CHAPTER 5 RESULTS

5.1 Biomechanical Testing Device

The design and construction of this device proved to be compatible for use in the Zwick testing machine. The device also facilitated a simple but extremely effective and scientifically reliable method for investigating the three-dimensional load-displacement properties of fracture stabilisation in synthetic mandibles.

All the load-displacement data obtained using the biomechanical testing device secured in the Zwick machine, showed small fluctuations in the initial phase of load application. This was ascribed to settling of the rounded compression pin in the prepared fossa of the occlusal surface of the first molar tooth in the test model. In order to standardise the measurements for each variable, the force resistance zero point was taken as the point when this fluctuation is stopped and a constant increase in force delivery was observed. This meant that measurement of placement or extension of the mandible only started at the point when there was a constant increase in force delivery.

5.2 Compression Load-Displacement Results

Fifteen compression test samples registered force delivery values at increments of 0.1mm displacement for each of the screw angle applications 90°, 75°, 60° and 45°, the failure point was arbitrarily set at 3.0mm displacement to reflect clinical inability for primary healing of fracture fragments. The load-pin delivered a compression force at a constant crosshead speed 0.1mm/min and the test sample terminated at a displacement of 5mm.

The recorded load-displacement data of the individual screw angle applications are listed in Table 2.

Table 2: Load-displacement values in compression for screws placed at 90°, 75°, 60° and 45° respectively

Displacement (mm)	Screw Angle (Degrees)	Load (Newton)
0.1	90	0.79
	75	0.58
	60	1.02
	45	0.85
0.2	90	1.54
	75	1.17
	60	1.96
	45	1.92
0.3	90	2.18
	75	1.74
	60	2.88
	45	2.65
0.4	90	2.73
	75	2.28
	60	3.17
	45	3.35
0.5	90	3.37
	75	2.86
	60	4.44
	45	3.88
0.6	90	4.03
	75	3.45
	60	4.97
	45	4.71
0.7	90	4.66
	75	3.96
	60	5.84
	45	5.40
0.8	90	5.43
	75	4.47
	60	5.57

Displacement (mm)	**Screw Angle (Degrees)**	**Load (Newton)**
	45	6.02
0.9	90	6.19
	75	4.95
	60	7.32
	45	6.46
1.0	90	6.91
	75	5.45
	60	8.09
	45	7.30

Displacement (mm)	**Screw Angle (Degrees)**	**Load (Newton)**
1.1	90	7.57
	75	6.00
	60	8.77
	45	8.00
1.2	90	8.20
	75	6.75
	60	9.08
	45	8.67
1.3	90	8.80
	75	7.14
	60	9.99
	45	9.31
1.4	90	9.37
	75	7.66
	60	10.63
	45	9.93
1.5	90	9.96
	75	8.19
	60	11.26
	45	10.40

Displacement (mm)	Screw Angle (Degrees)	Load (Newton)
1.6	90	10.58
	75	8.72
	60	12.00
	45	10.92
1.7	90	11.14
	75	9.17
	60	12.66
	45	11.54
1.8	90	11.69
	75	9.65
	60	13.01
	45	12.11
1.9	90	12.22
	75	10.15
	60	13.82
	45	12.66
2.0	90	12.63
	75	10.61
	60	14.36
	45	13.21
2.1	90	13.15
	75	11.10
	60	14.85
	45	13.73
2.2	90	13.68
Displacement (mm)	**Screw Angle (Degrees)**	**Load (Newton)**
	75	11.51
	60	15.47
	45	14.25
2.3	90	14.21
	75	11.94

Displacement (mm)	Screw Angle (Degrees)	Load (Newton)
	60	16.03
	45	14.75
2.4	90	14.75
	75	12.15
	60	16.30
	45	15.27
2.5	90	15.26
	75	12.65
	60	17.01
	45	15.81
2.6	90	15.76
	75	13.12
	60	17.52
	45	16.27
2.7	90	16.25
	75	13.57
	60	17.97
	45	16.76
2.8	90	16.72
	75	14.06
	60	18.48
	45	17.26
2.9	90	17.16
	75	14.51
	60	18.95
	45	17.72
3.0	90	17.62
	75	14.99
	60	19.14
	45	18.20
3.1	90	18.07
	75	15.45
	60	19.83

Displacement (mm)	**Screw Angle (Degrees)**	**Load (Newton)**
	45	18.66
3.2	90	18.46
	75	15.89
	60	20.23
	45	19.11
3.3	90	18.90
	75	16.34
	60	20.60
Displacement (mm)	**Screw Angle (Degrees)**	**Load (Newton)**
	45	19.54
3.4	90	19.29
	75	16.79
	60	21.02
	45	19.94
3.5	90	19.66
	75	17.24
	60	21.41
	45	20.34
3.6	90	20.02
	75	17.72
	60	21.51
	45	20.73
3.7	90	20.36
	75	18.16
	60	22.04
	45	21.12
3.8	90	20.63
	75	18.58
	60	22.32
	45	21.48
3.9	90	20.86
	75	18.97

Displacement (mm)	Screw Angle (Degrees)	Load (Newton)
	60	22.64
	45	21.82
4.0	90	21.14
	75	19.39
	60	23.02
	45	22.16
4.1	90	21.23
	75	19.82
	60	23.31
	45	22.50
4.2	90	21.25
	75	20.27
	60	23.33
	45	22.84
4.3	90	21.62
	75	20.71
	60	23.87
	45	23.16
4.4	90	21.92
	75	21.11
	60	24.06
	45	23.49
4.5	90	22.23
Displacement (mm)	**Screw Angle (Degrees)**	**Load (Newton)**
	75	21.56
	60	24.34
	45	23.78
4.6	90	22.50
	75	21.95
	60	24.72
	45	24.06
4.7	90	22.73

Displacement (mm)	Screw Angle (Degrees)	Load (Newton)
	75	22.37
	60	23.99
	45	24.31
4.8	90	22.98
	75	22.78
	60	24.05
	45	24.59
4.9	90	23.21
	75	23.19
	60	24.50
	45	24.88
5.0	90	23.43
	75	23.56
	60	24.72
	45	25.16

5.3 Statistical Analysis of Compression Evaluation

5.3.1 Mean Fixation

The average compression load-displacement values (Table 2) were used to derive a graphic illustration of load versus displacement for screws placed at 90°, 75°, 60° and 45° angles. Figure 33 indicates the relative fixation of the various compression screw angle tests (CSAT).

From Figure 33 it is clear that all compression test samples for angled screw applications of 45° and 60° demonstrated more stable results with less displacement for the same compression force delivery than test samples with conventional rectangular screw placement. The screw angle test sample with screws at 75° proved less favourable than all other test samples and can be explained by the minimal screw-tip shifting and travel due to the screw at 75° having bodily rotated through less than its 2mm diameter and having a slight shortening effect of the screw at the angle. It is also noted that with regard to displacement values at force applications of 0 to 5 Newton and 20 to 25 Newton, no significant stability difference between conventional rectangular screw testing and 75° test samples was demonstrated.

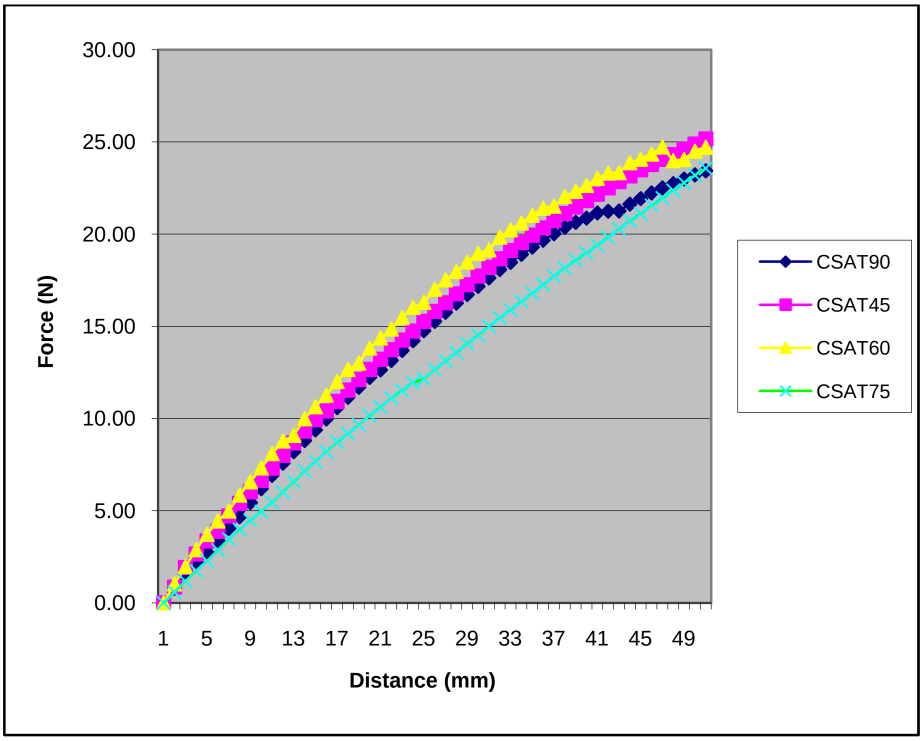

Figure 33: Mean fixation of all the CSAT tests

5.3.2 Statistical Comparison (P-values) of CSAT

Statistical analysis of data of the average CSAT was done. Mean values (x), standard deviation (SD) and the coefficient of variation (CV) for all variables were calculated after data were standardised (zeroed at starting point) and obvious outlying date were deleted after the 95% confidence levels were determined and taken into consideration. Thereafter the statistical variation between the standardised force delivery values of the compression screw angle tests for screws placed at angles of 90°, 75°, 60° and 45° were determined by applying Scheffe's multiple comparison procedure as described in abovementioned Statistix® 8 Analytical Software, Florida, USA.

The statistical comparison (P-values) of all the CSAT screw angle tests is presented in Table 3.

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Table 3: P-values of 90°, 75°, 60° and 45° CSAT tests at distances from 0,5 to 5mm extension

CSAT Angle (Degrees)	75°	60°	45°
0.5mm90°	0.067	0.1618	0.4757
1.0mm90°	0.0863	0.0865	0.2335
1.5mm90°	0.0365	0.0614	0.1909
2.0mm90°	0.0268	0.0658	0.1805
2.5mm90°	0.1961	0.0441	0.1029
3.0mm90°	0.358	0.0099	0.0263
3.5mm90°	0.439	0.0091	0.0124
4.0mm90°	0.1683	0.0044	0.0021
4.5mm90°	0.191	0.0232	0.0074
5.0mm90°	0.0359	0.0313	0.0007
0.5mm75°		0.0077	0.0749
1.0mm75°		0.0041	0.0199
1.5mm75°		0.0007	0.0047
2.0mm75°		0.0005	0.0029
2.5mm75°		0.0053	0.0168
3.0mm75°		0.0039	0.0115
3.5mm75°		0.0111	0.0153
4.0mm75°		0.0419	0.0236
4.5mm75°		0.1005	0.0351
5.0mm75°		0.4736	0.0593
0.5mm75°			0.1476
0.5mm60°			0.259
1.0mm60°			0.2468
2.0mm60°			0.2712
2.5mm60°			0.3184
3.0mm60°			0.3353
3.5mm60°			0.4458
4.0mm60°			0.3933
4.5mm60°			0.2897
5.0mm60°			0.0672

From the above P-values it is clear that none of the 75° angled test samples demonstrated significantly higher results that 90°; significantly higher force/displacement values were registered for 60° and 45° angled screw compared to 90°. This phenomenon registered at displacement values of 2.5 through to 5.0mm for 60° angled screws and at 3.0mm for 45° angled screws at an earlier point of displacement at 0.5mm.

5.3.3 Analysis of Load-Displacement Gradients or Slopes

The mean stability slope gradient values as presented in Table 4 were used to derive intercept points for specific load-displacement data.

Table 4: Mean slope gradient values of the force delivery of the SCAT test for screws placed at angles of 90º, 75º, 60º and 45º

	Slope 90	Intercept 90	Slope 45	Intercept 45	Slope 60	Intercept 60	Slope 75	Intercept 75
1	0.4214	7.5257	0.3834	12.022	0.3318	20.61	0.6713	6.8978
2	0.3665	16.15	0.3953	5.6569	0.3663	10.429	0.4794	4.3733
3	0.7418	2.3273	0.4854	11.73	0.4778	13.666	0.2984	8.4693
4	0.3941	15.559	0.4866	2.3069	0.5954	9.6033	0.439	9.3029
5	0.3972	13.822	0.4576	8.6313	0.3686	18.988	0.7265	11.184
6	0.442	8.0916	0.4467	13.391	0.5023	7.043	0.5053	8.2057
7	0.3112	4.43	0.3546	11.75	0.5039	13.339	0.3886	6.8265
8	0.3185	9.8328	0.3472	11.536	0.5551	24.831	0.5014	10.329
9	0.3971	9.2982	0.7798	16.629	0.4046	11.369	0.3388	8.1073
10	0.3887	13.791	0.7493	16.569	0.2916	5.7444	0.3463	8.5761
11	0.698	10.282	0.2674	4.0461	0.4107	8.8772	0.4632	5.5968
12	0.3919	12.792	0.2551	11.152	0.2178	6.8642	0.3041	10.41
13	0.3981	11.057	0.2317	14.963	0.3763	10.344	0.4734	8.0064
14	0.3667	11.995	0.3042	7.7491	0.3400	12.013	0.4377	5.3727
15	0.4224	9.9127	0.3993	15.561	0.2969	7.112	0.335	8.0902
					0.4926	13.537		

Significance was demonstrated for angled screw systems of 60° and 45°. This significance was evident to a displacement value of 4mm. This would appear to have clinical significance for a failure displacement relatively assured to be eminent at 3mm fragment displacement. The force resistance at 0.5mm displacements for all the different angles were compared to determine whether screw angles affect force delivery as shown in Table 2. Average slope values were calculated from data in Table 5.

Table 5: Average slope values for Inclined Screws Insertion (ISI)

	Slope 90	Slope 45	Slope 60	Slope75
1	0.4214	0.3834	0.3318	0.6713
2	0.3665	0.3953	0.3663	0.4794
3		0.4854	0.4778	0.2984
4	0.3941	0.4866	0.5954	0.4390
5	0.3972	0.4576	0.3686	0.7265
6	0.442	0.4467	0.5023	0.5053
7	0.3112	0.3546	0.5039	0.3886
8	0.3185	0.3472	0.5551	0.5014
9	0.3971		0.4046	0.3388
10	0.3887		0.2916	0.3463
11		0.2674	0.4107	0.4632
12	0.3919	0.2551	0.2178	0.3041
13	0.3981	0.2317	0.3763	0.4734
14	0.3667	0.3042	0.3400	0.4377
15	0.4224	0.3993	0.2969	0.3350
			0.4926	
AVG	0.3860	0.3700	0.4080	0.44700

When considering stress force curves of the individual screw angle plates, the slope of the curve give an indication of the relative fixation of the fracture, with higher slope values indicating better fixation. Therefore the slopes of all the stress force graphs for ISI placed at angles of 90°, 75°, 60° and 45° was determined and the statistical variation in slopes were determined by a One–Way ANOVA. The data is illustrated in Figure 34.

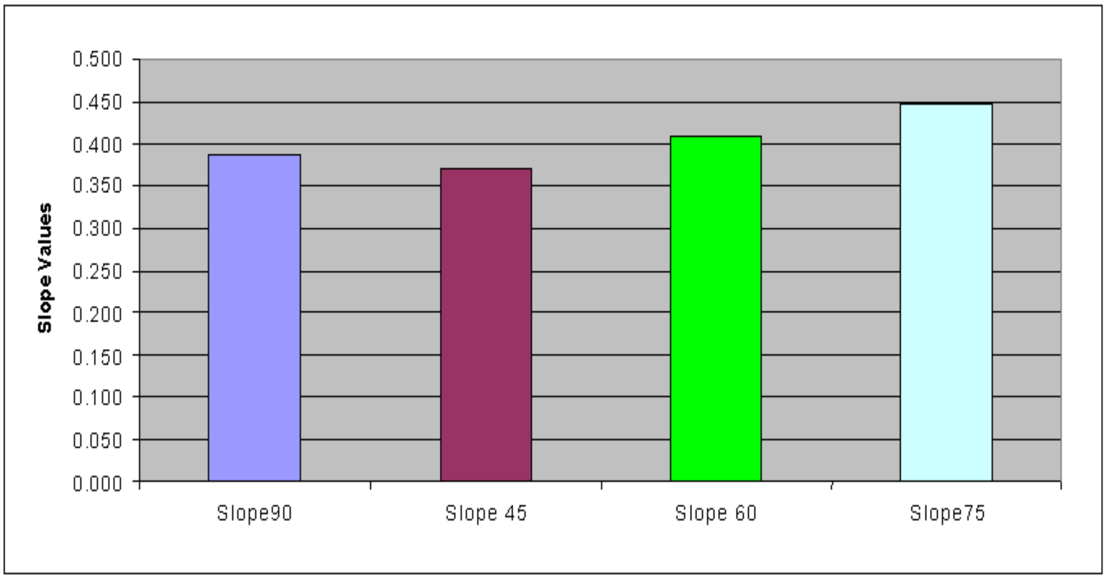


Figure 34: Mean slope values of the force for delivery graphs of the compression screw angle test for screws placed at angles of 90°, 75°, 60° and 45° as determined by the equation for calculating linear trend lines at a distance of 2-5mm extension

Bar graph of mean compression load-displacement slope values for ISI (90°, 75°, 60° and 45° groups) are illustrated in Figure 35. The significantly improved biomechanical stability of a 45° angled screw placement is evident.

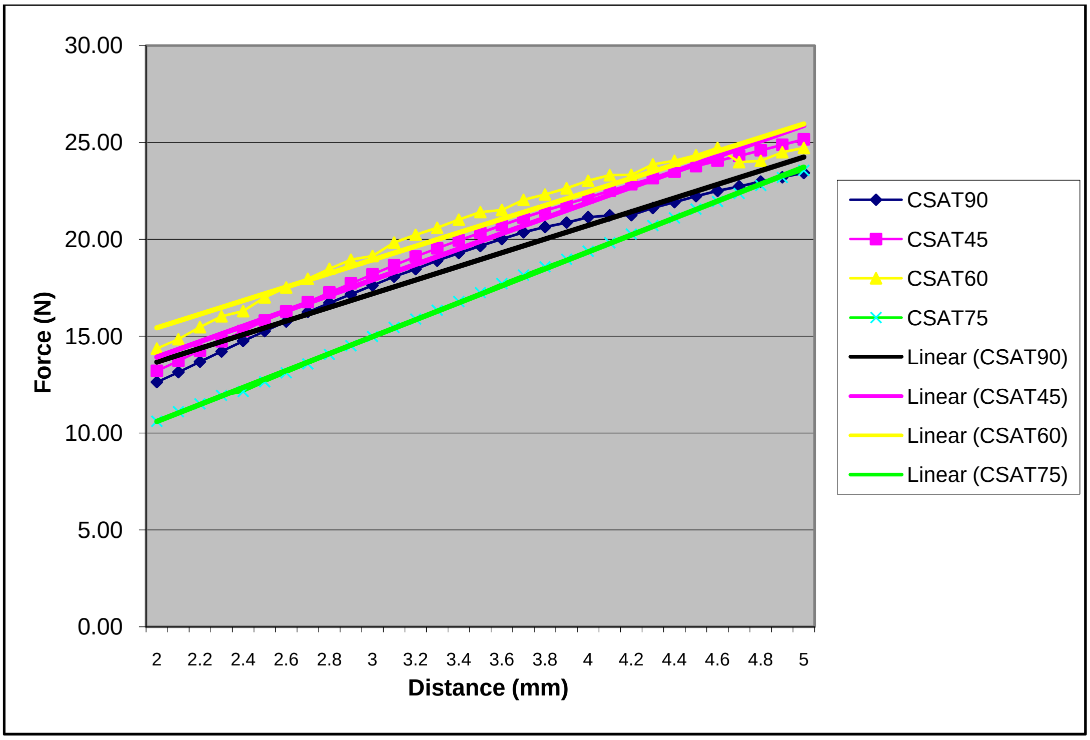


Figure 35: Linear trend lines for mean force delivery values of the tests for screws plant at angles of 90°, 75°, 60° and 45°TSAT.

5.3.4 Linear trend lines

Linear trend lines were calculated using the equation:

Y = m.x + b

Where **m** is the slope and **b** is the intercept and **x** is the mean load-displacement values.

This information was used to establish linear trend lines of the mean load-displacement values of the various screw angle tests. These results are illustrated in Figure 35. Linear trend lines demonstrated a less stable CSAT 75° angle screw insertion for, when compared to all other ISI angles – a phenomena which could be the result of the relatively small sample size of the groups and could be attributed to insignificant Screw-Tip Travel (STT) and Screw Tip-Shifting (STS).

With the development of multiple angle applications of the Inclined Screw Insertion (ISI) system it is an important consideration to determine the three-dimensional torsion effect on fixated simulations of fractures.

Torsion force displacement test (TSAT) values were registered for displacements at 2mm intervals due to minute measurable displacement values for applied force delivery during experimentation. Torsion was created at a crosshead speed of 1mm/min in an upward motion. The radius of rotation was kept constant by maintaining the same cable angle at the rotating wheel for all test samples.

The standardised data for stress delivery of the TSAT tests for the variables of ISI 90°, 75°, 60° and 45° at displacement values 2, 4 and 6mm, are given in Table 6 to 9.

Table 6: TSAT values of ISI at 90° placement angles

Sample	F-2mm	F-4mm	F--6mm
1	33.727	78.037	119.332
2	24.385	60.065	105.060
3	33.350	81.052	124.922
4	38.227	81.962	126.689
5	33.235	75.112	122.574
6	16.667	54.951	115.763
7	26.275	65.889	109.850
8	9.604	30.497	66.521
9	17.931	44.875	75.871
10	18.191	50.583	100.284
11	17.841	51.003	79.622
12	22.857	65.146	112.192
13	36.453	87.280	120.313
14	35.641	71.637	105.042
15	25.111	55.456	72.426

Table 7: Standardized load (Newton N) TSAT for ISI of 75°

Sample	F-2mm	F-4mm	F-6mm
1	36.140	82.003	125.523
2	30.452	72.169	119.071
3	32.086	66.916	104.004
4	31.207	72.097	113.250
5	36.683	80.059	121.729
6	35.651	77.356	117.020
7	30.936	76.290	121.335
8	37.052	76.729	111.070
9	34.381	71.213	107.143
10	30.618	69.772	113.465
11	31.941	74.008	119.904
12	35.683	70.997	109.669
13	35.827	77.656	119.142
14	34.659	82.219	128.041
15	36.194	80.278	124.948

Table 8: Standardized TSAT for ISI of 60°

Sample	F-2mm	F-4mm	F-6mm
1	35.978	77.522	97.466
2	29.794	66.981	107.72
3	26.942	66.899	109.529
4	33.104	73.71	113.25
5	28.248	65.211	106.61
6	42.737	78.332	126.422
7	19.546	44.621	78.304
8	10.843	30.899	54.364
9	9.941	32.266	64.229
10	34.19	67.792	108.992
11	24.036	49.33	84.478
12	29.343	66.782	108.499
13	34.527	76.625	120.749
14	39.725	81.55	121.704
15	*	*	*

Table 9: Standardized TSAT for ISI of 45°

Sample	F-2mm	F-4mm	F-6mm
1	20.422	51.712	86.368
2	31.6	72.032	108.952
3	36.435	78.134	122.399
4	45.897	92.56	138.696
5	33.81	74.144	114.308
6	29.189	72.529	117.096
7	36.265	80.654	124.818
8	38.128	80.774	116.777
9	43.722	94.001	141.945
10	35.231	78.848	120.87
11	41.064	92.018	140.318
12	29.739	72.006	121.384
13	32.874	72.159	113.723
14	9.707	26.786	50.778
15	19.606	40.189	70.746

The above force displacement data was graphically displayed where load force application in Newton (N) and displacement in tenths of a millimetre was plotted for each angled ISI plate of which Figure 36 is an example.

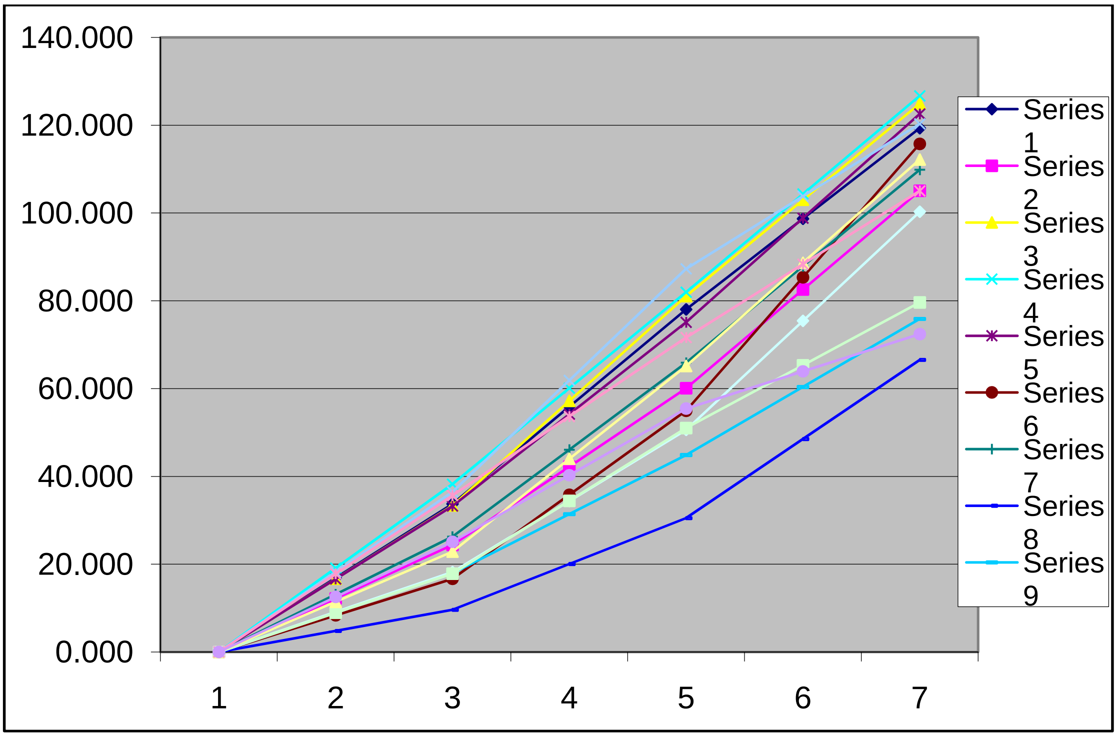


Figure 36: Example of Graphic display of raw data for: TSAT Torsion Screw Angle Test of ISI 60° angle (n-15) test sample

All data gathered during the determination of stress/torsion resistance showed small fluctuations in initial stability. This was ascribed to the settling of the cable. In order to standardize the measurements for each variable the stress resistance zero point was registerd at the point where this fluctuation stopped and a constant increase in stress delivery was observed. This meant that measurement of fragment displacement started only after slack in the cable was eliminated and constant increase was observed in torsion force delivery. The load applied to obtain torsional displacement of 2, 4 and 6mm respectively, showed similar incremental increases in all the angles TSAT evaluations.

5.3.5 Statistical Analysis of TSAT

The data obtained in the TSAT evaluations, was used to calculate the mean values (x), standard deviations (SD) and coefficient of variation (CV). After standardisation and deletion of outlying data, (only data at 95% confidence level was taken into consideration.) The analysis was done using Statix® 8 Analytical Software.

5.3.6 Mean TSAT Stability

The derived load displacement torsion screw angle test (TSAT) values are expressed in Table 10. Additional mean TSAT forces for displacements of 1, 3 and 5mm were calculated and is reflected in Table 11 below and used to express trend line behaviour for values 1-6mm displacement.

Table 10: The load displacement application for TSAT for displacement values of 2, 4 and 6mm

Inclined Screw Insertion (ISI) Angle (Degrees)	Displacement (mm)	Load (Newton)
90°	**2**	25.028
	4	64.290
	6	100.370
75°	**2**	33.967
	4	75.317
	6	117.020
60°	**2**	34.952
	4	78.044
	6	120.590
45°	**2**	32.608
	4	67.946
	6	106.980

Table 11: Mean torsion force (stress) values of screw angle tests for screws placed at angles of 90°, 75°, 60° and 45°

	Displacement (mm)					
ISI angles	1	2	3	4	5	6
90°	13.54363	27.08707	44.91378	64.8103	85.80013	109.366
75°	16.98367	33.96733	54.6424	75.31747	96.54057	116.2338
60°	15.34233	29.5708	49.47844	67.89583	87.74387	107.438
45°	16.78654	33.14288	54.58699	76.03111	96.29369	117.8141

The statistical variation between the standardized stress force values for screws placed at 90°, 75°, 60° and 45° (ISI) was determined by applying Scheffe's Multiple Pair-wise Comparison Procedure – thus investigating the patterns among the means that produce these results, the pair-wise comparisons of interest are data was data scanned for significant differences. Table 12 illustrates the clinical relevant displacement from 1-3mm of the fragments fixated with the same length of screw clearly demonstrate higher torsion force (N) values for the same amount of displacement in the inclined screw insertion groups for all of the angles 75°, 60° and 45°, when compared to the conventional 90° screw angle insertion group. For the 60° ISI group (n=15), with same lengths of screws (7mm), no significant difference could be demonstrated (P=> 0.05) when compared to the 90° conventional group; all other angles of screw insertion angles (75° and 45°) demonstrated significance (P=<0.05) in torsion force biomechanical stability improvement. The statistical comparison of the derived P-values is given in Table 12.

Table 12: Graphic illustration of P-values of TSAT tests for 1 to 6mm displacement. The shaded areas express significance

Displacement (mm)/ISI Angle (Degrees)	**Inclined Screw Insertion (ISI) Angle P-Values**		
	75°	**60°**	**45°**
1mm/90°	0.0000	0.0059	0.0000
2mm/90°	0.0000	0.0721	0.0000
3mm/90°	0.0000	0.0001	0.0000
4mm/90°	0.0000	0.0691	0.0000
5mm/90°	0.0000	0.0108	0.0000
6mm/90°	0.0000	0.0600	0.0000
1mm/75°		0.0000	0.4974
2mm/75°		0.0000	0.1509
3mm/75°		0.0000	0.9372
4mm/75°		0.0000	0.4679
5mm/75°		0.0000	0.7978
6mm/75°		0.0000	0.2394
1mm/60°			0.0000
2mm/60°			0.0001
3mm/60°			0.0000
4mm/60°			0.0000
5mm/60°			0.0000

Displacement (mm)/ISI Angle (Degrees)	Inclined Screw Insertion (ISI) Angle P-Values		
6mm/60°			0.0000

The gradient of slope values of ISI angles are listed in Table 13.

Table 13: Gradient of slope values of ISI angled TSAT

Specimen	ISI Angle (Degrees) slope values			
	90°	**75°**	**60°**	**45°**
1	17.844	21.208	15.813	19.736
2	17.557	19.99	18.725	18.453
3	17.871	18.165	19.545	20.464
4	18.318	19.099	19.569	19.736
5	18.169	20.488	18.638	19.211
6	19.232	19.696	18.703	19.824
7	18.522	20.573	19.519	21.002
8	17.975	18.701	18.659	20.085
9	18.894	17.937	18.659	19.736
10	16.640	19.006	18.254	20.383
11	18.408	20.134	19.712	19.728
12	19.048	18.189	18.936	20.574
13	19.547	20.008	17.914	19.736
14	17.577	20.002	18.684	19.736
15	17.791	20.999	18.659	19.736
AVG	18.226	19.613	18.665	19.876

The mean slope values are demonstrated in Figure 37.

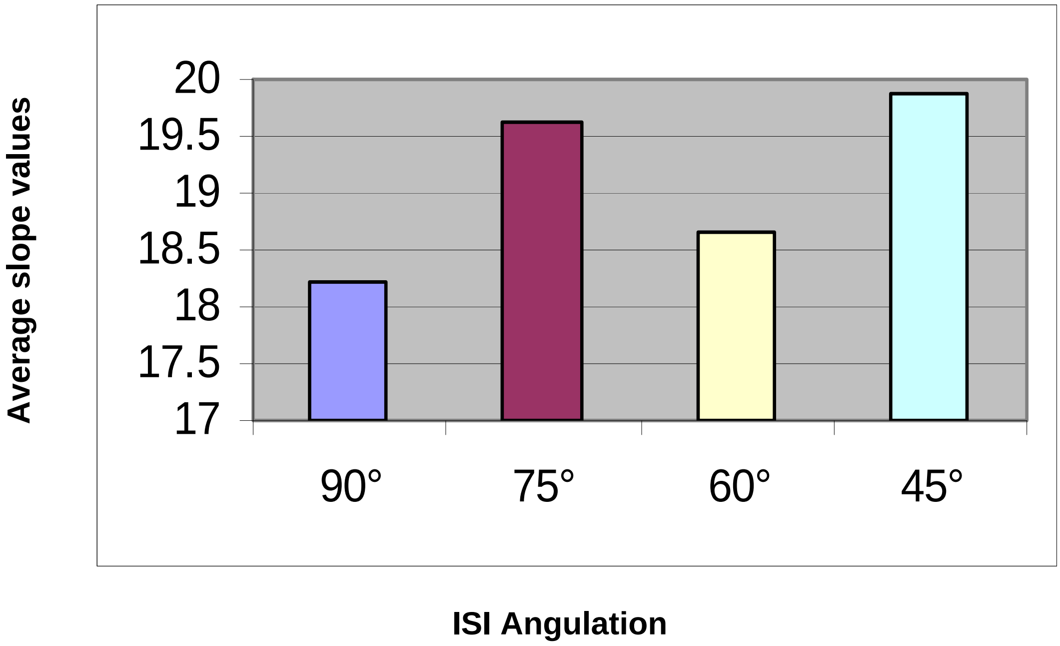


Figure 37: Bar graph of mean slope values of TSAT for ISI angles

When average slope values for torsion screw angle testing (TSAT) is considered as in Table 13 and Figure 37, the force displacement stability for the Inclined ISI group of 75°, 60° and 45° clearly demonstrates superiority when compared to the conventional rectangular 90° screw angle group. Significance was proven for (ISI) angles of 75° and 45° with non-significant better results for 60° of (ISI) – this clearly can be expected to be different if the sample size of the *in vitro* study is increased- all indications according to the trend lines (Figure 38) are proof thereof. Mean force (N) values for displacement at 1, 3 and 5mm were calculated to enable trend-line expression (Figure 38).

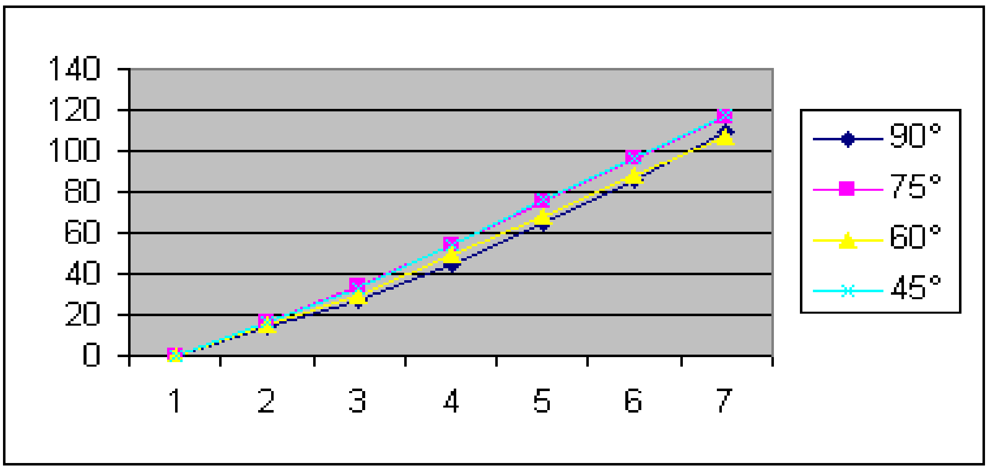


Figure 38: Linear torsion trend-lines

There was no significant difference between ISI of 60° and 75°, however, 45° seem to be showing a very strong trend towards being significantly better when compared to ISI of 75°. When considering P-values of ISI at 45°angle and ISI 60° there seem to be no significant difference in stability between these groups. These values in the specific application in the testing device was seen to be design sensitive – the ISI plates are manufactured with a connecting bar between upper and lower plate holes, which has to correspond to the created fracture line separating the proximal and distal poly-urethane segments for fixation. This connecting bar proved to be too short with the result that the angulated plate hole Nr. 3, therefore closest to the fracture line, when inclined at 45°, results in cortical bone destruction when pilot drilling – the slight lag effect seem to have compensated for the resultant biomechanical instability. Increasing the connecting bar length would result in an increase in the plate-hole distance to the fracture-gap and permit angle drilling without the destruction seen for both CSAT and TSAT, ISI - 45° and 60°, angle testing.

The statistical comparison (P-values) of the mean slope values are compared in Table 14.

Table 14: P-values of the mean slope values for TSAT evaluation

TSAT Angle	**ISI Angle Degrees**		
Degrees	**75°**	**60°**	**45°**
90°	0.0000	0.0003	0.0019
75°		0.1564	0.0556
60°			0.2740

5.4.1 TSAT Linear Trend Lines

Results of the mean slope value comparison (in Table 15) demonstrates significant better (TSAT) results for ISI 75°, 60° and 45° when compared to conventional 90° screw angle insertion. The regression trend lines derived from the slope value for a given displacement are listed in Table 15. The formula: **y = m.x + b** is applied.

Table 15: Mean slope values of the torsion force (TSAT) of the screw angle tests for screws placed at angles of 90°, 75°, 60° and 45°

Specimen	90°	75°	60°	45°
1	40.231	42.243	33.394	*
2	35.086	39.893	36.035	36.729 *
3	42.247	34.684	36.854	40.890
4	42.380	38.064	38.036	46.275
5	40.960	40.856	35.679	38.326
6	38.557	39.277	41.486	39.463
7	36.916	40.936	25.999	41.884
8	22.043	37.289	18.315	39.298
9	25.456	35.826	21.501	47.611
10	33.324	37.955	36.058	40.623
11	27.203	40.178	27.873	47.191
12	37.887	36.432	36.294	40.942
13	41.177	39.926	40.435	38.045
14	35.112	43.168	40.694	16.941
15	24.762	41.893	*	23.282

* Data excluded due to experimental set-up failure noticed after completion of the *in vitro* biomechanical testing."

CHAPTER 6 INTERPRETATION OF RESULTS

6.1 Trigonometric - Mathematical Formulation of Angled Screw Application Results

Optimum mono-cortical screw length is equal to the cortex thickness available and determined by the specific anatomical site of the mandible. If screws are placed (applied) perpendicular to the bone surface, as is the case in conventional practice, and screw length which exceeds the optimal cortical thickness is placed mono-cortically it will have a screw thread portion in medullary bone. This section of the screw is in less dense bone than homogenous compact cortical bone. The polyurethane mandibles effectively simulate normal human anatomy by having a dense outer cortical layer and less dense medullary component. A screw of 7mm length, placed anatomically at the external oblique ridge would have a section of screw transecting the cortex. Optimally the cortical thickness can vary and be equal to 3.5mm + 0.6 = 4.1mm in the mandibular angle region distal to the third molars (Figure 11 B) therefore cortical component of the screw would represent 4.1mm of the 7mm, resulting in 7mm – 4.1mm = 2.9mm screw length in medullary bone, if placed perpendicular to the bone surface.

If for the same anatomical position on the mandible, as standardised in the protocol, the angle of screw insertion is changed to an angle less than 90°, the medullary screw portion will rotate out of cancellous, less stable bone into amorphous cortical bone with a resultant biomechanical stability improvement. This amount of screw tip travel (STT) can be calculated and predicted mathematically thus explaining the improved load/displacement outcome for screw angle variation between 90° and 45° angles (Figure 39).

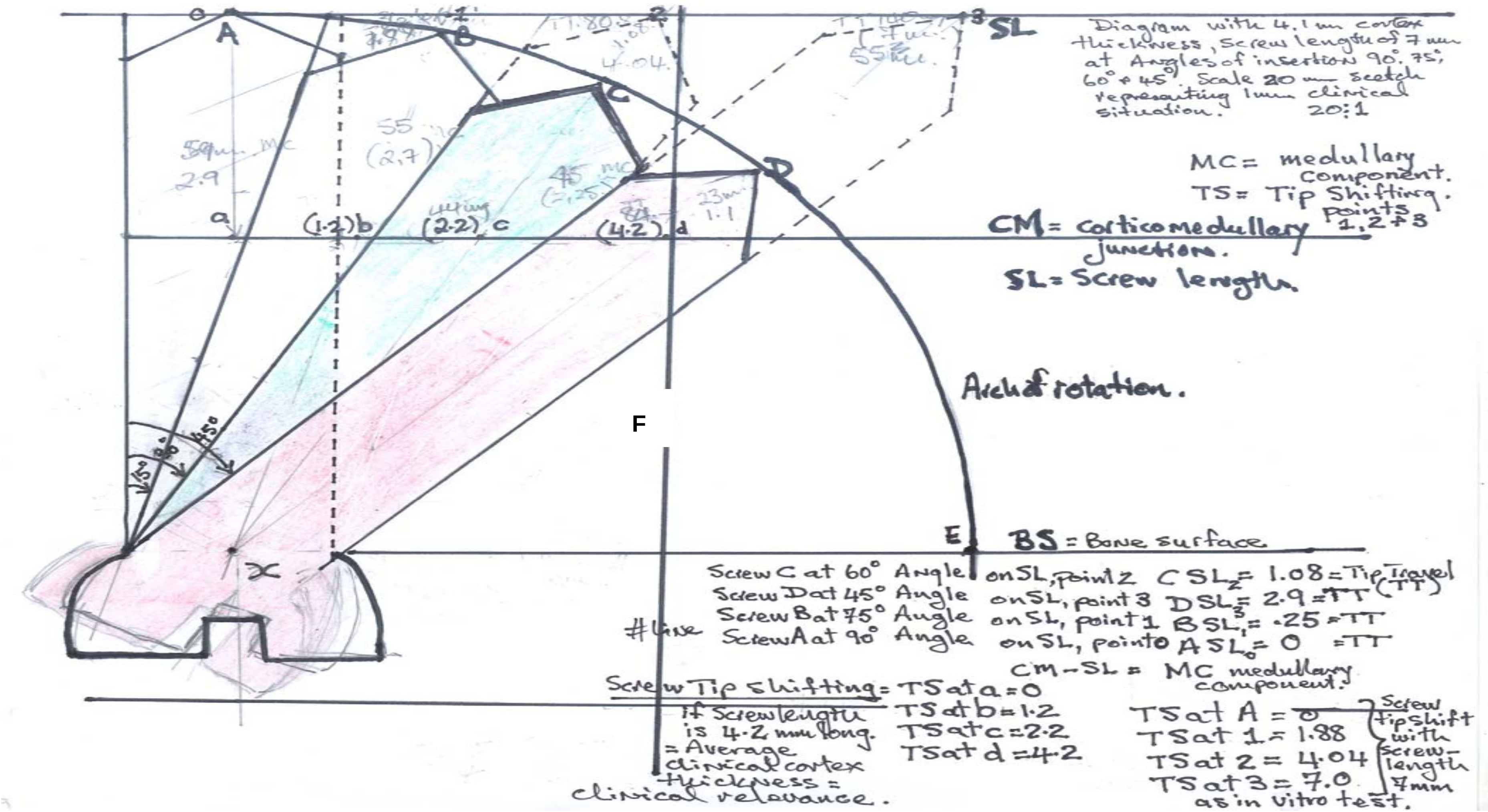


Figure 39: Screw tip travel and shifting of Inclined Screw Insertion in a mono-cortical application with screw length 7mm and screw diameter 2mm

The screw rotation from 90° rectangular to 45° optimizes screw tip travel through dense cortex allowing the full 7mm screw length to transect cortex with minimal or no medullary engagement explaining higher values in biomechanical stability for screw angles 45° and 60°.

The initial rotation through 15° for a screw angle of 75° has no significance for a screw length of 7mm and 2mm diameter in terms of stability compared to 90°. The screw apex or tip, screw tip shifting (STS) has moved minimal through point A-B and the screw portion in medullary bone, differs very little from the 2mm diameter medullary screw engagement seen at 90°angle position.

Screw tip travel between point A and C along an arc shortens the screw length in medullary bone as it rotates around the screw head (midpoint x) from 90° to 60°. A lesser shorter screw length engages medullary bone with more significant screw length transecting better quality more dense cortical bone optimizing cortical screw length in cortex as it further rotates to point D (Figure 39) where theoretically all of the 7mm mono-cortical screw transects cortex with no medullary component involved (z-y = 0mm).

The mathematical calculation of screw tip travel (STT) between points A, B, C and D from point-A in increments of 15° from 90°; to 75°; 60° and 45° angles can be determined by trigonometry when triangles AX1; AX2 and AX3 are used for calculations. The known constant in all cases would be the length of XA which is the standardised 7mm screw length used in the investigation also known are the angles of screw insertion AxB; AxC and AxD with values 15°; 30° and 45° to AX, measured 15 from point x in a clockwise direction. Point X is a common rotation axis positioned midpoint at the screw neck.

If this amount of screw shortening for medullary engagement or lengthening for cortical engagement is to be calculated the following linear lengths should be measured and DZ as they increase in length and lines A_0 B_1, C_2 and XB_1; XC_2 and XD_3 where XA_0 equals 7mm and D_3 as they decrease until point D is reached on the arch of rotation as the optimal cortical travel angle for the 7mm screw length where minimal medullary engagement is seen and cortical bone engagement is optimal. It was determined by means of CAD – three-dimensional simulation that a screw of 2mm diameter placed at AXE angle of 30° to the plate surface would have thread partially outside bone on the inner surface of the plate, lifting it from the bone without engaging cortex (Figure 40).

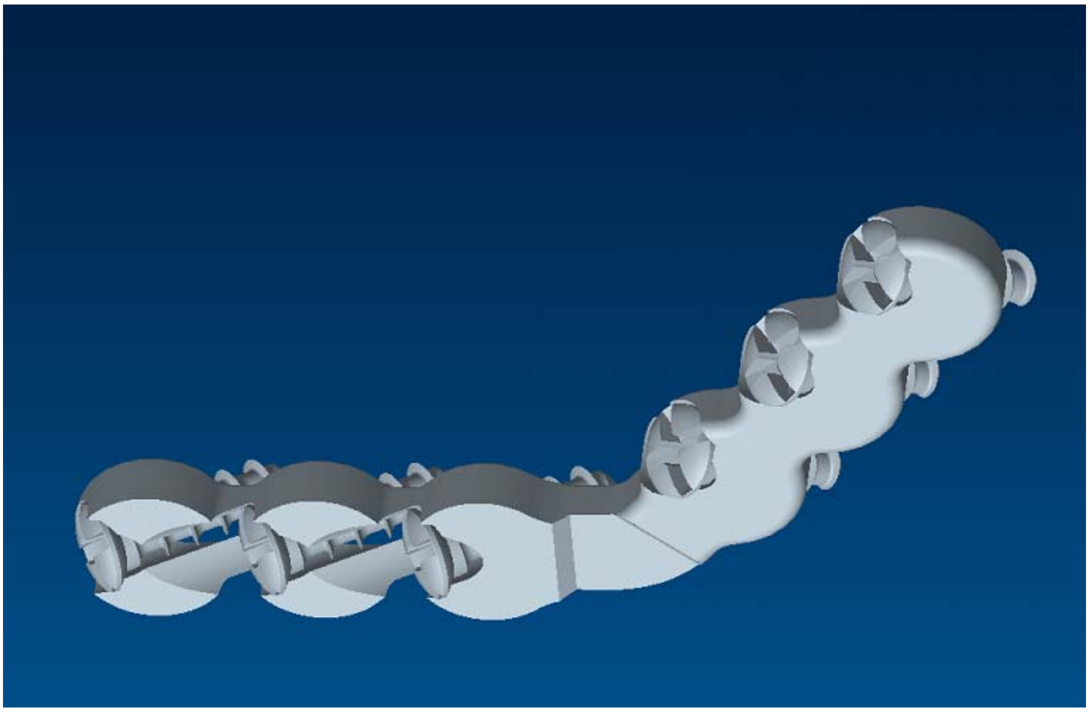


Figure 40: Three CAD simulation of screw angle placement of 30°

6.2 Defining and Measuring of STS (Screw Tip Shifting)

Screw tip shifting (Figure 40) refers to the distance travelled by the screw apex along a line of optimal screw length (SL) or the cortico-medullary junction line (CM) for different angles of screw placement where 0 is 15°, 30° or 45° reflected as angles AXB_1; AXC_2 or AXD_3. The linear measurement (Figure39) :

SL_1 = screw tip shifting along optimal screw length, line SL at - 15° (AXB_1) angle measured from A (screw at rectangle 90° and 7mm length) along SL.

SL_2 = Screw tip shifting distance along optimal screw length line SL, at 30° AXC_2 angle measured from point A.

SL_3 = screw tip shifting distance, along optimal screw length line, SL, at 45° AXD_3 angle, measured from A.

6.3 Clinical/Experimental Significance of STS (Screw Tip Shifting)

The screw tip shifting (Figure 40) is a reflection of lag potential of a screw for a particular angle of application measured in relation to conventional rectangular screw placement. It reflects the ability of a screw to transect an oblique fracture line relative to the anterior cortex surface.

1. Screw tip shifting can be measured for the optimum screw length, if inserted at angles 75°, 60° and 45° at 15° intervals to rectangular, along optimal screw length line SL to reflect length difference to 7mm screw length at 90°.
2. Screw tip shifting can be measured at the cortico-medullary (CM) junction for insertion angles 75°, 60° or 45° along line CM (at points a b c d) to reflect lag potential within a given amount of cortex available (The cortex is 4.1mm. thick at the angle of mandible).

For rectangular screw placement the entry point of a screw at the outer cortex bone surface corresponds and is in line (Xa) with the inner cortex CM-junction and is utilised referred to as the conventional gold standard in clinical application.

6.4 Defining and Measuring of Screw Tip Travel (STT)

Optimal screw length for a given angle of application is measured relative to a 7mm screw length for rectangular screw placement and is defined as screw tip travel. This value is a reflection of the change in screw length related to the screw insertion angles of 15°, 30° and 45° for a screw of 7mm length. Screw travel through bone should increase progressively for angles 75°, 50° and 45° - longer screws can be used for more acute screw angle placements and has clinical relevance until the angle 30° (AXE) is reached on the arch of rotation when the screw thread of a 2mm diameter screw travels to close to the bone plate interface rendering it unstable.

It should be possible to calculate an optimum screw tip travel (STT) increase for:

a) Optimal screw length on line SL where screw length at point A_0 for rectangular screw angle was 7mm and points XSL_1, XSL_2 and XSL_3 for angles 15° - 45° from 90°.

b) Optimal screw length on line CM where DCa equals 4.1mm cortex available at rectangular screw placement and Xb at 15° from, 90° (75°); Xc at 30° from 90° (60°) and Xd at 45° from 90° (45°).

I. Screw tip shifting (STS) determination

(1) Optimal screw length screw tip shifting for screw angle 15° from 90° (angle 75° application)

a) The screw tip shifting for 15° angled, optimal screw along line SL is determined TAN – where $SXSL_1$ = 15°

$\therefore$ tan 15° = ASL_1 / AX

$\therefore$ tan 15° x Ax = ASL_1

$\therefore$ ASL_1 = tan 15° x 7mm

ASL_1 = 1.88mm

where A0 is the screw tip position for 90° rectangular screw placement. A screw tip 1.88mm from A_0 reflects a significant increased lag potential of 1.88mm.

b) Screw tip shifting for 15° angles screw on line CM at point b optimal cortex available:

tan 15° =ab/ax

tan 15° x ax = ab

tan 15° x 4.1 = ab

ab = 1.10mm

(2) Optimal Screw Tip Shifting for Screw Angle Application 30° from 90° (60°)

a) Measured on SL at point SL_2: - Optimal screw length

tan 30° = ASL_2/ Ax

tan Ax n 30° x 7mm = ASL_2 = 4.04mm

(b) Measured on CM at point C : - optimal cortex engagement

tan 30° = ab/ax

tan 30° x 4.1mm = ab

ab = 2.37mm

(3) Optimal screw tip shifting for screw angle application 45° from rectangular (90°) equal to a 45° screw angle application

(a) Measured on SL at point ASL_3 determined by

tan 45° = ASL_3/AX

tan 45° x AX = ASL_3

tan 45° x 7,0mm = ASL_3

ASL_3 = 7.0mm

(b) Measure on CM at point d = optimal cortex engagement

tan 45° = ad/Xa

tan 45° x Xa = ad

∴ ad = tan 45° x 4.1

ad = 4.1mm

Screw tip shifting is determined using tan of the angle of screw application (15°, 30° and 45°) multiplied by optimal screw length 7mm. For optimal screw length shifts along line SL or optimal cortex engagement along line CM which calculated the tip shifting in linear measurement from point A or a which is the exit point for rectangular screw AX or Xa.

A screw can shift along an imaginary line SL (Figure 39) to compare the tip shift at placement angles of 75°, 60° and 45° with a screw tip position when placed rectangular at length 7mm. The screw shift will represent a different exit point for a screw tip at the inner surface of the bone cortex in relation to the entry point on the outer cortical surface. The tip shift is a reflection of screw ability to align itself more rectangular to the fracture line as opposed to screw angle rectangular to the bone or plate surface. Tip shift will predict lagging ability of screw across an oblique fracture line.

Table 16: **Screw tip-shifting results**

Application Angle	At Line SL	At Line CM
90°	0mm	0mm
75°	1.88mm	1.10mm
60°	4.04mm	2.37mm
45°	7.0mm	4.1mm

II. 1. Screw Tip Travel Determination at 15° angle Application from Rectangular (75°)

a) Screw tip travel (STT) represents an increase in screw length at angle 15° less than 90^0 measured on SL - reflecting optimal screw length application at 75^0 compared to 7mm screw length if placed at 90^0 angle.

Angle = $AXSL_1$

Cos 15° ($AXSL_1$) = XA / XSL_1

∴ XSL_1 = XA / Cos 15° = 7.25mm

XSL_1 – XB = 0, 25 when

(XA rectangular is 7.0mm)

b) Screw tip travel screw length for angle 15° measured at CM – screw length arrangement for optimal cortex available 4.1mm

Cos 15° = Xa / Xb

Cos 15° / Xa = 1 / xb

∴ xb = 4.24mm

2. Screw Tip Travel Determination at 30° from 90° Angle Application (60°)

a) Measured at SL reflecting optimal screw length for angle 30°. Determined by Cos $AXSL_2$

Cos 30° = XA (7mm) / XSL_2

Cos 30° / XA = 1 / XSL_2

∴ XSL_2 = 7mm / Cos 30°

∴ XSL_2 = 9.08mm

b) Measured at CM reflecting optimal available cortex available 4.1 at angle 30°

Cos 30° = Xa / Xc

Xc = Xa / Cos 30°

Xc = 4.1 / Cos 30

∴ Xc = 4.73mm

3) Screw tip travel determined at 45° from rectangular measured at

a) SL_1 reflecting optimal screw length for Angle 0 = $AXSL_3$

Cos 45° = AX (7mm) / XSL_3

Cos 45° / 7mm = 1 / XSL3

∴ SXL_3 = 7mm / Cos 45°

∴ SXL_3 = 9.89mm

b) Measured at CM reflecting optimal screw length for available cortex thickness 4.1mm to be engaged. Angle - = aXd = 45°

Cos 45° = Xa / Xd

Cos 45° / 4.1= 1 / Xd

∴ Xd = 4.1 / Cos 45°

∴ Xd = 5.79mm

Screw tip travel is determined by cos of the angle of screw application (15°, 30° and 45°) and dividing it into the given cortex thickness of 4.1mm for the anatomical site of the angle of the mandible to calculate the maximum screw length to be used at a given angle and known cortical thickness of 4.1mm.

By calculating the difference between standard screw length of 7mm and the new screw travel distance possible for a given cortical bone thickness an increase in screw length application is to be expected as the angle of screw insertion changes from 90° to 75°, 60° and 45° with increments of 15° from conventional rectangular screw position as indicated in Table 17.

Table 17: **Screw tip travel results (lengthening)**

Angle of Application to	Bone/Plate Surface	Measured at SL	Measured at CM	Screw Length Increase At SL	Screw Length Increases at CM
90°	Point A_0	0mm	0mm	0mm	0mm
75° (15°)	Point SL_1	7.25mm	4.24mm	+ .25mm	+ 0.14mm
60° (30°)	Point SL_2	8.08mm	4.73mm	+1.08mm	+ 0.63mm
45° (45°)	Point SL_3	9.89mm	5.79mm	+2.89mm	+ 1.69mm

Calculation and determination is made for a given cortical thickness of 4.1mm along line CM (cortico-medullary junction line) or for a given optimal screw length along line SL measured from point X – a mid-rotation point located at the screw head.

6.5 Clinical Relevance of Trigonometric Calculations

From the screw tip travel and screw tip shifting results it is concluded that longer screws can optimally be used when applying mono-cortical screws at angles smaller than 90° and that tip travel will also contribute to lagging across the fracture line of a mandibular angle fracture (Figure 39).

Its relevance is angle related and will vary according to the substrate thickness transected by a screw of optimal length. In the biomechanical stability study conducted using screws of same length, the screw will rotate for different angles and provided the screw length utilized equals the cortex thickness at all times it will produce superior significant biomechanical stability results if compared to a screw placed rectangular. No significant stability difference is expected and was demonstrated with an angle change of 15° - screw sip shift only 1,09mm and tip travel-lengthening 0,14mm if screw angle placement is 75°.

For angle placement of 60° in 4.1mm cortex the screw tip shift was 2,37 and the tip travel (lengthening) was 0,63 with expected significant stability improvement.

For angle placement of 45° in 4.1mm cortex tip shifting was 4.1mm cortex and screw tip travel (lengthening) was 1,69mm where lagging across a fracture line (represented by vertical line F in Figure 39), becomes evident.

It should be noted that a screw tip shift of 1.09mm indicates a bodily shift of the screw of approximately fifty percent of its 2mm diameter and no biomechanical stability improvement is to be expected.

For horizontally and vertically unfavourable mandibular angle fractures[40] mono-cortical screws at angles 60° and 45° can be expected to improve fracture fragment stability by resisting forces in both horizontal (Figure 31) and vertical dimensions (Figure 32) when compared to rectangular screw placement for screws of same length due to fracture-line orientation.

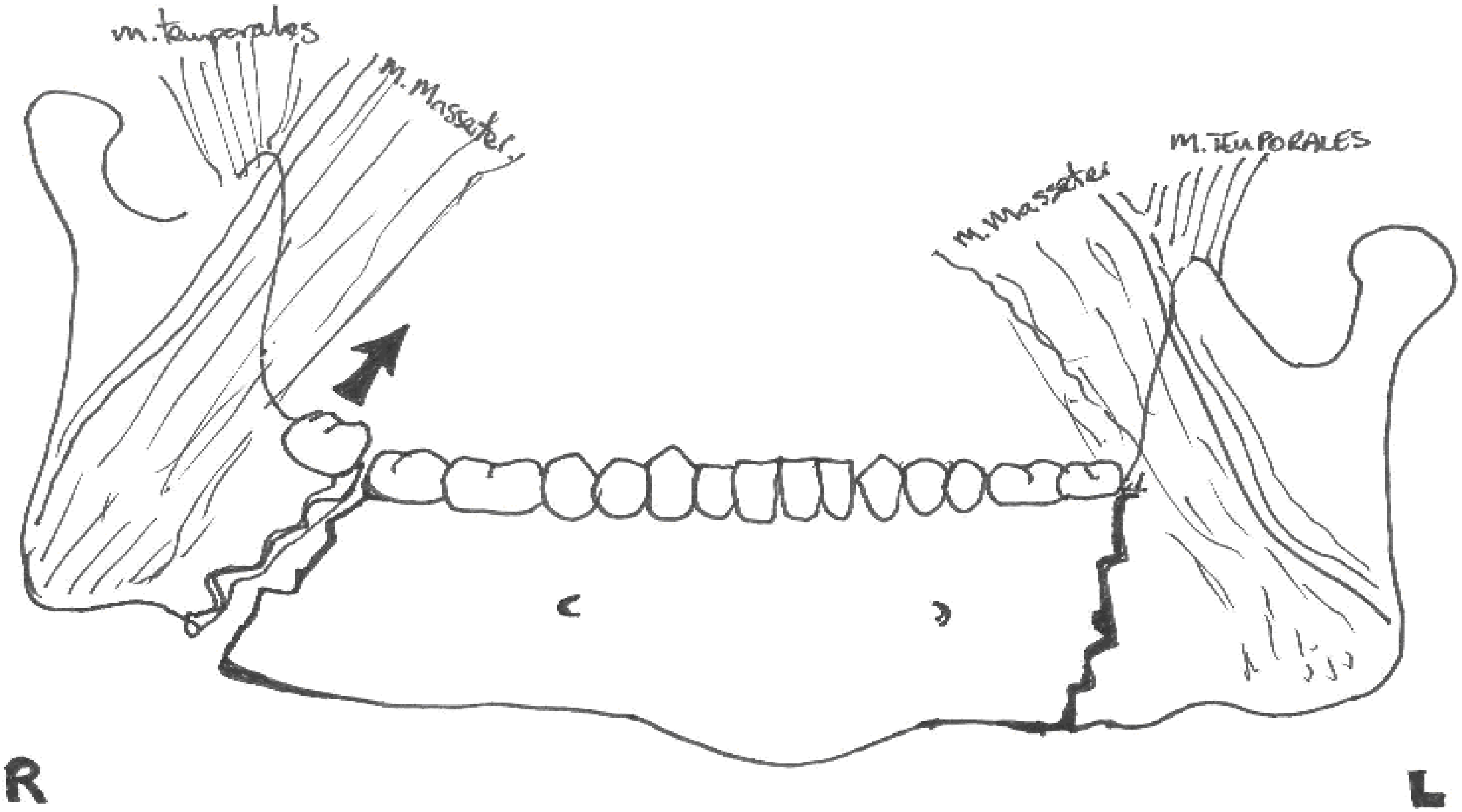
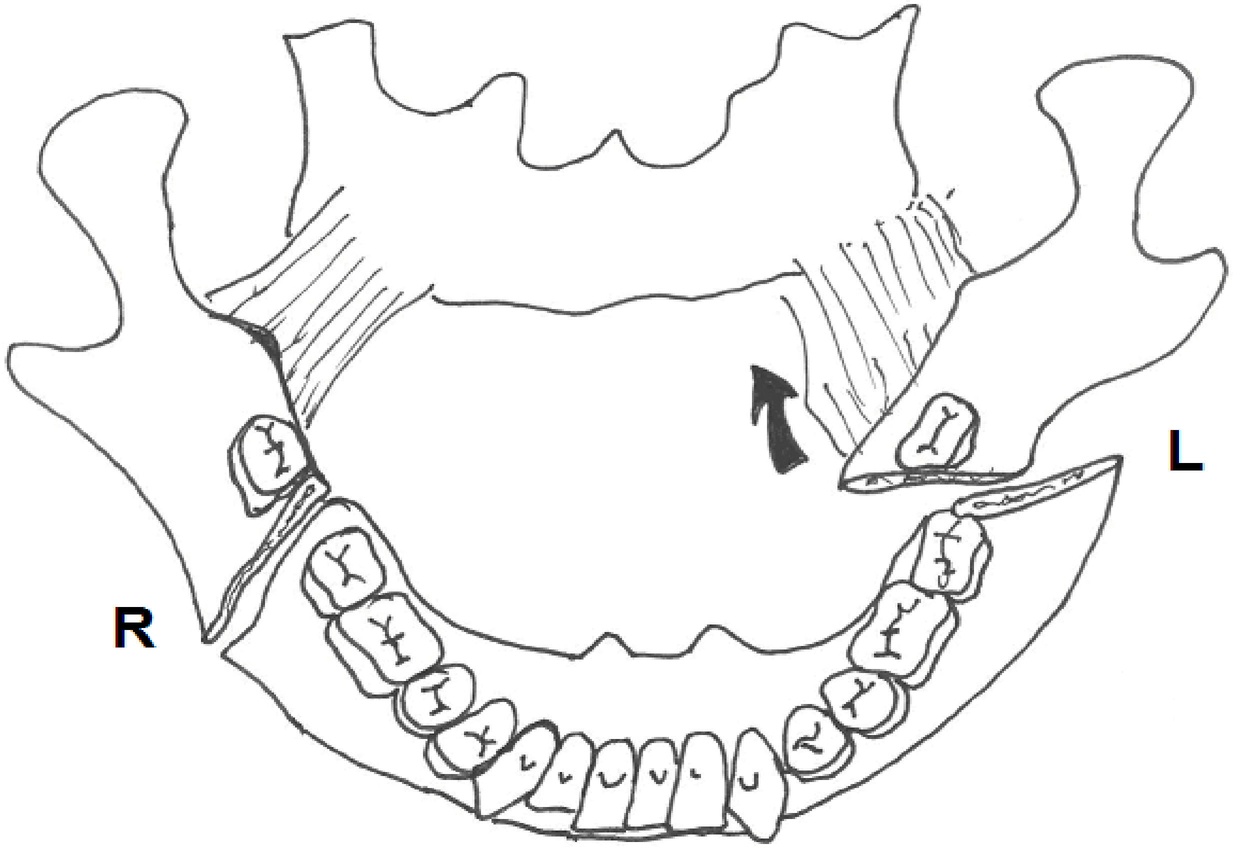


Figure 31: Horizontally unfavorable fracture right angle of the mandible



R = Vertical favourable fracture angle of mandibular

L = Vertical unfavourable fracture angle of mandibular

Figure 42: Medial pterygoid muscle action on the proximal fragment of a mandibular angle fracture