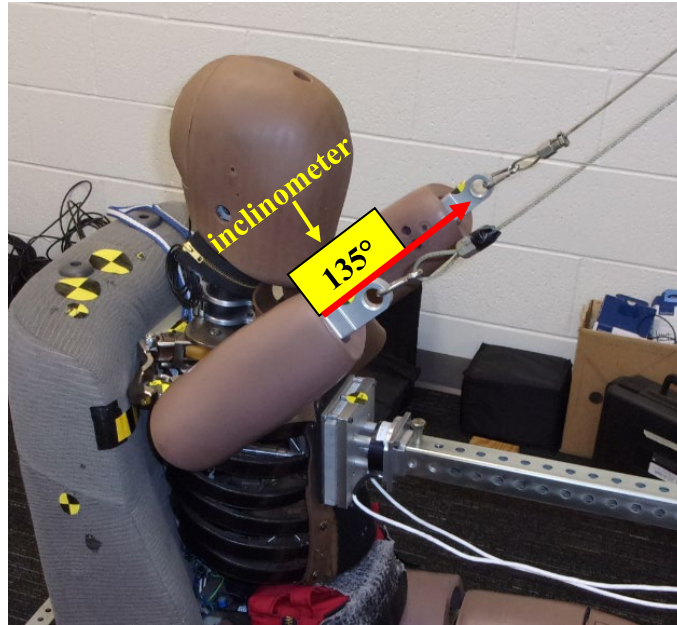


Figure 55. Angle pull determination

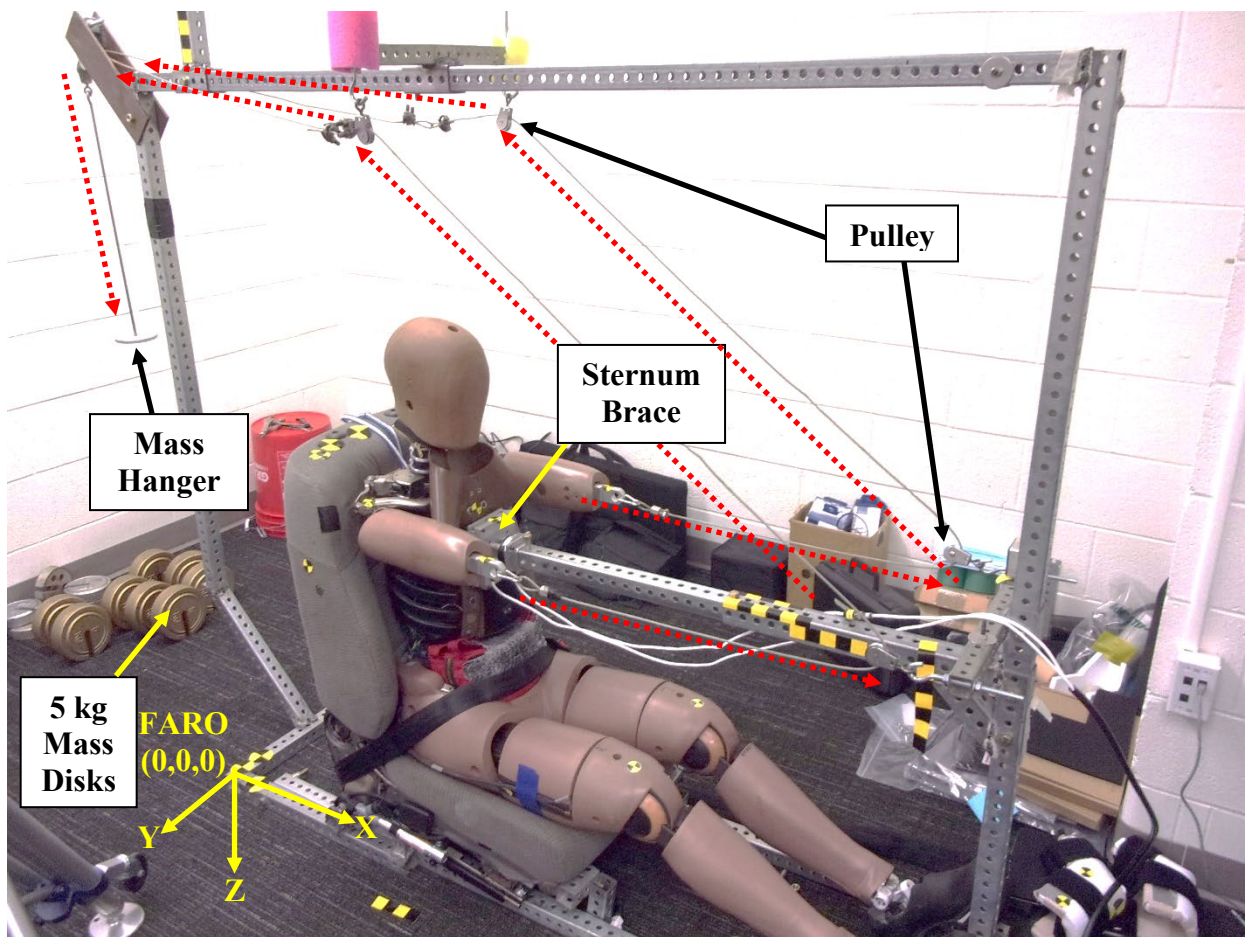


Figure 56. Test setup for arm pull tests

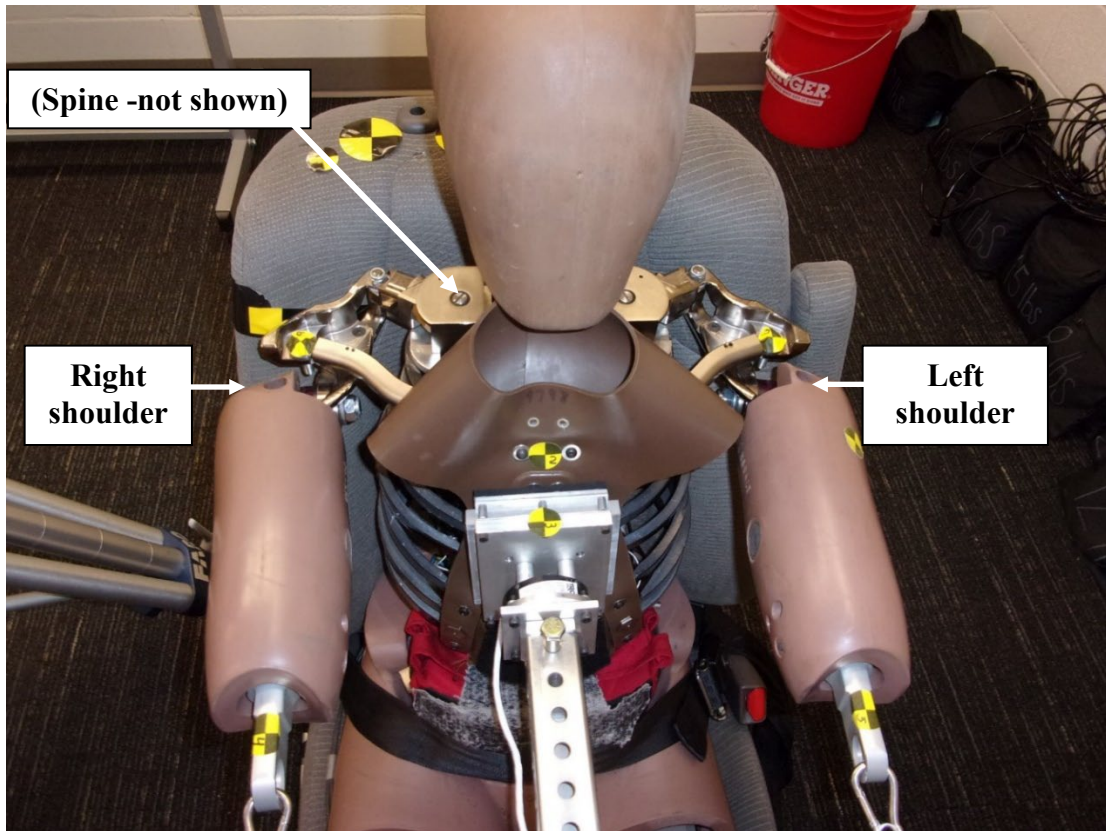


Figure 57. Targets for FARO 3-D location measurements

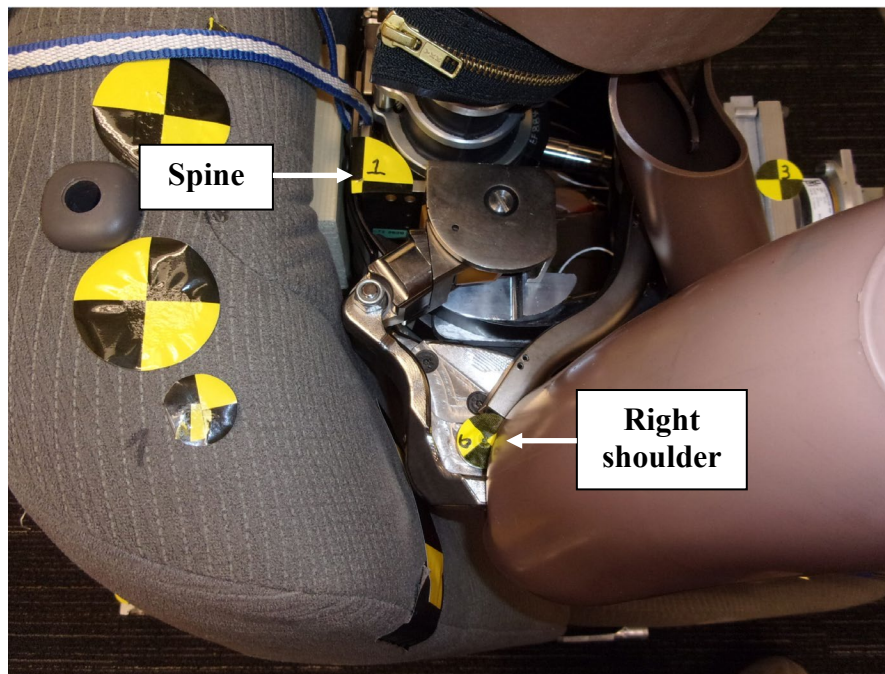


Figure 58. Target for FARO 3-D measurement of spine and (right) shoulder

Six series of three tests at each orientation were conducted using either the Option “A” XNBR 80A or baseline shoulders for comparison (Table 15). The Option “A” XNBR 80A shoulder with molded rubber spring serial number V005 was installed on the left side, and molded rubber spring serial number V006 was installed on the right side. The adjustable friction element in the baseline shoulder was again set to 1.5 Nm for these tests. Once these tests were completed, the same THOR-50M was reconfigured with the baseline shoulders and the tests were conducted again.

Table 15. Test Matrix for Biofidelity (Tornvall) Tests

Shoulder Version	Series 1	Series 2	Series 3
Option “A” XNBR 80A Shoulder	3 tests 90° arm angle	3 tests 135° arm angle	3 tests 170° arm angle
	0-200 N each arm	0-200 N each arm	0-200 N each arm
Shoulder Version	Series 4	Series 5	Series 6
Baseline Shoulder	3 tests 90° arm angle	3 tests 135° arm angle	3 tests 170° arm angle
	0-200 N each arm	0-200 N each arm	0-200 N each arm

### Arm Pull Test Results

Since each test series consisted of three repeat tests, an analysis of the results showed that in all six series the tests were very repeatable. Left and right shoulder movement as well as spine position in the X and Z directions were analyzed. Repeatability was excellent in these test scenarios, with %CVs less than 1 percent in all cases. In these test results, averages from both left and right shoulders were calculated, then the average of each series (3 tests) was reported.

To compare the arm pull test results to the Tornvall corridor, the average Tornvall response was determined as the midpoint (average) of the upper and lower corridor bounds. In addition, Tornvall et al. (2005) designated the origin for each range of motion versus force curve as the unloaded position, where the volunteer was upright, in a relaxed position, with the thorax and forearm perpendicular to the lower extremities and floor. So, to compare the THOR results in this study with the volunteer data, calculations were done to place the THOR at the volunteer origin for each test. The following steps were taken for both X-axis and Z-axis positions; calculations for the X-position are shown below, with Z-position following the same procedures.

1. Average the left and right shoulder X position, where  $n$  is the force level applied on each arm (0, 25, 49 N, etc.).

$$X_{AVGLRSHLD(n)} = (X_{LSHLD(n)} + X_{RSHLD(n)})/2$$

2. Subtract the spine movement from the average left/right shoulder position to get the average left/right shoulder position relative to the spine.

$$X_{AVGLRSHLDSP(n)} = X_{AVGLRSHLD(n)} - X_{SP(n)}$$

3. Zero the average left/right shoulder position relative to the spine, by subtracting the first value (position at no load,  $X_{SP(0)}$ ) of the spine (T1).

$$X_{AVGLRSHLD_{SP_{zero}(n)}} = X_{AVGLRSHLD_{SP(n)}} - X_{SP(0)}$$

4. Add the average Tornvall initial value (position at no load,  $X_{AVGTornvall(0)}$ ) to each value of the left/right zeroed shoulder; this step places the THOR at the same origin as the Tornvall volunteers.

$$X_{AVGLRSHLD_{POSITION(n)}} = X_{AVGLRSHLD_{SP_{zero}(n)}} + X_{AVGTornvall(0)}$$

5. Average the result from step 4 for each of the three repeats from each test series, to obtain the average shoulder position at each load ( $X_{AVGSHLD_{POSITION(n)}}$ ).

Results for the arm pull tests are presented below for each arm pull angle (Table 16 and Table 17). Because the tests entailed pulling simultaneously on both arms up to a total of approximately 400 N, the force on each arm was considered as half of the pull force; therefore, the tables are incremented in approximately 25 N steps up to 200 N. Note that the force on each arm matches the Tornvall force increments rather than the actual loading force which varied slightly from Tornvall et al. (2005) (Table A-1 and Table A-18); the displacements in Table 16 and Table 17 were interpolated to reflect the displacements at the Tornvall loads in order to correctly perform biofidelity calculations and comparisons. These tables and plots show the average of the three tests for the baseline shoulder and Option “A” XNBR 80A shoulders at a designated pull angle; the Appendix offers the results from individual tests which were used to calculate the averages, along with the spine positions.

Plots from the arm pull tests are also presented in Figure 59 to Figure 64. All plots follow the SAE J-211 sign convention. Since the Tornvall et al. (2005) data was collected using the right-hand-rule polarity reference, the Z-position Tornvall corridors were inverted to comply with SAE J-211 (this is noted in the figure legends). These plots show the average X and Z-displacements relative to the spine (T1) for the baseline and Option “A” XNBR 80A shoulders. The Tornvall corridor is included for reference, along with the corridor midpoint, which is used for the biofidelity rating calculations.

Table 16. Arm Pull Test Results for Baseline and Option “A” XNBR 80A Shoulders in X Direction

Force (each arm) (N)	Avg. X Shoulder Position (mm)					
	Baseline Shoulder			Option “A” XNBR 80A Shoulder		
	90° Pull	135° Pull	170° Pull	90° Pull	135° Pull	170° Pull
0	50	27	-7	50	27	-7
25	51	28	-7	58	31	-6
50	52	30	-6	69	37	-6
75	55	31	-6	82	45	-4
100	66	32	-6	93	57	1
125	77	36	-4	103	65	10
150	87	41	0	111	69	10
175	95	52	3	113	68	11
200	100	55	4	116	68	11

Table 17. Arm Pull Test Results for Baseline and Option “A” XNBR 80A Shoulders in Z Direction

Force (each arm) (N)	Avg. Z Shoulder Position (mm)					
	Baseline Shoulder			Option “A” XNBR 80A Shoulder		
	90° Pull	135° Pull	170° Pull	90° Pull	135° Pull	170° Pull
0	-31	-24	-48	-31	-24	-48
25	-31	-24	-49	-30	-24	-49
50	-30	-24	-51	-29	-23	-50
75	-30	-25	-52	-27	-26	-56
100	-28	-29	-58	-25	-44	-73
125	-27	-43	-82	-24	-56	-105
150	-27	-53	-103	-26	-71	-115
175	-28	-69	-116	-27	-78	-120
200	-29	-75	-124	-29	-83	-126

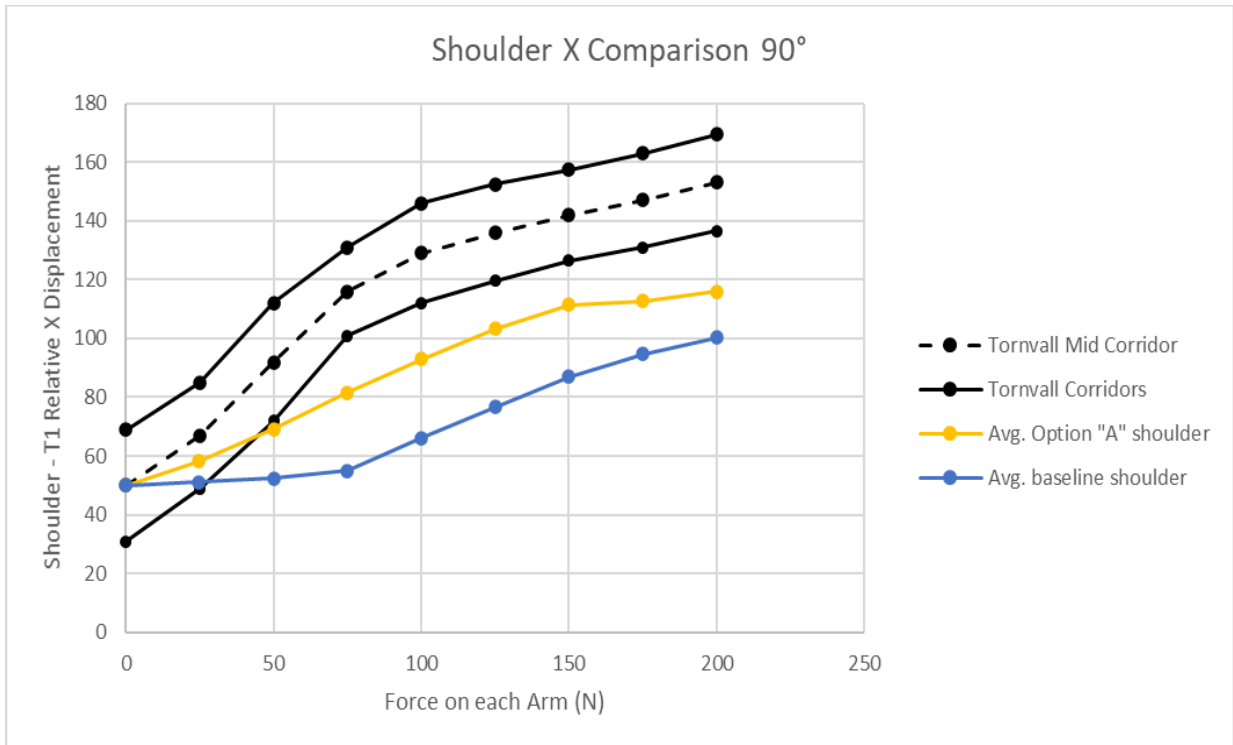


Figure 59. Baseline and Option "A" XNBR 80A shoulders compared to X-axis Tornvall corridor in 90° arm pull tests

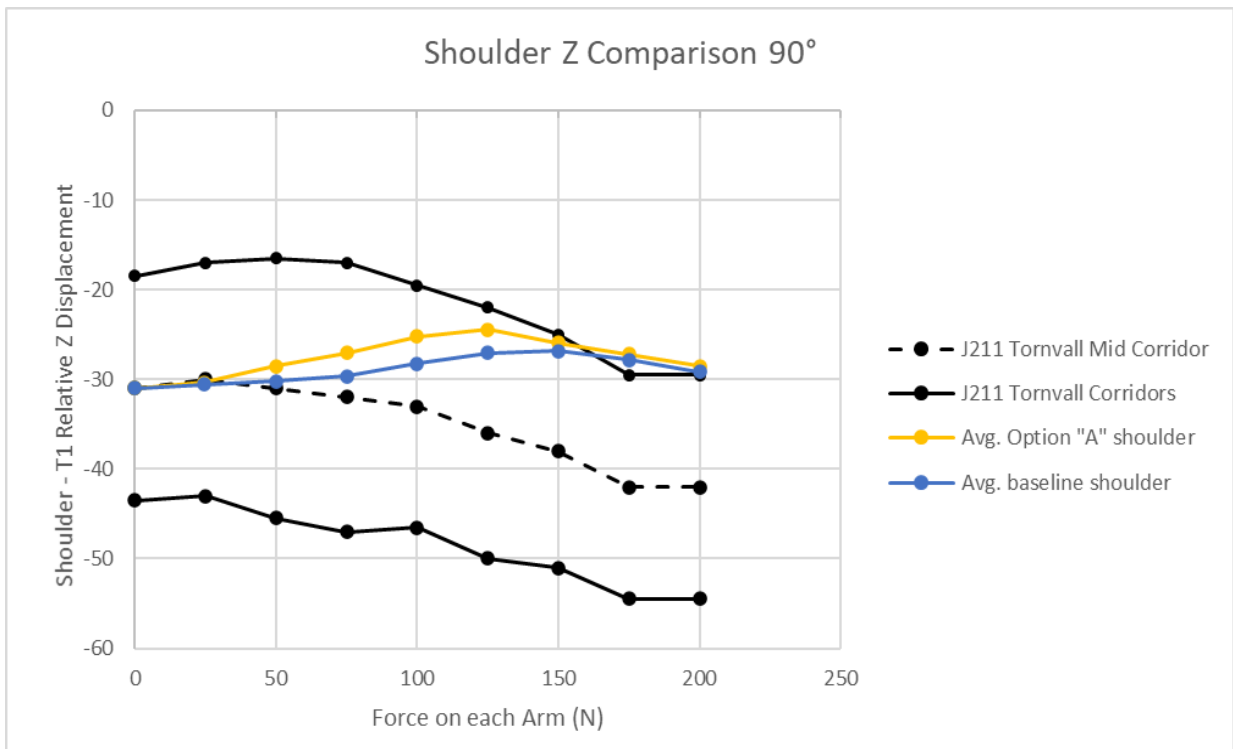


Figure 60. Baseline and Option "A" XNBR 80A shoulders compared to Z-axis Tornvall corridor in 90° arm pull tests

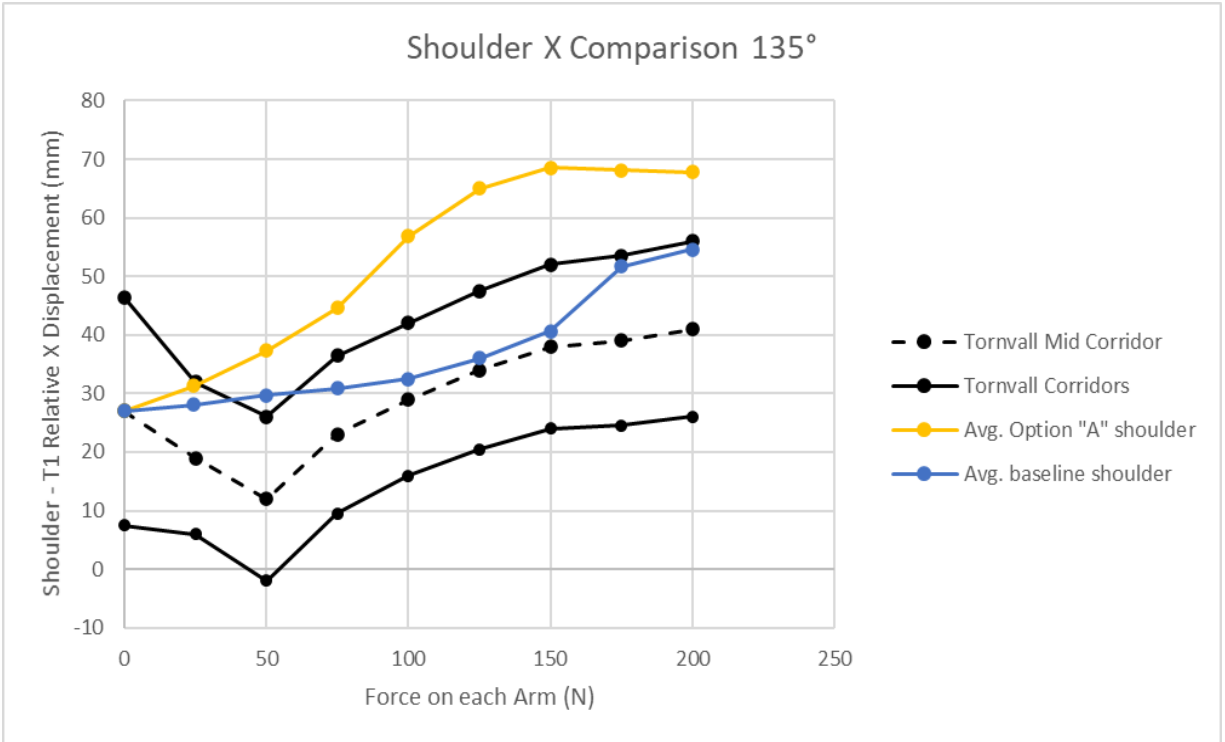


Figure 61. Baseline and Option “A” XNBR 80A shoulders compared to X-axis Tornvall corridor in 135° arm pull tests

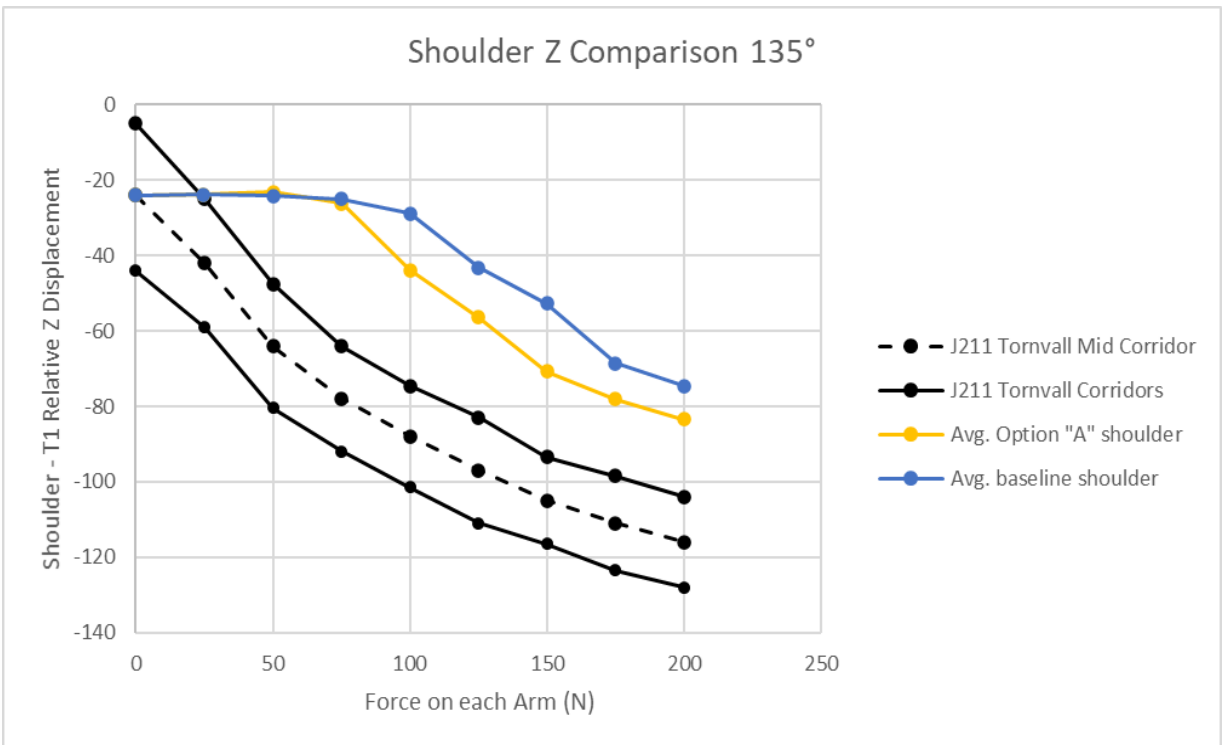


Figure 62. Baseline and Option “A” XNBR 80A shoulders compared to Z-axis Tornvall corridor in 135° arm pull tests

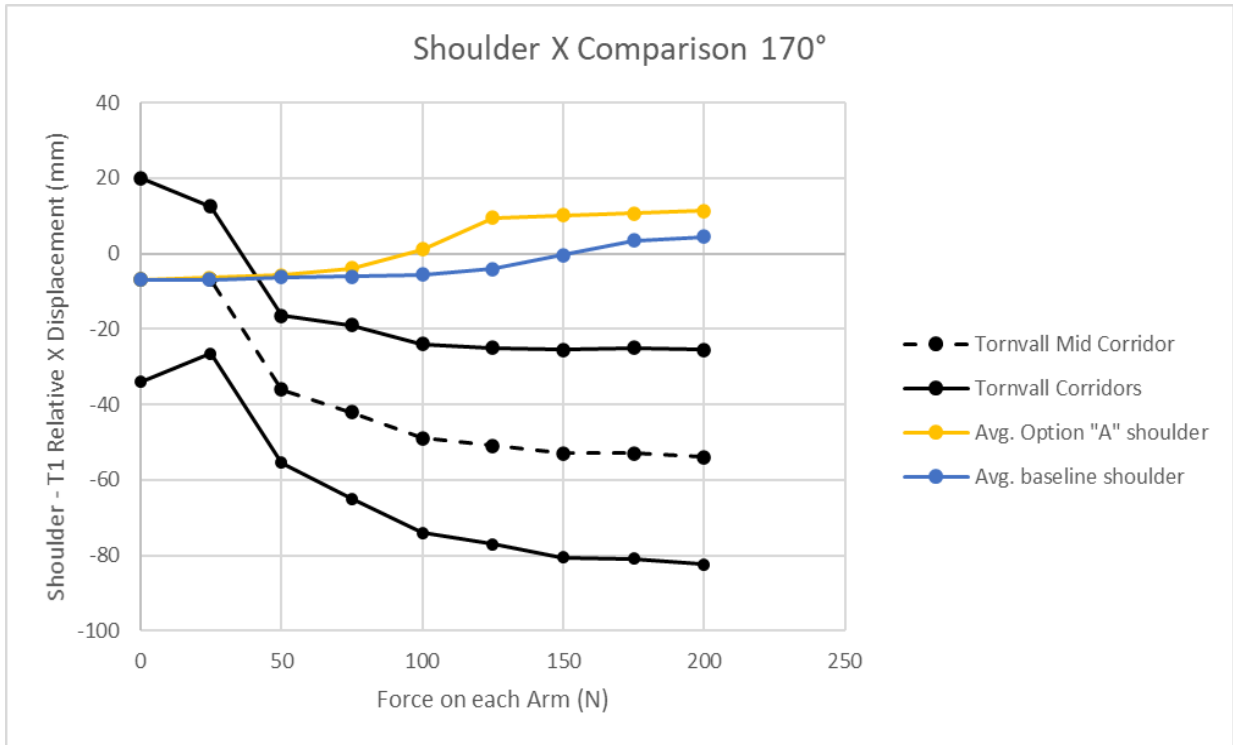


Figure 63. Baseline and Option “A” XNBR 80A shoulders compared to X-axis Tornvall corridor in 170° arm pull tests

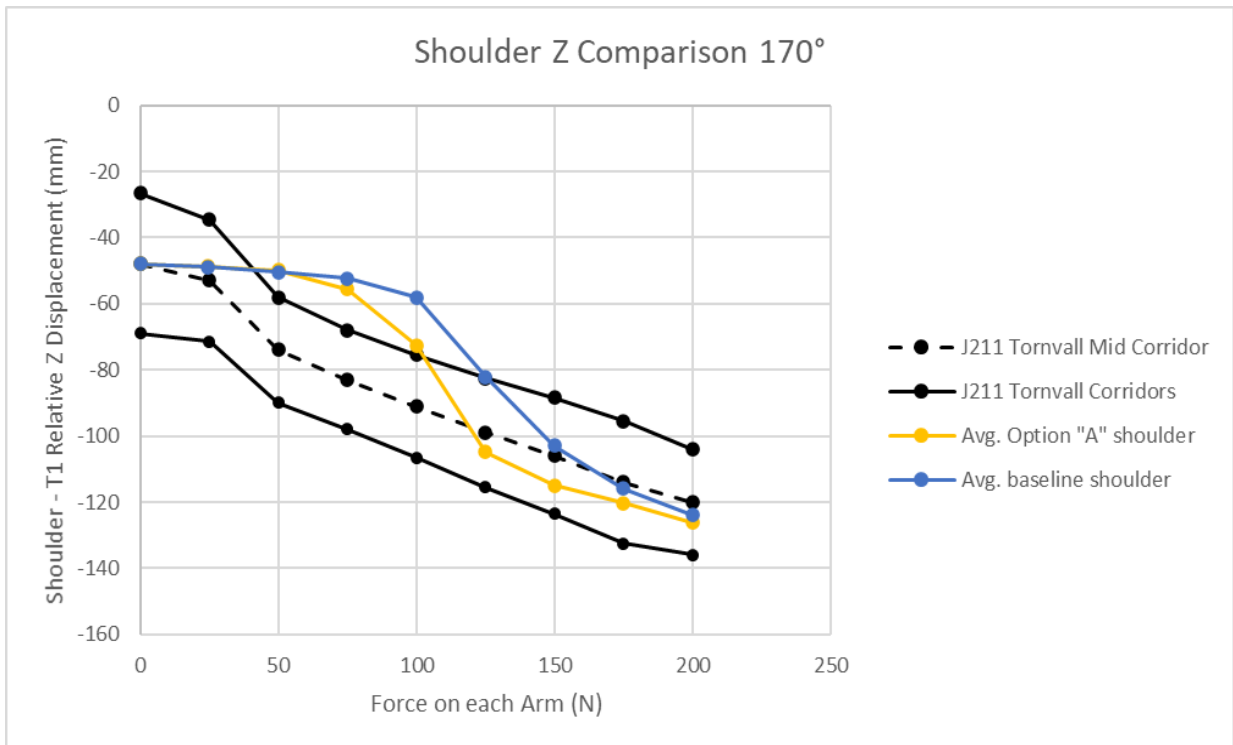


Figure 64. Baseline and Option “A” XNBR 80A shoulders compared to Z-axis Tornvall corridor in 170° arm pull tests

## Biofidelity Ranking Results

To assess the biofidelity of the shoulders in the Tornvall test scenario, biofidelity ranking scores (BRS) calculations were performed as described in Hagedorn et al. (2022). The Tornvall displacement versus force corridors were used as the basis for comparison with the baseline and Option “A” XNBR 80A shoulders. As such, the phase response aspect of the BRS scores described by Hagedorn et al. is not used in this evaluation. Since three repeat tests were performed, as shown in the previous section, the averages from each test setup were used in the BRS calculations.

Table 18 shows the results of the biofidelity ranking. Any BRS score over 2 indicates that the THOR response varies from the mean corridor by more than two standard deviations, on average; scores under 2 are therefore considered good biofidelity. All but three BRS calculations were below 2; these include the 90° X baseline shoulder BRS and the 135° Z BRS for both shoulder versions (indicated by red text in Table 18). Despite these outliers, the average X and Z BRS scores for each shoulder showed good biofidelity. To determine the overall BRS score for each shoulder, all the X and Z BRS scores for each shoulder were averaged. The overall BRS scores for the baseline (1.43) and Option “A” XNBR 80A (1.37) shoulders show very close agreement and good biofidelity. Overall, the Option “A” XNBR 80A shoulders display biofidelity as good as, or better than, the baseline shoulders.

*Table 18. Biorank scores for Biofidelity Arm Pull Tests for Baseline and Option “A” XNBR 80A Shoulders*

Arm Angle (deg)	X Corridor BRS		Z Corridor BRS	
	Baseline Shoulder	Option “A” XNBR 80A Shoulder	Baseline Shoulder	Option “A” XNBR 80A Shoulder
90	2.60	1.54	0.46	0.56
135	0.53	1.60	2.77	2.22
170	1.44	1.66	0.75	0.66
AVG BRS	1.52	1.60	1.33	1.15
Overall BRS	Baseline Shoulder		Option “A” XNBR 80A Shoulder	
	1.43		1.37	

## Conclusions

A comparison of various shoulder designs revealed that there is a viable alternative shoulder option to the baseline THOR-50M shoulder. At the start of this study, a patent attorney was consulted to give an opinion as to whether either of the alternative shoulder designs violated the patent for the baseline shoulder. As a result of the review, the patent attorney deemed that neither of the alternative shoulder designs posed any issues with either literal infringement or infringement under the doctrine of equivalents.

The alternative shoulder selected was the Option “A” XNBR 80A shoulder design; the fit within the THOR-50M for this design was acceptable. Quasi-static rotation tests showed that this design most closely matched the baseline shoulder compared to other alternatives evaluated. In addition, upper thorax qualification tests with the baseline and Option “A” XNBR 80A shoulders passed all specifications; repeat qualifications revealed that both shoulder designs performed in a repeatable manner and were equivalent when data from both shoulders were combined.

Sled tests also demonstrated that the THOR-50M responded in a similar manner whether it was equipped with the baseline or Option “A” XNBR 80A shoulder. The Option “A” XNBR 80A shoulder was also deemed durable by comparing quasi-static tests conducted before and after sled tests.

The data from the Option “A” XNBR 80A shoulder in biofidelity tests correlates as well as the baseline shoulder when compared to the Tornvall data in both X and Z-axes. Both shoulders have good, comparable, biofidelity (BRS below 2) for the average BRS of each shoulder in X and Z as well as the overall BRS. In summary, the Option “A” XNBR 80A shoulder shows similar biofidelity to the baseline shoulder.

Overall, the results of this study show that the Option “A” XNBR 80A shoulder responds in a comparable manner to the baseline shoulder and is a suitable alternative design.

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## **Appendix A**

Table A-1. Left Shoulder Position for 90° Arm Pull Tests for Option “A” XNBR 80A Shoulders

	Test 1		Test 2		Test 3	
Force (each arm) (N)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)
0	376	-731	374	-732	376	-730
25	389	-731	385	-731	387	-729
49	401	-729	401	-729	403	-727
74	413	-729	416	-727	421	-725
98	427	-728	429	-726	434	-724
123	439	-726	441	-725	446	-723
147	451	-729	452	-727	455	-725
172	455	-731	457	-729	459	-727
196	459	-733	461	-731	462	-729

Table A-2. Right Shoulder Position for 90° Arm Pull Tests for Option “A” XNBR 80A Shoulders

	Test 1		Test 2		Test 3	
Force (each arm) (N)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)
0	362	-742	358	-742	360	-742
25	369	-743	368	-741	368	-742
49	380	-742	380	-740	379	-741
74	394	-742	394	-740	392	-741
98	407	-740	407	-739	405	-739
123	421	-740	417	-738	418	-741
147	433	-741	429	-740	429	-744
172	436	-743	434	-742	433	-746
196	440	-744	439	-744	437	-748

*Table A-3. Spine Position for 90° Arm Pull Tests for Option “A” XNBR 80A Shoulders*

	<b>Test 1</b>		<b>Test 2</b>		<b>Test 3</b>	
<b>Force (each arm) (N)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>
0	309	-740	306	-739	307	-738
25	310	-740	309	-739	309	-739
49	312	-741	311	-740	311	-740
74	315	-741	314	-740	314	-740
98	316	-742	316	-741	316	-741
123	317	-742	317	-741	318	-741
147	320	-743	320	-742	320	-742
172	323	-743	323	-743	323	-743
196	325	-744	326	-744	326	-744

*Table A-4. Left Shoulder Position for 90° Arm Pull Tests for Baseline Shoulders*

	<b>Test 1</b>		<b>Test 2</b>		<b>Test 3</b>	
<b>Force (each arm) (N)</b>	<b>X Left Shoulder Position (mm)</b>	<b>Z Left Shoulder Position (mm)</b>	<b>X Left Shoulder Position (mm)</b>	<b>Z Left Shoulder Position (mm)</b>	<b>X Left Shoulder Position (mm)</b>	<b>Z Left Shoulder Position (mm)</b>
0	372	-732	370	-730	377	-730
25	375	-732	373	-730	379	-730
49	379	-732	379	-730	382	-730
74	383	-732	383	-729	387	-730
98	404	-729	405	-727	403	-729
123	418	-728	418	-726	420	-727
147	427	-727	428	-726	431	-727
172	435	-727	437	-726	440	-727
196	442	-727	444	-728	445	-727

*Table A-5. Right Shoulder Position for 90° Arm Pull Tests for Baseline Shoulders*

	<b>Test 1</b>		<b>Test 2</b>		<b>Test 3</b>	
<b>Force (each arm) (N)</b>	<b>X Right Shoulder Position (mm)</b>	<b>Z Right Shoulder Position (mm)</b>	<b>X Right Shoulder Position (mm)</b>	<b>Z Right Shoulder Position (mm)</b>	<b>X Right Shoulder Position (mm)</b>	<b>Z Right Shoulder Position (mm)</b>
0	368	-738	363	-740	364	-741
25	371	-738	365	-739	367	-741
49	373	-738	368	-740	369	-741
74	376	-739	370	-740	373	-742
98	384	-739	374	-740	378	-741
123	395	-739	385	-740	390	-741
147	408	-740	403	-741	405	-742
172	418	-743	416	-745	418	-745
196	424	-746	424	-747	424	-748

*Table A-6. Spine Position for 90° Arm Pull Tests for Baseline Shoulders*

	<b>Test 1</b>		<b>Test 2</b>		<b>Test 3</b>	
<b>Force (each arm) (N)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>
0	313	-735	313	-734	313	-735
25	315	-735	314	-735	315	-735
49	317	-735	317	-735	317	-736
74	318	-736	319	-736	319	-736
98	320	-736	320	-736	321	-737
123	323	-737	322	-737	323	-737
147	325	-738	325	-738	325	-738
172	327	-738	328	-738	328	-739
196	330	-739	329	-739	330	-739

Table A-7. Left Shoulder Position for 135° Arm Pull Tests for Option “A” XNBR 80A Shoulders

	Test 1		Test 2		Test 3	
Force (each arm) (N)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)
0	381	-729	378	-729	380	-729
25	385	-729	382	-729	386	-729
49	394	-730	391	-729	393	-729
74	402	-733	401	-735	404	-736
98	420	-756	420	-758	421	-759
123	430	-768	429	-768	430	-769
147	435	-780	435	-780	436	-779
172	438	-789	437	-789	438	-788
196	440	-797	438	-797	440	-796

Table A-8. Right Shoulder Position for 135° Arm Pull Tests for Option “A” XNBR 80A Shoulders

	Test 1		Test 2		Test 3	
Force (each arm) (N)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)
0	356	-740	359	-740	359	-741
25	362	-740	366	-740	366	-741
49	370	-740	373	-741	371	-741
74	376	-742	381	-744	379	-743
98	388	-757	393	-757	392	-759
123	403	-775	405	-774	404	-775
147	409	-795	411	-794	409	-796
172	411	-803	413	-802	412	-804
196	414	-809	415	-808	414	-810

Table A-9. Spine Position for 135° Arm Pull Tests for Option “A” XNBR 80A Shoulders

	Test 1		Test 2		Test 3	
Force (each arm) (N)	X Spine Position (mm)	Z Spine Position (mm)	X Spine Position (mm)	Z Spine Position (mm)	X Spine Position (mm)	Z Spine Position (mm)
0	306	-737	306	-737	307	-738
25	307	-737	307	-738	308	-738
49	309	-738	309	-738	309	-738
74	310	-739	310	-739	311	-739
98	312	-740	313	-740	314	-740
123	316	-741	316	-742	316	-742
147	318	-743	318	-743	319	-743
172	320	-744	321	-744	321	-744
196	323	-746	323	-746	324	-746

Table A-10. Left Shoulder Position for 135° Arm Pull Tests for Baseline Shoulders

	Test 1		Test 2		Test 3	
Force (each arm) (N)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)
0	373	-734	369	-733	369	-734
25	376	-734	371	-733	371	-735
49	377	-735	374	-734	375	-735
74	380	-735	378	-735	379	-736
98	385	-736	382	-736	383	-737
123	390	-739	388	-739	389	-740
147	397	-748	394	-747	401	-754
172	425	-781	425	-781	425	-780
196	429	-790	429	-789	430	-790

*Table A-11. Right Shoulder Position for 135° Arm Pull Tests for Baseline Shoulders*

	<b>Test 1</b>		<b>Test 2</b>		<b>Test 3</b>	
<b>Force (each arm) (N)</b>	<b>X Right Shoulder Position (mm)</b>	<b>Z Right Shoulder Position (mm)</b>	<b>X Right Shoulder Position (mm)</b>	<b>Z Right Shoulder Position (mm)</b>	<b>X Right Shoulder Position (mm)</b>	<b>Z Right Shoulder Position (mm)</b>
0	370	-739	363	-740	362	-739
25	372	-739	365	-741	363	-740
49	374	-739	367	-742	365	-740
74	376	-741	369	-744	367	-742
98	378	-748	370	-749	369	-750
123	382	-777	375	-779	375	-777
147	382	-782	375	-786	375	-787
172	383	-789	376	-791	376	-791
196	384	-792	376	-794	381	-794

*Table A-12. Spine Position for 135° Arm Pull Tests for Baseline Shoulders*

	<b>Test 1</b>		<b>Test 2</b>		<b>Test 3</b>	
<b>Force (each arm) (N)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>
0	311	-735	312	-736	312	-736
25	312	-735	313	-736	313	-736
49	313	-736	314	-736	314	-736
74	315	-737	315	-737	316	-737
98	316	-738	316	-738	317	-738
123	318	-739	319	-739	319	-739
147	318	-739	319	-740	320	-740
172	321	-740	322	-741	322	-741
196	322	-741	323	-741	323	-741

Table A-13. Left Shoulder Position for 170° Arm Pull Tests for Option “A” XNBR 80A Shoulders

Force (each arm) (N)	Test 1		Test 2		Test 3	
	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)	X Left Shoulder Position (mm)	Z Left Shoulder Position (mm)
0	374	-731	371	-731	377	-730
25	374	-731	372	-731	378	-732
49	373	-732	374	-732	378	-733
74	376	-737	375	-737	381	-743
98	382	-755	385	-766	385	-760
123	396	-788	396	-788	397	-788
147	399	-799	399	-800	400	-798
172	401	-806	401	-807	401	-806
196	401	-812	401	-812	402	-812

Table A-14. Right Shoulder Position for 170° Arm Pull Tests for Option “A” XNBR 80A Shoulders

Force (each arm) (N)	Test 1		Test 2		Test 3	
	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)
0	360	-740	360	-741	356	-742
25	361	-741	360	-742	357	-742
49	362	-743	361	-744	357	-743
74	363	-749	361	-749	358	-747
98	365	-759	366	-762	362	-757
123	378	-804	377	-802	376	-802
147	380	-815	380	-816	379	-815
172	381	-821	382	-822	381	-821
196	384	-827	384	-826	383	-826

*Table A-15. Spine Position for 170° Arm Pull Tests for Option “A” XNBR 80A Shoulders*

	<b>Test 1</b>		<b>Test 2</b>		<b>Test 3</b>	
<b>Force (each arm) (N)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>	<b>X Spine Position (mm)</b>	<b>Z Spine Position (mm)</b>
0	305	-737	304	-738	304	-738
25	305	-738	304	-738	305	-738
49	305	-738	304	-738	305	-738
74	305	-739	304	-739	305	-739
98	304	-739	305	-740	305	-740
123	308	-741	308	-741	308	-742
147	310	-742	311	-743	311	-743
172	311	-744	312	-744	312	-744
196	313	-745	312	-745	313	-745

*Table A-16. Left Shoulder Position for 170° Arm Pull Tests for Baseline Shoulders*

	<b>Test 1</b>		<b>Test 2</b>		<b>Test 3</b>	
<b>Force (each arm) (N)</b>	<b>X Left Shoulder Position (mm)</b>	<b>Z Left Shoulder Position (mm)</b>	<b>X Left Shoulder Position (mm)</b>	<b>Z Left Shoulder Position (mm)</b>	<b>X Left Shoulder Position (mm)</b>	<b>Z Left Shoulder Position (mm)</b>
0	347	-753	344	-750	356	-749
25	347	-755	344	-751	356	-750
49	347	-756	344	-753	356	-751
74	347	-758	344	-755	356	-753
98	347	-761	344	-757	356	-757
123	349	-766	346	-764	357	-765
147	356	-798	358	-800	362	-802
172	368	-821	370	-821	369	-819
196	371	-828	372	-828	372	-827

Table A-17. Right Shoulder Position for 170° Arm Pull Tests for Baseline Shoulders

	Test 1		Test 2		Test 3	
Force (each arm) (N)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)	X Right Shoulder Position (mm)	Z Right Shoulder Position (mm)
0	345	-747	344	-748	348	-749
25	344	-749	344	-749	348	-749
49	344	-750	344	-751	347	-751
74	344	-754	343	-753	346	-754
98	344	-760	343	-758	347	-762
123	346	-802	346	-801	349	-807
147	349	-812	350	-813	352	-817
172	354	-826	354	-825	354	-825
196	355	-833	355	-833	355	-833

Table A-18. Spine Position for 170° Arm Pull Tests for Baseline Shoulders

	Test 1		Test 2		Test 3	
Force (each arm) (N)	X Spine Position (mm)	Z Spine Position (mm)	X Spine Position (mm)	Z Spine Position (mm)	X Spine Position (mm)	Z Spine Position (mm)
0	292	-745	291	-745	291	-746
25	292	-745	291	-745	291	-746
49	291	-746	291	-746	290	-746
74	290	-746	290	-746	289	-747
98	290	-747	290	-747	289	-747
123	291	-748	290	-748	290	-748
147	293	-750	293	-750	291	-750
172	295	-752	295	-752	295	-752
196	296	-753	296	-753	296	-753

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