PERFORMANCE REPORT

MECHANICAL EVALUATION OF "OFF THE SHELF" AND CUSTOM KNEE BRACES: PARAMETERS OF STABILITY AND COMPONENT FAILURE

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A Study Conducted By

^Department of Orthopedics
Children's Hospital, San Diego

*Department of Orthopaedics
University of California – San Diego

Primary Investigator: Andrew Mahar, MS^*

Co-Investigators: Richard Oka, BA^
Tim Odell^
Michelle Wedemeyer, BS^

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INTRODUCTION

Injuries to the knee, involving partial or full rupture of the anterior cruciate ligament (ACL), are being seen in an increasing percentage of the population. In the case of prophylactic bracing after partial injury and the case of bracing following ligament repair, substantial varus/valgus stability is required; as well as restraint from full knee extension where the ACL experiences the greatest strain. For this purpose, many types of braces are currently available as “off the shelf” and custom models. As brace technology develops, evaluations of these braces are required to establish clinically important biomechanical parameters.

PURPOSE

The purpose of this study was to examine the biomechanical performance of several “off the shelf” and custom braces in the mechanical parameters of stability and failure strength.

CLINICAL SIGNIFICANCE

These results are clinically relevant in that they may identify those braces that perform well for a variety of tests involving stabilizing the knee and resisting failure at the strap or the extensor locking mechanism. This information may assist a treating physician with decision making for an ideal brace for a particular application or patient population.

METHODS

Ten medium-sized functional knee braces (FKBs) were selected for the study. All braces were obtained from the manufacturers via third party resources. Some represented "off the shelf" devices while others were "custom" braces (Table 1). The custom brace designs were taken from patients with medium dimensions and without significant valgus/varus angulation or other limb deformity. Therefore, all braces were mechanically "new" braces without previous patient prescription and representing those most currently available on the market. Three samples of each brace were used for mechanical testing.

Table 1: Description of Knee Braces

Make	Model	Custom/OTS*
DonJoy	Armor	OTS
	Fource Point	OTS
	Defiance	Custom
BREG	X2K	Custom=OTS^
Innovation Sports	Edge	OTS
	CTi2	Custom
Townsend	Rebel	OTS
	Premier	Custom
Medi	M4	OTS
Generation II	3DX	Custom=OTS^

^ Vendors report identical biomechanics between custom and OTS braces

*OTS = Off the Shelf

All mechanical testing was conducted using a MTS 858 servohydraulic bi-axial machine in displacement control with load and torque cells rated to 2200lb and 1000in-lb, respectively. Non-destructive testing was first performed on the entire brace in varus/valgus loading (n=3 tests per direction per brace type) (Figure 1).

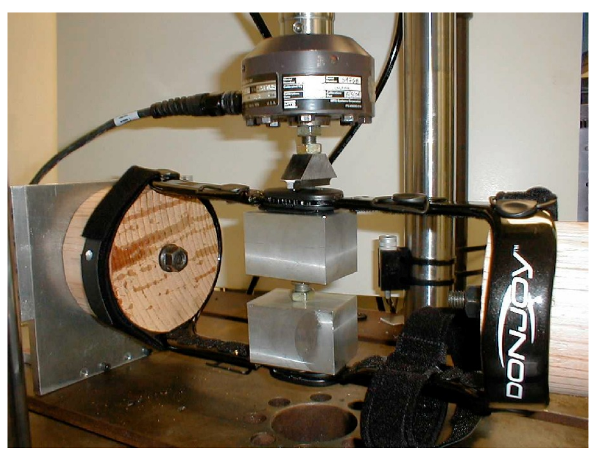


Figure 1: Varus/Valgus Testing.

For varus/valgus loading, a custom fixation rig rigidly held the brace horizontally. The fixation rig entailed two circular drums that simulated the diameter of a patient's thigh and calf. The braces were fitted around these ends such that there was firm contact with the fixation rig. The most proximal and distal straps were in complete contact with the respective drums simulating the clinical scenario of rigid attachment. In this manner, the brace was prevented from sliding in the axial direction or rotating around the brace's axis – limiting all possible motion to the varus or valgus bending of the hinges and frame. The hinges were then braced with a strut simulating femoral condyles in a patient, allowing both hinges to be loaded simultaneously. Thus, the variation across stiffness results for varus and valgus loading would be entirely related to the structural and material differences between braces.

The servohydraulic piston applied a downward load at the hinge at 0.1in/sec to an excursion of 0.5inches. Each test underwent 5 loading cycles – the first three cycles were used for preconditioning, allowing the braces to settle into the fixation rig. The last two loading cycles were used to determine hinge stiffness. This test was repeated with the brace flipped 180 degrees to complete both varus and valgus direction loading. Data was collected for displacement (in) and force (lb) at 10Hz and stiffness (lb/in) was calculated for each direction across braces.

Following varus/valgus testing, the braces were sectioned to isolate strap tabs (strap attachments) and the hinge. Two strap-tabs were selected from each brace (n=6 tab tests per brace type). One side of the strap-tab was attached to the servohydraulic piston by a nylon strap and pin. (Figure 2) The length of the nylon strap was held constant across all testing to prevent strap material properties from affecting the calculated stiffness of the strap-tabs themselves. The loop of the nylon strap was rigidly fixed through the connecting loop of the strap tab. The strap tab remained fixed to the section of the brace frame that was in turn attached to the load cell using a custom bracket. Tensile loads were applied in-line with the strap tab attachment at 0.25in/sec until strap-tab failure. Data for displacement (in) and force (lb) were collected at 10Hz and failure load (lb) and stiffness (lb/in) were calculated for each test.

Figure 2: Strap-Tab Testing

Destructive testing of the extension-locking hinge mechanism was the final test. The lateral hinge of each brace was removed by cutting the frame. (n =3 tests per brace type) The hinge was rigidly fixed horizontally, with the flexion/extension plane of motion in-line with the servohydraulic piston, and with the anterior aspect of the hinge directed upwards – such that the patella would be facing upwards. (Figure 3)

The frame of the brace superior to the hinge (and lateral to the thigh) was rigidly fixed to a loading bracket. The loading

Figure 3: Extension-Locking Hinge Mechanism Testing

bracket was mounted on a slider, allowing translation of the pivot point in order apply only an extension moment on the hinge (an open kinetic chain simulation). The inferior aspect of the hinge (and lateral to the calf) was attached to the servohydraulic piston at a distance of 3.94in (10cm) from the center of the 10 degree flexion endstop within the hinge. The distance was held consistent for each hinge mechanism across all braces and each manufacturer's 10 degree flexion endstop was used. The servohydraulic piston applied an upward distraction (hyperextension) at 0.25in/sec ramped until full failure of the hinge mechanism. Data for displacement (in) and force (lb) was collected at 10Hz for the duration of the test. Failure torque (in*lb), failure hyperextension angle (degrees hyperextension) and failure stiffness (in*lb/deg) were calculated for each hinge mechanism.

Across tests, stiffness data was computed from the linear portion of the load-deformation curve using a linear regression fit. Data for each brace type was averaged within tests for descriptive statistics. Absolute magnitudes for each test were used for statistical analysis using a one-way ANOVA ($p<0.05$), with a Tukey's *post-hoc* correction test for multiple comparisons.

Following statistical analysis, a brace "score" was created in the following manner. (Equation 1)

Score Brace X [test(y)] = [Mean(braceX)-Mean(group)]/[SD(group)] ***Equation 1***

For each biomechanical test, the group average and group standard deviation was calculated by averaging all braces together. The brace score was obtained by subtracting the group average from the average for each individual brace type and then dividing by the group standard deviation. The performance of a particular brace across all tests was then computed as the average of the scores for each brace type across all tests. Braces were then ranked based on the score, with a positive number indicating improved performance compared to the grouped average and a negative score indicating decreased performance compared to the grouped average.

RESULTS

The results for all tests are shown in Appendix 1.

Valgus/Varus Testing

Non-destructive valgus testing generally demonstrated a three tier distribution of stiffness results (Table 2) with an ANOVA significance of $p<0.0015$. The average across braces for valgus stiffness was 193 lb/in. The DonJoy Armor, DonJoy Defiance, Townsend Premier, Innovation CTi2, and Generation II 3DX braces formed the statistically stronger tier (mean 268lb/in). The DonJoy Fource Point, Townsend Rebel and Innovation Sports Edge braces formed the second tier (148lb/in), while the Breg X2K and Medi M4 braces formed the lowest tier for valgus stiffness (74lb/in).

The same brace trends were expressed for varus testing with a three tier result, reporting an ANOVA result of $p<0.0001$. The same braces comprised the high-stiffness group in varus bending, though stiffness values among these were somewhat lower compared to the valgus tests (mean 209lb/in). Identical braces comprised the second tier group (107lb/in) and the same braces in the third tier (74lb/in).

Table 2: Valgus/Varus Stiffness	Valgus (lb/in)	Varus (lb/in)
DonJoy	**131.5**	**106.2**
Fource Point	16.9	0.6
DonJoy	**309.2**	**165.4**
Armor	35.3	20.9
DonJoy	**259.6**	**221.9**
Defiance	45.8	31.6
Townsend	**139.5**	**103.8**
Rebel	9.1	14.1
Townsend	**292.8**	**253.2**
Premier	167.7	58.3
Breg	**71.7**	**73.5**
X2K	6.8	6
Innovation Sports	**261.3**	**238.4**
CTi2	44.5	31.5
Innovation Sports	**172.1**	**111.9**
Edge	27.5	20.7
Generation II	**218.1**	**167.1**
3DX	69.4	10.8
Medi	**75.8**	**75.3**
M4	0.7	3.6

Strap Tab Testing

Tests were conducted on the proximal strap-tabs for each brace. The peak failure loads for strap-tabs in the DonJoy Fource Point and Breg X2K braces were significantly greater than that for all other braces tested. ($p<0.001$) (Table 3) The DonJoy Armor, Donjoy Defiance and Innovation Sports Edge braces were statistically similar in peak failure loads and all greater than the remaining braces (Appendix 2, Tab Fail ANOVA). The Townsend Premier and the Generation II 3DX braces had significantly low failure loads compared to all other braces. ($p<0.001$)

Table 3: Tab Failure Data	Failure Stiffness (lb/in)	Failure Load (lb)
DonJoy	**1185.2**	**419.7**
Fource Point	245.0	38.7
DonJoy	**737.9**	**256.8**
Armor	345.3	14.5
DonJoy	**796.2**	**283.3**
Defiance	51.4	7.4
Townsend	**213.6**	**150.6**
Rebel	19.9	6.9
Townsend	**121.2**	**45.4**
Premier	64.1	35.5
Breg	**173.4**	**379.1**
X2K	46.7	23.1
Innovation Sports	**92.3**	**129.9**
CTi2	6.3	38.0
Innovation Sports	**765.6**	**303.6**
Edge	81.7	3.4
Generation II	**31.0**	**31.4**
3DX	2.9	0.3
Medi	**205.8**	**108.7**
M4	8.9	1.1

The strap tab stiffness for the DonJoy Fource Point brace approached, but did not achieve, statistical significance compared to the DonJoy Defiance brace ($p=0.065$). However, the DonJoy Fource Point had significantly greater strap tab stiffness compared to all other brace types ($p<0.04$). The DonJoy Armor, DonJoy Defiance and Innovation Sports Edge braces formed a second tier of strap tab stiffness and were significantly stiffer than all remaining braces ($p<0.000$). The Innovation Sports CTi2 and Generation II 3DX braces represented the braces with lowest strap tab stiffness.

Extension Locking Mechanism Testing

Failure torques (Table 4) and modes (Appendix 1) were collected during the extension locking mechanism failure test. The DonJoy Fource Point and DonJoy Armor demonstrated the greatest failure torques and were statistically similar to the DonJoy

Defiance and both Townsend braces (Rebel/Premier) In fact, the DonJoy Armor brace had greater failure torque compared to all other brace designs (p<0.03). There were no differences in failure torque for the DonJoy Defiance, Townsend Rebel, Townsend Premier, Breg X2K, Innovation Sports Edge, Innovation Sports CTi2, Generation II 3DX or Medi M4 braces.

Table 4: Extension Locking Mechanism Failure Data

	Failure Stiffness (in-lb/deg)	**Failure Angle (degrees hyperextension)**	**Failure Torque (in*lb)**
DonJoy	**46.4**	**16.1**	**609.3**
Fource Point	5.9	5.1	21.1
DonJoy	**57.5**	**17.7**	**725.4**
Armor	13.4	7.4	141.7
DonJoy	**23.3**	**9.0**	**425.5**
Defiance	10.5	4.9	29.4
Townsend	**17.1**	**19.6**	**419.4**
Rebel	3.7	2.7	39.8
Townsend	**20.8**	**13.0**	**329.9**
Premier	11.5	13.0	47.2
Breg	**18.5**	**2.1**	**209.9**
X2K	2.2	1.3	26.6
Innovation Sports	**12.7**	**29.3**	**349.2**
CTi2	9.4	4.9	252.1
Innovation Sports	**18.4**	**33.3**	**209.9**
Edge	2.1	13.7	57.5
Generation II	**5.2**	**19.3**	**205.8**
3DX	5.4	1.4	28.3
Medi	**13.7**	**4.7**	**187.2**
M4	2.0	6.0	17.4

For extensor mechanism hinge stiffness, the DonJoy Fource Point and DonJoy Armor were statistically equivalent and both were statistically stiffer than all other braces (p<0.03). There were no statistical differences in hinge stiffness between remaining braces. The extensor hinge mechanism failed, generally, between 5 and 20 degrees of hyperextension. However, both Innovation Sports CTi2 and Innovation Sports Edge braces demonstrated failure angles of approximately 30 degrees. This was likely related to the hinge mechanism design from that particular manufacturer.

Overall Results

The performance of a brace across all tests was computed as the average of all scores so as to prevent the performance of a particular test from imparting too much influence on the overall score. (Table 5) The resulting rank is thus based with each test given *equal weight*. A positive score therefore results in improved performance while a negative score results in decreased performance. The magnitude of the value represents the number of standard deviations above or below the average performance across braces.

Table 5: Rankings of Braces Following Normalization

Manufacturer	Brace	Score	Rank
Donjoy	**Armor**	1.12	**1**
DonJoy	**Fource Point**	0.8	**2**
DonJoy	**Defiance**	0.59	**3**
Townsend	**Premier**	0.05	**4**
Innovation Sports	**CTI**	-0.02	**5**
Innovation Sports	**Edge**	-0.08	**6**
Townsend	**Rebel**	-0.4	**7**
Breg	**X2K**	-0.52	**8**
Generation II	**3DX**	-0.64	**9**
Medi	**M4**	-0.9	**10**

Only four braces ranked above the group average, indicating improved performance compared to the group average. (Table 5) The DonJoy Armor brace was beyond one full standard deviation (1.12) above the group average. The DonJoy Fource Point and Defiance braces were within 0.8 and 0.6 standard deviations of the group. The Townsend Premier was only slightly better than the group average (0.05). The remaining braces had a gradual degradation in performance. As this analysis generates a unitless data point (%), the scores should be considered a percentage of performance compared to the group average. So, a general analysis of a brace compared to the group can give the practitioner an idea of how that brace may be expected to perform. However, a specific analysis may provide the practitioner with a factoral comparison between two specific braces.

DISCUSSION

Individual tests of off the shelf and custom braces provided a variety of results. In general, the DonJoy Armor brace performed better than or equal to other braces in each test. (Appendix 3) This interpretation was confirmed when evaluating the ranked performance of braces based on an equal weighting across performance tests. This correction technique calculated the average number of standard deviations above or below the average brace performance for each brace for each test. The DonJoy Armor brace was more than one standard deviation beyond the average performance of the brace. The DonJoy Fource Point brace was 80% greater than the group average while the DonJoy Defiance was approximately 60% greater in performance across tests. The only other brace to show improved performance compared to the average was the Townsend Premier (5%). Thus, across a variety of tests for which brace technology is developed and for which physicians prescribe braces, the DonJoy consortium of braces may have biomechanical advantages compared to other braces. Overall, structural and material differences among currently available knee braces appear to affect their biomechanical performance across a variety of tests. Physicians should be aware of brace performance on several mechanical variables as this may assist regarding patient prescription.

APPENDIX 1: Failure Information and Raw Data

Table 1: Failure Modes for Extension Locking Mechanism

Donjoy	Test 1	hinge failure - gear teeth break
Fource Point	Test 2	hinge failure - gear teeth break
	Test 3	hinge failure - gear teeth break
Donjoy	Test 1	some frame deformation, hinge action jammed at end-stop
Armor	Test 2	some frame deformation, hinge - endstop deforms, wedged laterally
	Test 3	some frame deformation, hinge - endstop deforms, wedged laterally
DonJoy	Test 1	fracture through distal frame, near rivets to hinge, slight impingement to hinge action
Defiance	Test 2	rivets through hinge tear through distal frame, no effect on hinge mechanism
	Test 3	rivets through hinge tear through distal frame, no effect on hinge mechanism
Townsend	Test 1	frame deformation
Rebel	Test 2	frame deformation
	Test 3	frame deformation
Breg	Test 1	hinge failure - plastic endstop deformed, wedged laterally, hinge expands laterally
X2K	Test 2	frame deformation, some deformation of pastic endstop, hinge expands laterally
	Test 3	hinge failure - plastic endstop deformed, wedged laterally, hinge expands laterally
Innovation Sports	Test 1	hinge deformation - shearing of pins, deformation of endstop. Frame/hinge action intact
Edge	Test 2	hinge deformation - shearing of pins, deformation of endstop. Frame/hinge action intact
	Test 3	hinge deformation - shearing of pins, deformation of endstop. Frame/hinge action intact
Innovation Sports	Test 1	no apparent damage
CTi 2	Test 2	no apparent damage
	Test 3	no apparent damage
Townsend	Test 1	metal core of strut tore out of shell
Premier	Test 2	metal core of strut tore out of shell
	Test 3	hinge opened laterally (different construction)
Medi	Test 1	hinge spread/distorted laterally, jammed
M4	Test 2	hinge spread/distorted laterally, jammed - frame tore
	Test 3	hinge spread/distorted laterally, jammed - frame tore
Generation II	Test 1	frame tore out of joint
3DX	Test 2	frame tore out of joint
	Test 3	frame tore out of joint

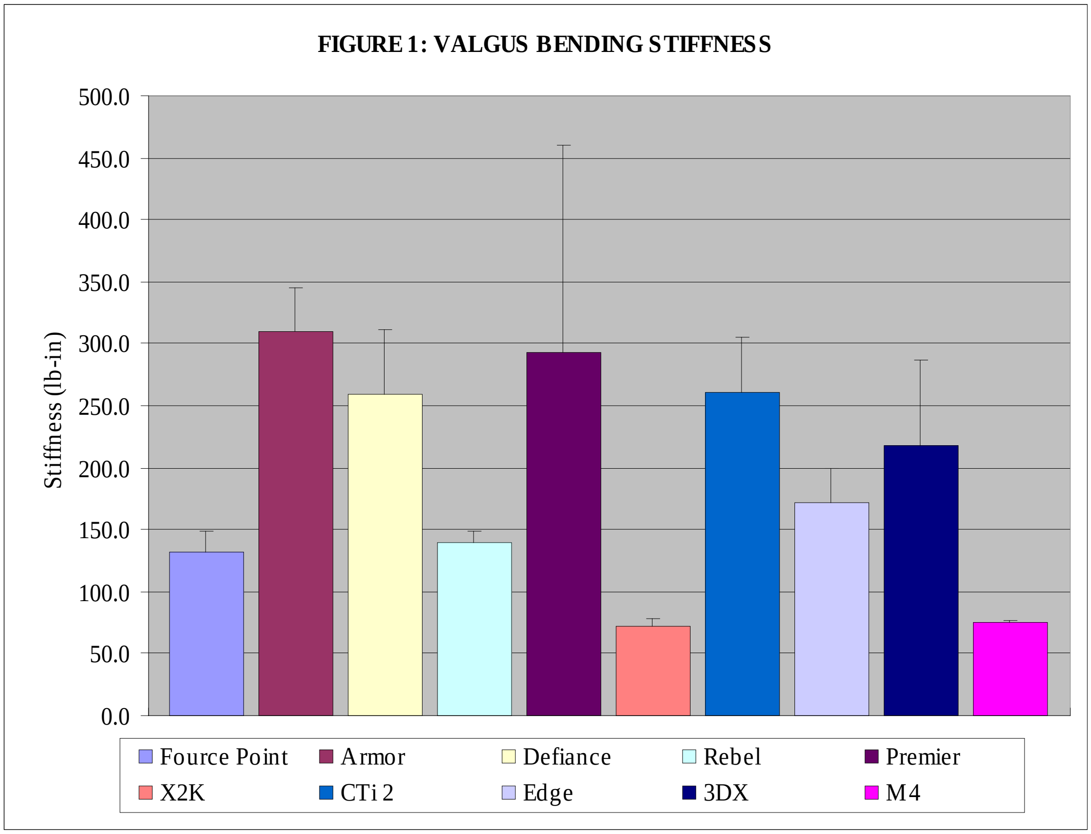


FIGURE 1: VALGUS BENDING STIFFNESS
Stiffness (lb-in)
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
Fource Point
Armor
Defiance
Rebel
Premier
X2K
CTi 2
Edge
3DX
M4

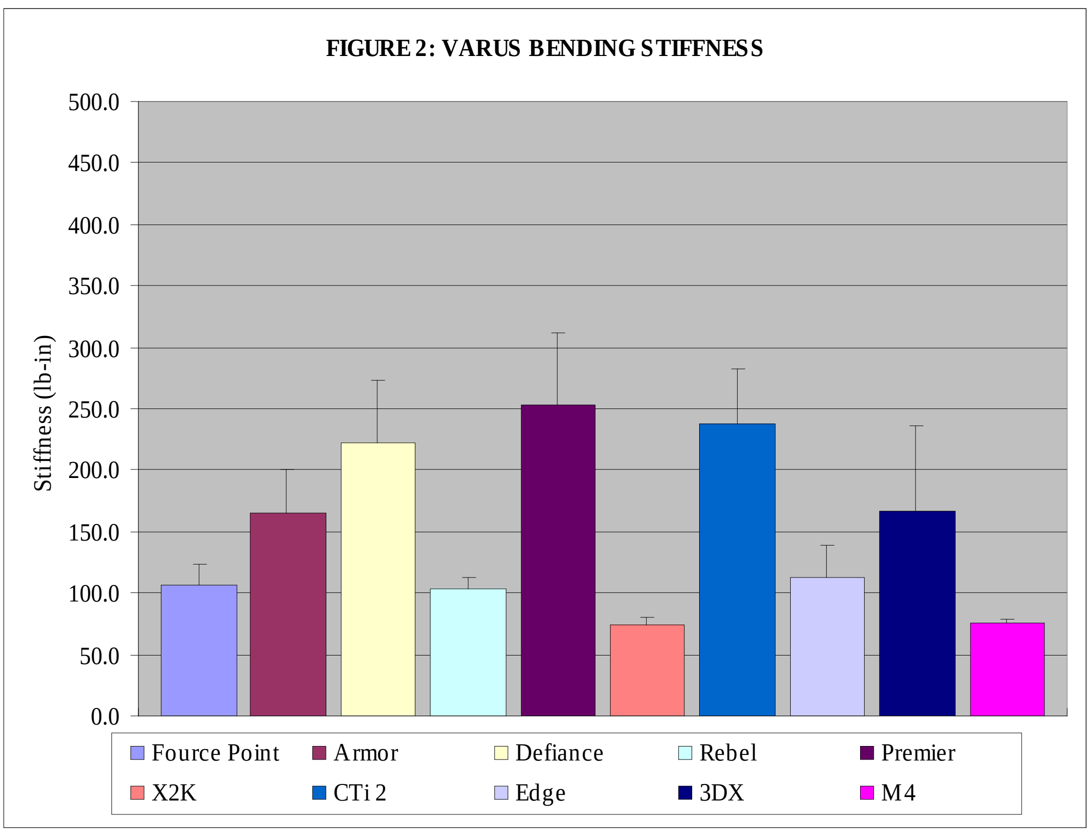


FIGURE 2: VARUS BENDING STIFFNESS
Stiffness (lb-in)
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
Fource Point
Armor
Defiance
Rebel
Premier
X2K
CTi 2
Edge
3DX
M4

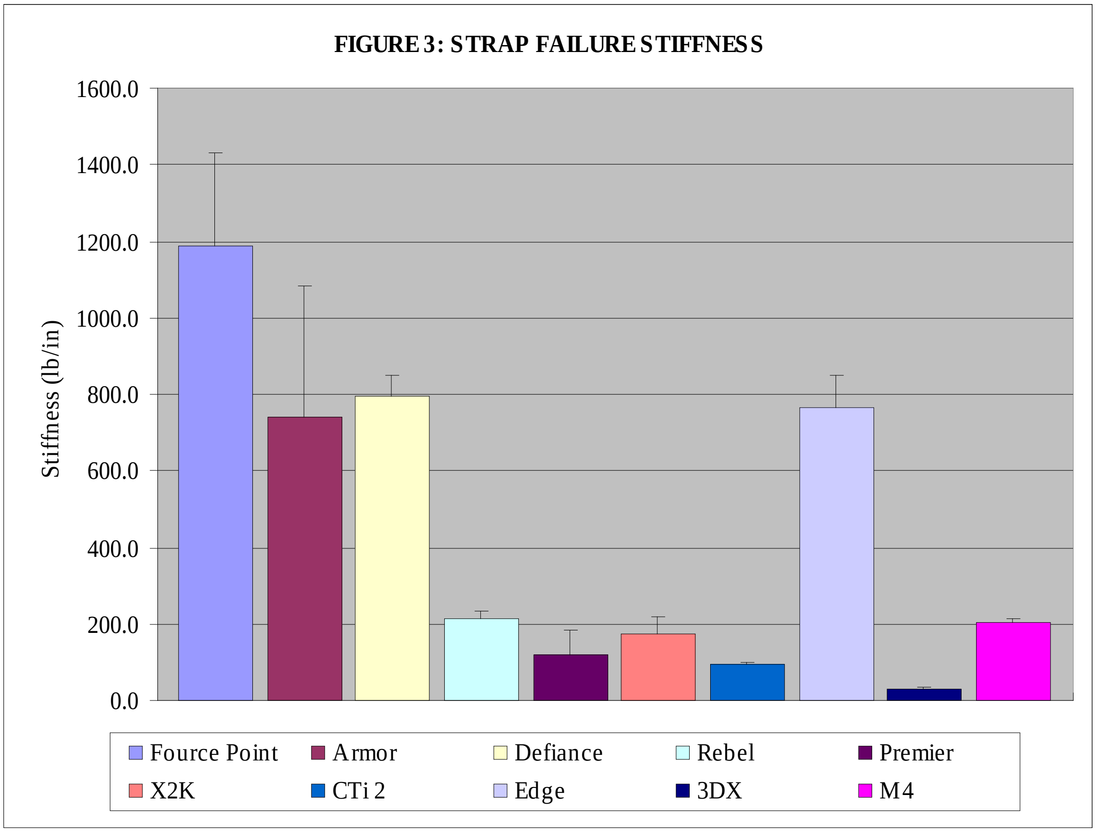


FIGURE 3: STRAP FAILURE STIFFNESS
Stiffness (lb/in)
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
Fource Point
Armor
Defiance
Rebel
Premier
X2K
CTi 2
Edge
3DX
M4

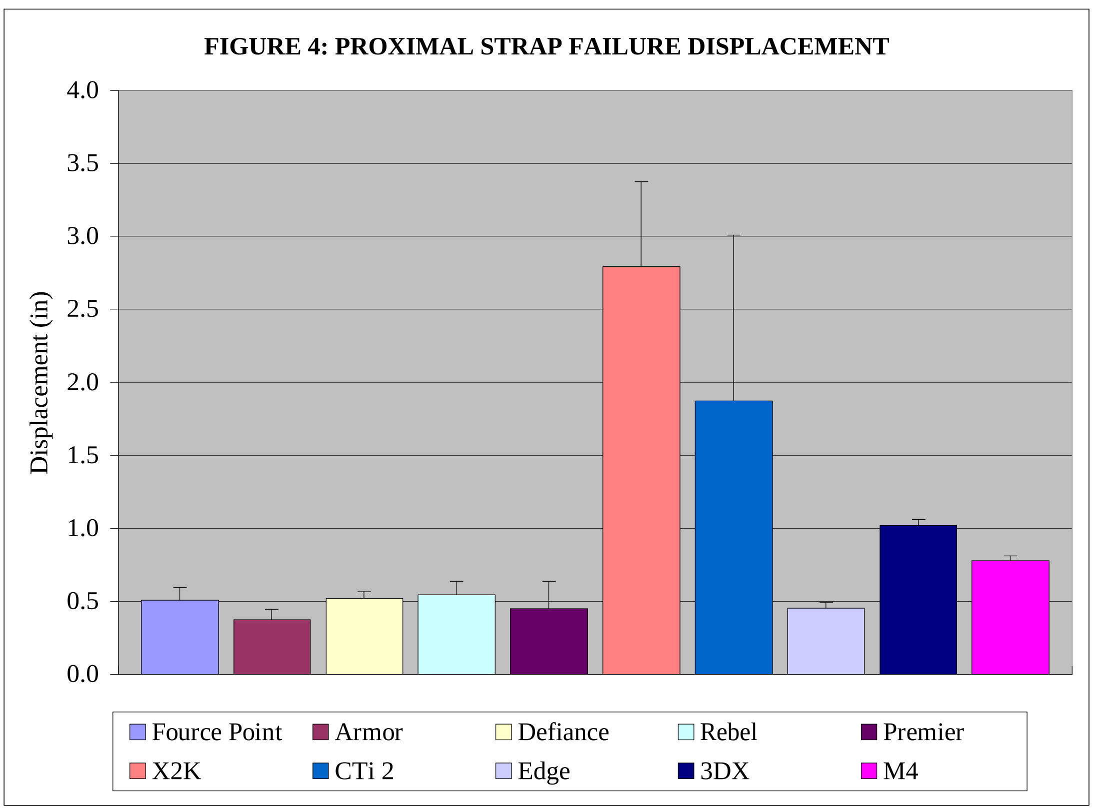


FIGURE 4: PROXIMAL STRAP FAILURE DISPLACEMENT
Displacement (in)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Fource Point
Armor
Defiance
Rebel
Premier
X2K
CTi 2
Edge
3DX
M4

FIGURE 5: PROXIMAL STRAP FAILURE LOAD

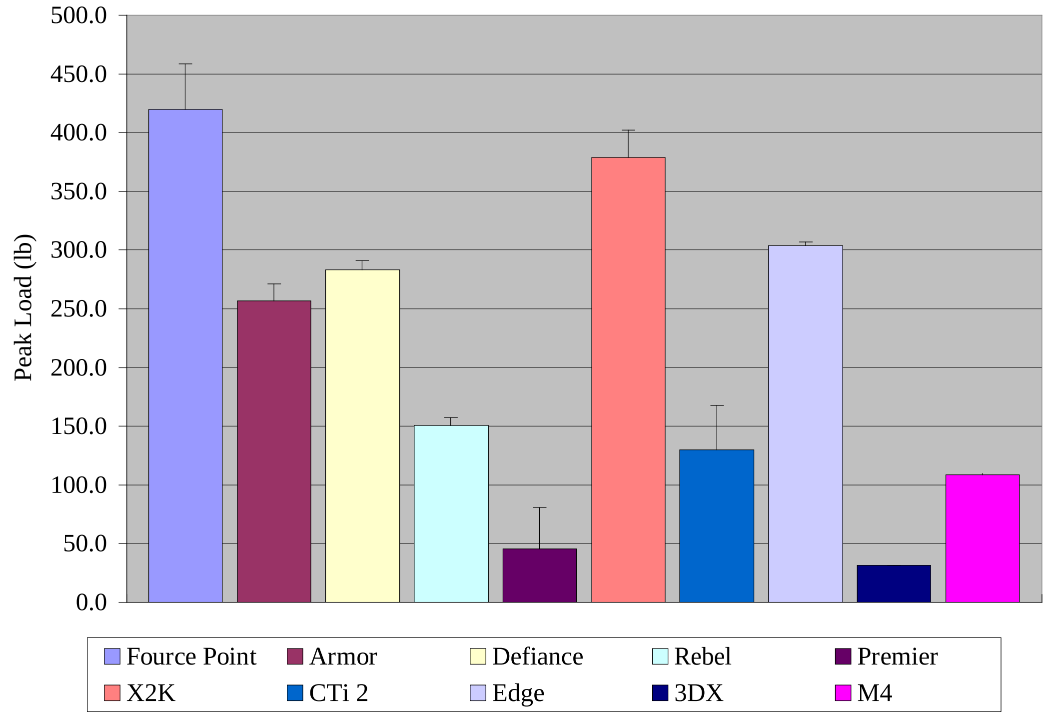


FIGURE 6: LOCKING MECHANISM FAILURE STIFFNESS

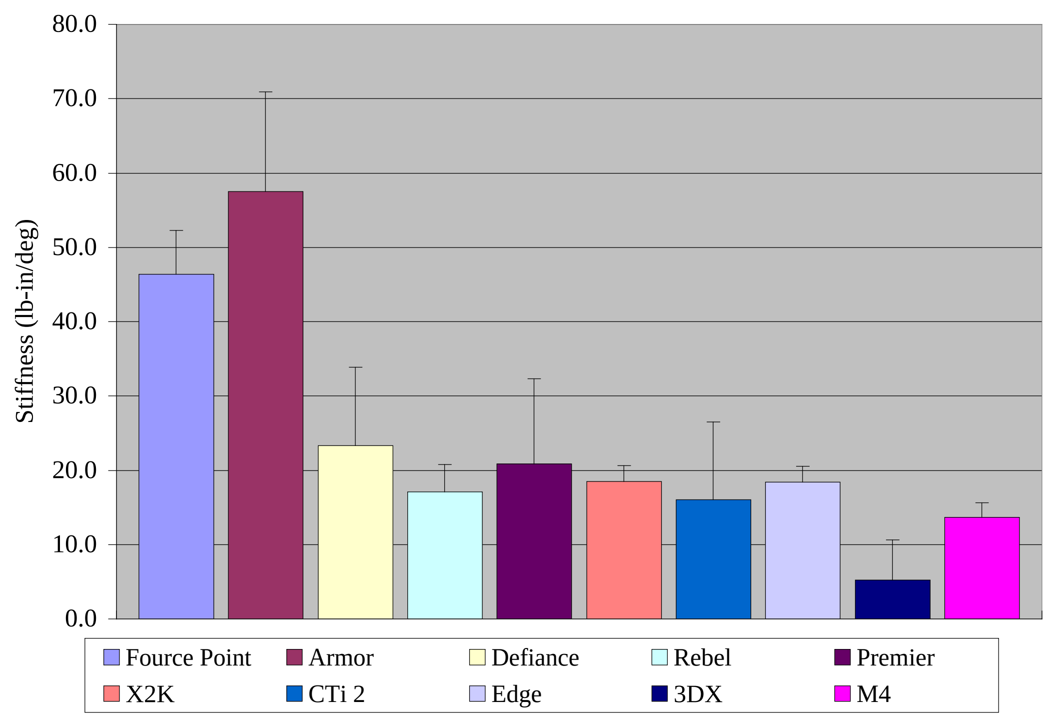


FIGURE 7: LOCKING MECHANISM FAILURE ANGLE

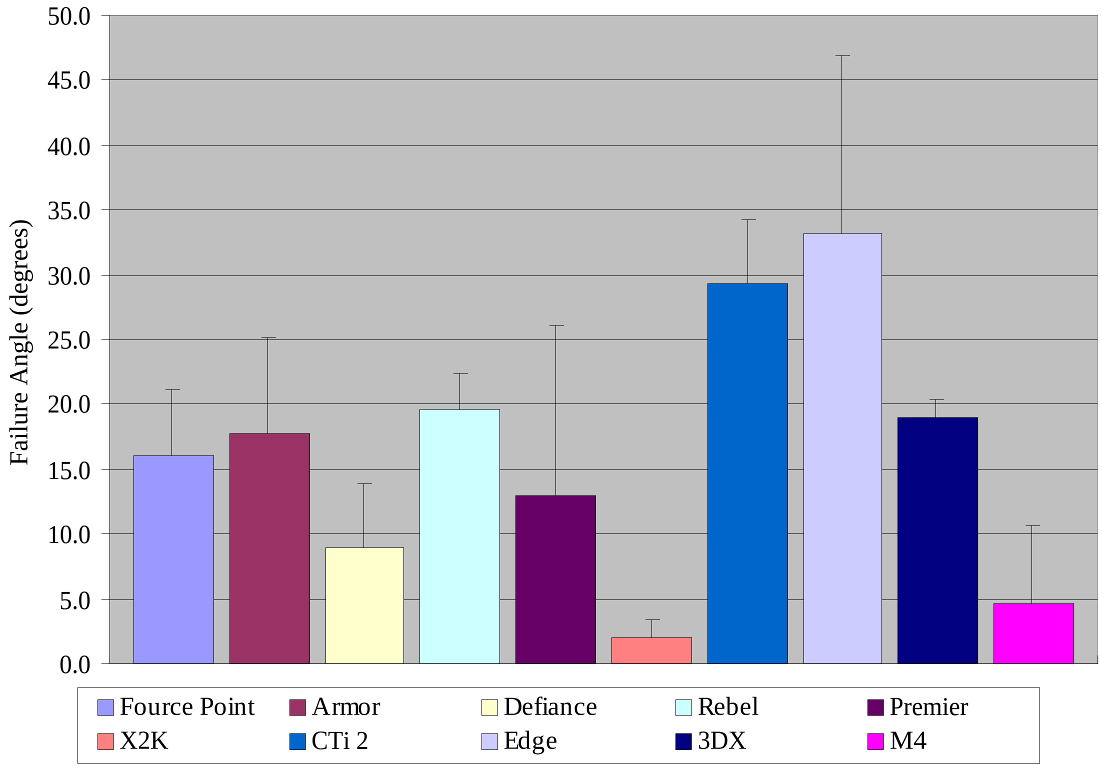
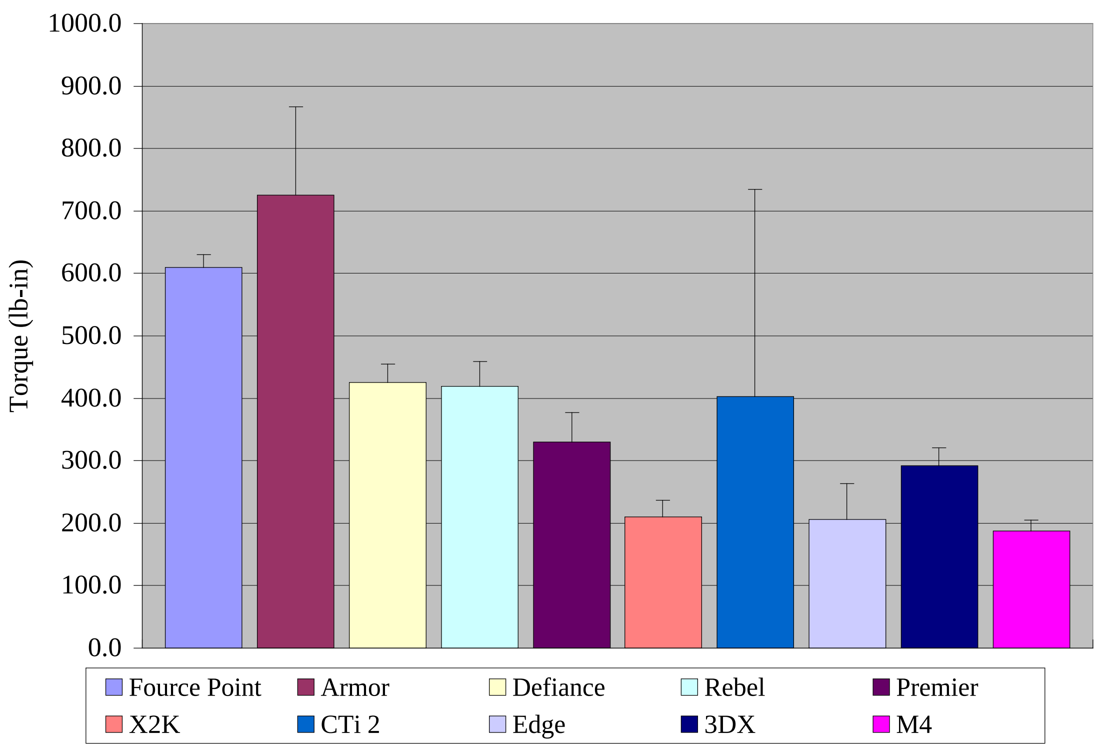


FIGURE 8: LOCKING MECHANISM FAILURE TORQUE



NAME KEY

DonJoy **Fource Point**	Breg **X2K**
DonJoy **Armor**	Innovation Sports **CTi2**
DonJoy **Defiance**	Innovation Sports **Edge**
Townsend **Rebel**	Generation II **3DX**
Townsend **Premier**	Medi **M4**

	Valgus		**Varus**		**Strap Tab**		**Strap Tab**	
	Avg lb/in	Scaled	Avg lb/in	Scaled	lb/in	Scaled	Avg Fail lb	Scaled
Fource Point	131.45	-0.69	106.16	-0.66	1185.17	1.88	419.66	1.53
Armor	309.22	1.38	165.40	0.24	737.91	0.76	256.84	0.34
Defiance	259.29	0.76	221.35	1.03	796.23	0.91	283.33	0.53
Rebel	139.46	-0.60	103.80	-0.70	213.62	-0.55	150.58	-0.44
Premier	292.76	1.18	253.23	1.58	121.16	-0.78	45.44	-1.21
X2K	71.74	-1.39	73.55	-1.16	173.44	-0.65	379.07	1.23
CTi2	261.28	0.82	238.38	1.36	92.28	-0.85	129.87	-0.59
Edge	172.13	-0.22	111.94	-0.58	765.57	0.83	303.58	0.68
3DX	218.07	0.31	167.06	0.27	30.99	-1.00	31.41	-1.31
M4	75.77	-1.34	75.29	-1.14	205.75	-0.57	108.74	-0.75
Mean	191.12		149.62		432.21		210.85	
St Dev	85.89		65.46		400.46		136.64	

Hinge Ext		**Hinge Ext**		**Rank Totals**		
Avg in*lb/deg	Scaled	Avg Fail in*lb	Scaled	Average	Rank	
46.37	1.43	609.25	1.32	0.80	2	**Fource Point**
57.48	2.12	725.36	1.95	1.12	1	**Armor**
23.33	0.00	425.51	0.32	0.59	3	**Defiance**
17.08	-0.39	419.37	0.28	-0.40	7	**Rebel**
20.82	-0.16	329.88	-0.20	0.05	4	**Premier**
18.46	-0.30	209.86	-0.86	-0.52	8	**Breg X2K**
12.73	-0.66	349.18	-0.10	-0.02	5	**CTI**
18.4	-0.30	209.86	-0.86	-0.08	6	**Edge**
5.19	-1.13	205.76	-0.88	-0.64	9	**Gen2**
13.66	-0.60	187.23	-0.98	-0.90	10	**Medi**
23.36		367.13				
16.7		183.38				

APPENDIX 2: Post-Hoc Comparison Tables.

Highlighted values represent a significance level below ($p<0.05$) as computed using Tukey's *post-hoc* HSD (honest significant difference) test. In the Varus ANOVA table below, the general p-value is reported ($p<0.0001$) indicating that *some* statistical comparison was significantly different. To follow proper statistical analysis while maintaining the integrity of the statistical significance, a multiple comparisons test must be completed. To specifically analyze a comparison, the row (1 = DonJoy Fource Point) should be followed across the row with the each number indicating the significance of that particular comparison. In the case of the first comparison in column 2 (2 = DonJoy Armor) the value was found to be statistically similar (0.147).

1 = DonJoy Fource Point
2 = DonJoy Armor
3 = DonJoy Defiance
4 = Townsend Rebel
5 = Townsend Premier
6 = Breg X2K
7 = Innovation Sports CTi2
8 = Innovation Sports Edge
9 = Generation II 3DX
10= Medi M4

Varus Testing ANOVA = $p<0.0001$

	1	2	3	4	5	6	7	8	9	10
Mean	106.2	165.4	221.9	103.8	253.2	73.5	238.4	111.9	167.1	75.3
1		0.147	0.001	1.000	0.000	0.814	0.000	1.000	0.127	0.855
2	0.147		0.187	0.119	0.008	0.005	0.038	0.242	1.000	0.006
3	0.001	0.187		0.000	0.845	0.000	0.997	0.001	0.216	0.000
4	1.000	0.119	0.000		0.000	0.868	0.000	1.000	0.101	0.902
5	0.000	0.008	0.845	0.000		0.000	0.999	0.000	0.009	0.000
6	0.814	0.005	0.000	0.868	0.000		0.000	0.651	0.004	1.000
7	0.000	0.038	0.997	0.000	0.999	0.000		0.000	0.046	0.000
8	1.000	0.242	0.001	1.000	0.000	0.651	0.000		0.211	0.703
9	0.127	1.000	0.216	0.101	0.009	0.004	0.046	0.211		0.005
10	0.855	0.006	0.000	0.902	0.000	1.000	0.000	0.703	0.005	

Valgus Testing ANOVA = $p<0.0015$

	1	2	3	4	5	6	7	8	9	10
Mean	131.5	309.2	259.6	139.5	292.8	71.7	261.3	172.1	218.1	75.8
1		0.075	0.368	1.000	0.134	0.975	0.351	0.998	0.816	0.993
2	0.075		0.993	0.100	1.000	0.007	0.994	0.287	0.772	0.023
3	0.368	0.993		0.449	1.000	0.052	1.000	0.808	0.998	0.120
4	1.000	0.100	0.449		0.174	0.947	0.431	1.000	0.883	0.982
5	0.134	1.000	1.000	0.174		0.014	1.000	0.444	0.909	0.041
6	0.975	0.007	0.052	0.947	0.014		0.048	0.672	0.217	1.000
7	0.351	0.994	1.000	0.431	1.000	0.048		0.792	0.997	0.114
8	0.998	0.287	0.808	1.000	0.444	0.672	0.792		0.996	0.820
9	0.816	0.772	0.998	0.883	0.909	0.217	0.997	0.996		0.376
10	0.993	0.023	0.120	0.982	0.041	1.000	0.114	0.820	0.376	

Tab Stiff ANOVA = p<0.001

	1	2	3	4	5	6	7	8	9	10
Mean	1185.2	737.9	796.2	213.6	121.2	173.4	92.3	765.6	30.9	205.8
1		0.023	0.065	0.000	0.000	0.000	0.000	0.038	0.000	0.000
2	0.023		1.000	0.005	0.001	0.003	0.001	1.000	0.000	0.005
3	0.065	1.000		0.002	0.000	0.001	0.000	1.000	0.000	0.002
4	0.000	0.005	0.002		0.998	1.000	0.983	0.003	0.833	1.000
5	0.000	0.001	0.000	0.998		1.000	1.000	0.001	0.998	0.999
6	0.000	0.003	0.001	1.000	1.000		0.999	0.002	0.954	1.000
7	0.000	0.001	0.000	0.983	1.000	0.999		0.000	1.000	0.989
8	0.038	1.000	1.000	0.003	0.001	0.002	0.000		0.000	0.003
9	0.000	0.000	0.000	0.833	0.998	0.954	1.000	0.000		0.864
10	0.000	0.005	0.002	1.000	0.999	1.000	0.989	0.003	0.864	

Tab Fail ANOVA = p<0.001

	1	2	3	4	5	6	7	8	9	10
Mean	419.7	256.9	283.3	150.6	45.4	379.1	129.9	303.6	31.4	108.7
1		0.000	0.000	0.000	0.000	0.482	0.000	0.000	0.000	0.000
2	0.000		0.899	0.001	0.000	0.000	0.000	0.304	0.000	0.000
3	0.000	0.899		0.000	0.000	0.001	0.000	0.979	0.000	0.000
4	0.000	0.001	0.000		0.001	0.000	0.975	0.000	0.000	0.442
5	0.000	0.000	0.000	0.001		0.000	0.005	0.000	0.998	0.061
6	0.482	0.000	0.001	0.000	0.000		0.000	0.015	0.000	0.000
7	0.000	0.000	0.000	0.975	0.005	0.000		0.000	0.001	0.972
8	0.000	0.304	0.979	0.000	0.000	0.015	0.000		0.000	0.000
9	0.000	0.000	0.000	0.000	0.998	0.000	0.001	0.000		0.012
10	0.000	0.000	0.000	0.442	0.061	0.000	0.972	0.000	0.012	

Hinge Fail Stiffness ANOVA = p<0.001

	1	2	3	4	5	6	7	8	9	10
Mean	46.4	57.5	23.3	17.1	20.8	18.5	12.7	18.4	5.2	13.7
1		0.705	0.028	0.003	0.012	0.005	0.001	0.005	0.000	0.001
2	0.705		0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.028	0.001		0.986	1.000	0.998	0.754	0.998	0.141	0.833
4	0.003	0.000	0.986		1.000	1.000	0.999	1.000	0.628	1.000
5	0.012	0.000	1.000	1.000		1.000	0.932	1.000	0.284	0.966
6	0.005	0.000	0.998	1.000	1.000		0.992	1.000	0.489	0.998
7	0.001	0.000	0.754	0.999	0.932	0.992		0.992	0.954	1.000
8	0.005	0.000	0.998	1.000	1.000	1.000	0.992		0.489	0.998
9	0.000	0.000	0.141	0.628	0.284	0.489	0.954	0.489		0.913
10	0.001	0.000	0.833	1.000	0.966	0.998	1.000	0.998	0.913	

Hinge Fail Torque ANOVA = p<0.001

	1	2	3	4	5	6	7	8	9	10
Mean	609.3	725.4	425.5	419.7	329.9	209.9	349.2	209.9	205.8	187.2
1		0.888	0.413	0.372	0.050	0.002	0.081	0.002	0.002	0.001
2	0.888		0.029	0.025	0.002	0.000	0.004	0.000	0.000	0.000
3	0.413	0.029		1.000	0.962	0.225	0.991	0.225	0.207	0.137
4	0.372	0.025	1.000		0.975	0.256	0.995	0.256	0.235	0.157
5	0.050	0.002	0.962	0.975		0.868	1.000	0.868	0.846	0.723
6	0.002	0.000	0.225	0.256	0.868		0.747	1.000	1.000	1.000
7	0.081	0.004	0.991	0.995	1.000	0.747		0.747	0.718	0.576
8	0.002	0.000	0.225	0.256	0.868	1.000	0.747		1.000	1.000
9	0.002	0.000	0.207	0.235	0.846	1.000	0.718	1.000		1.000
10	0.001	0.000	0.137	0.157	0.723	1.000	0.576	1.000	1.000	

Hinge Fail Angle ANOVA = p<0.002

	1	2	3	4	5	6	7	8	9	10
Mean	26.1	27.7	18.9	29.6	23	12.1	39.3	43.3	29.3	14.7
1		1.000	0.983	1.000	1.000	0.418	0.498	0.192	1.000	0.671
2	1.000		0.942	1.000	0.998	0.285	0.660	0.296	1.000	0.509
3	0.983	0.942		0.844	1.000	0.987	0.142	0.047	0.867	1.000
4	1.000	1.000	0.844		0.980	0.173	0.829	0.454	1.000	0.340
5	1.000	0.998	1.000	0.980		0.720	0.244	0.076	0.986	0.917
6	0.418	0.285	0.987	0.173	0.720		0.007	0.002	0.191	1.000
7	0.498	0.660	0.142	0.829	0.244	0.007		1.000	0.801	0.017
8	0.192	0.296	0.047	0.454	0.076	0.002	1.000		0.421	0.004
9	1.000	1.000	0.867	1.000	0.986	0.191	0.801	0.421		0.370
10	0.671	0.509	1.000	0.340	0.917	1.000	0.017	0.004	0.370	

APPENDIX 3: Radar Chart

This chart depicts the overall scores across braces. For the data analyzed, the brace with the greatest area within the figure would represent the brace with the greatest performance. In addition, the circularity of the brace indicates the consistency of the brace across all methods of testing. This chart is to be used in concert with Table 5 to ease the comprehension of brace differences.