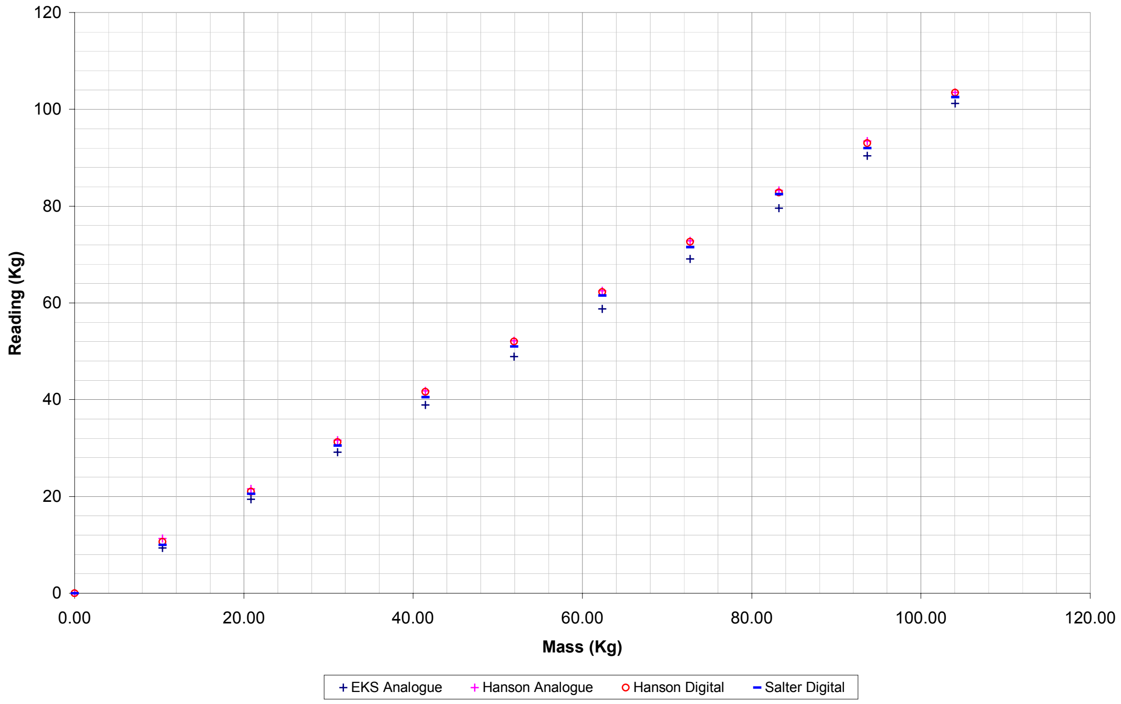
Appendix A: Detailed Experimental Data

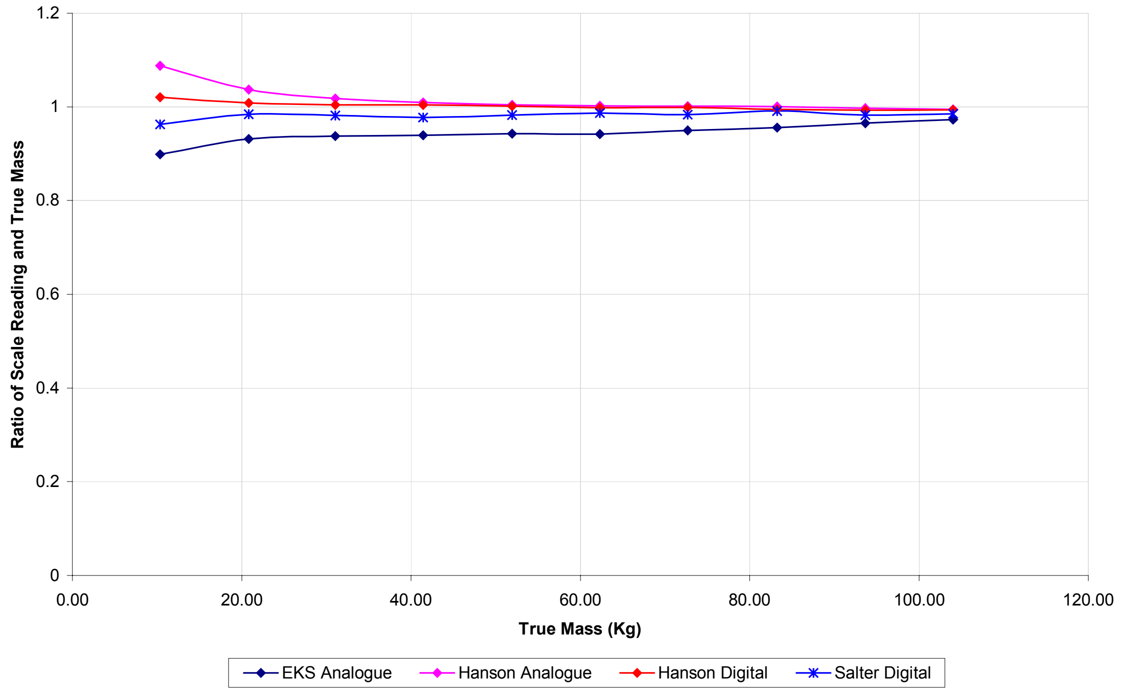
Section 3.1

Plot of Scale Reading vs. Mass

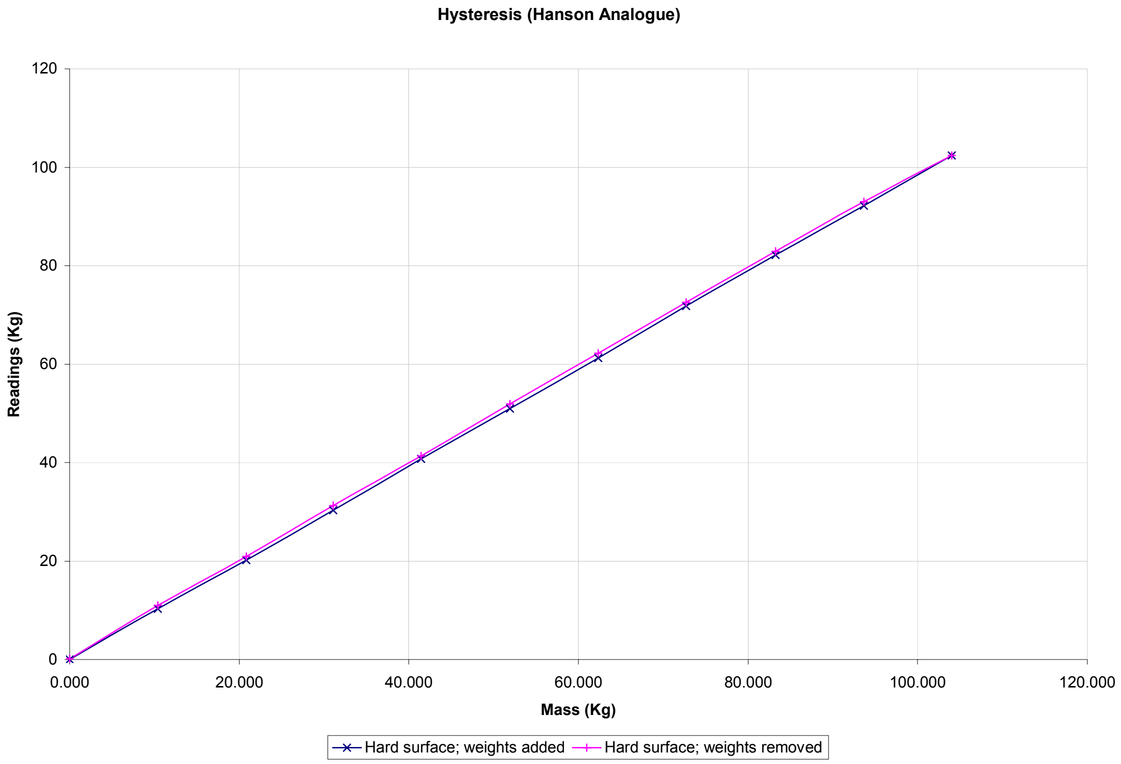


(R^2 values = 1.0000)

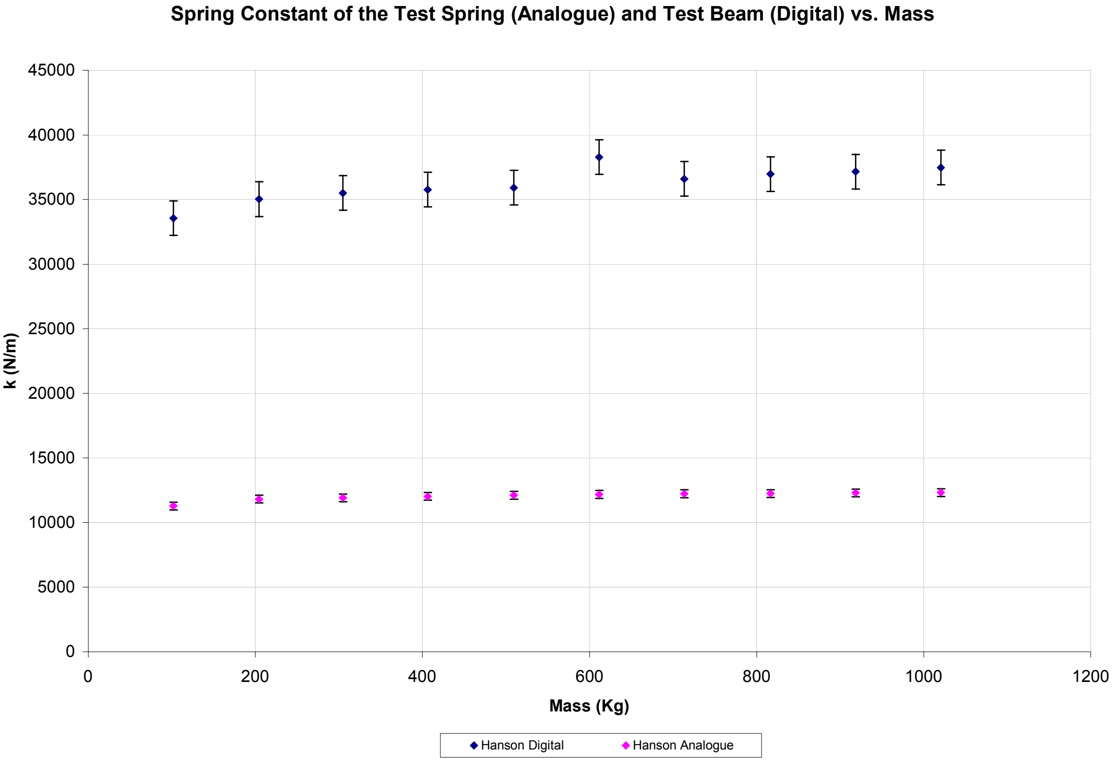
Plot of Scale Reading Divided by True Mass vs. True Mass



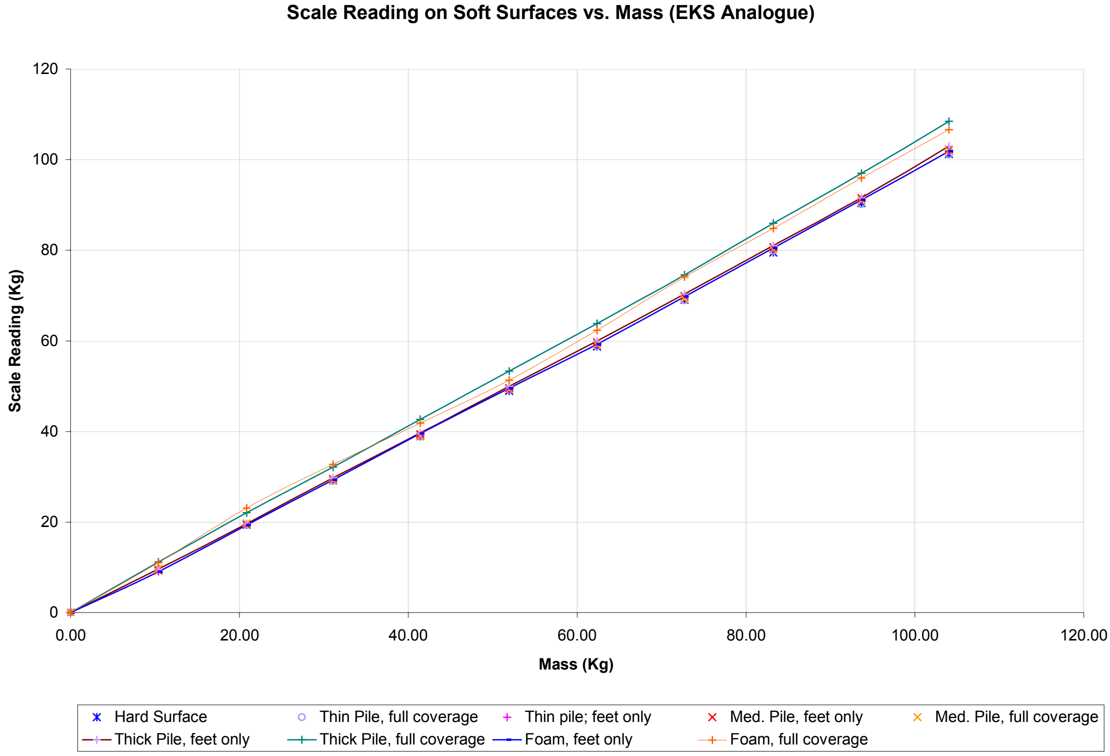
Section 3.2

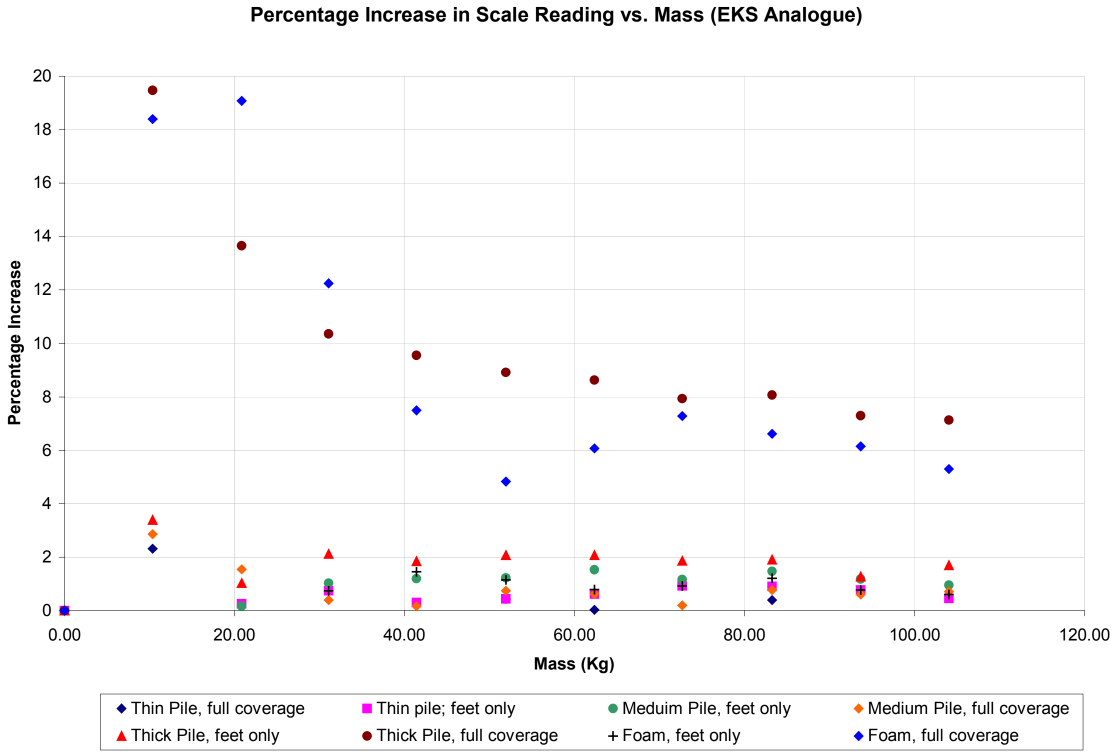


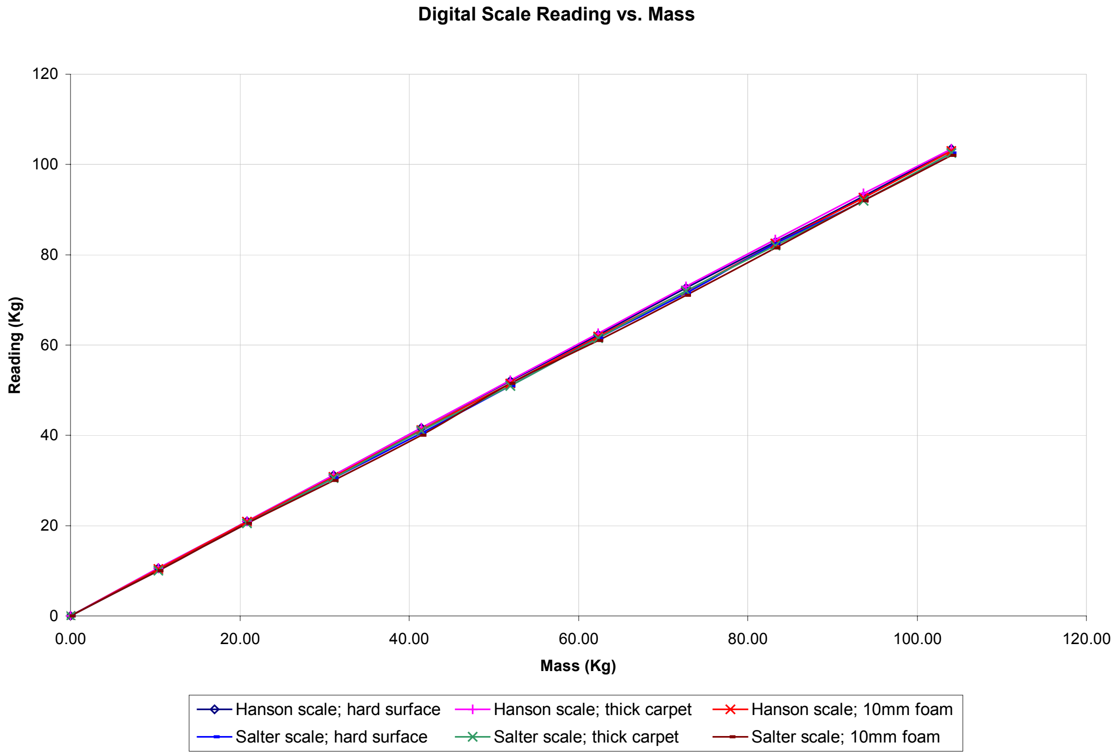
Section 3.3



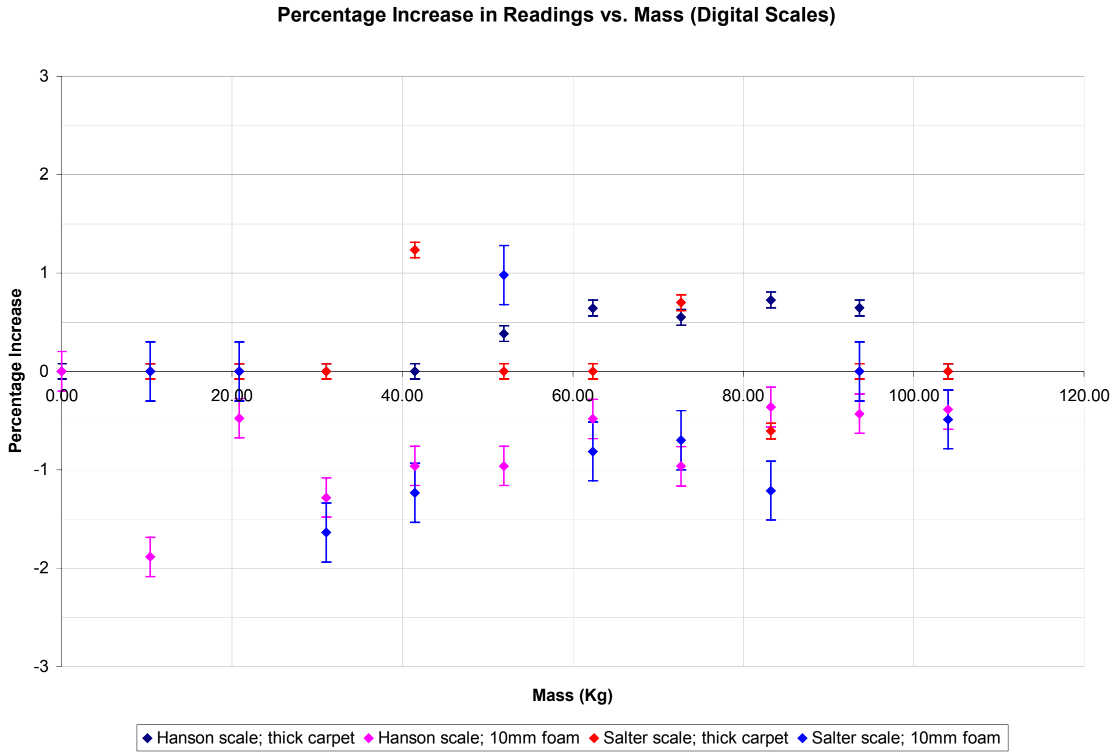
Section 3.4


Scale Reading on Soft Surfaces vs. Mass (EKS Analogue)
Scale Reading (Kg)
Mass (Kg)
0
20
40
60
80
100
120
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Hard Surface
Thin Pile, full coverage
Thin pile; feet only
Med. Pile, feet only
Med. Pile, full coverage
Thick Pile, feet only
Thick Pile, full coverage
Foam, feet only
Foam, full coverage


Percentage Increase in Scale Reading vs. Mass (EKS Analogue)
Percentage Increase
Mass (Kg)
0
2
4
6
8
10
12
14
16
18
20
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Thin Pile, full coverage
Thin pile; feet only
Meduim Pile, feet only
Medium Pile, full coverage
Thick Pile, feet only
Thick Pile, full coverage
Foam, feet only
Foam, full coverage

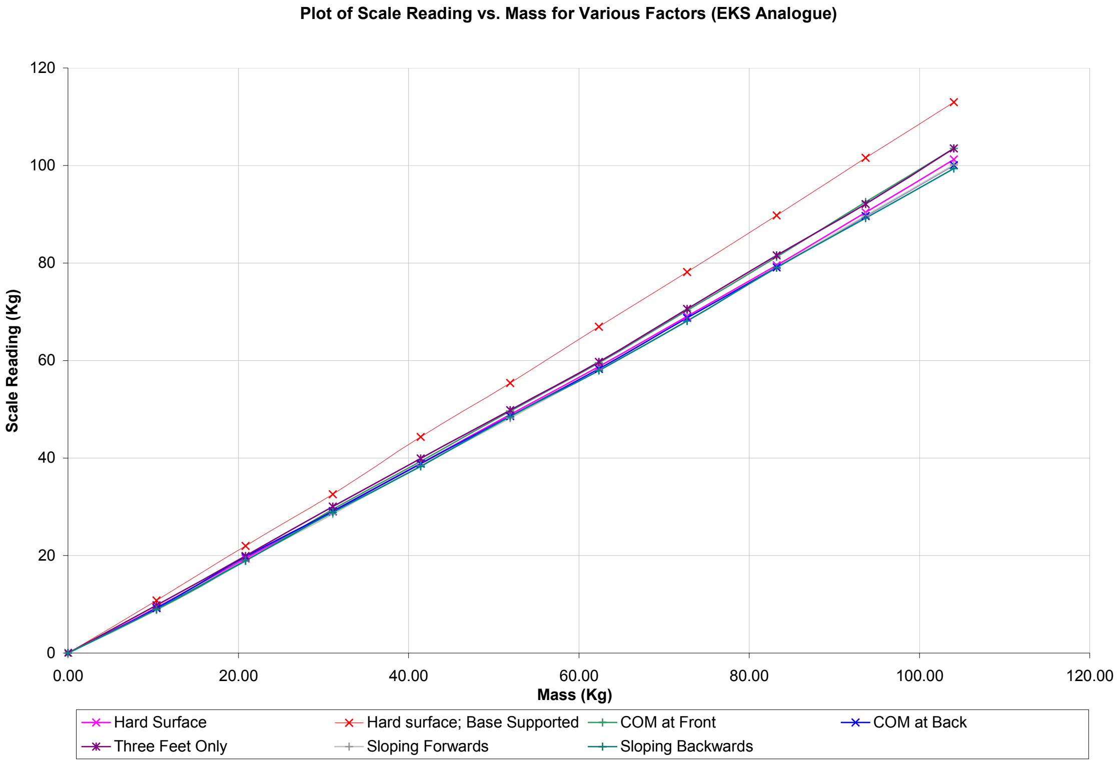


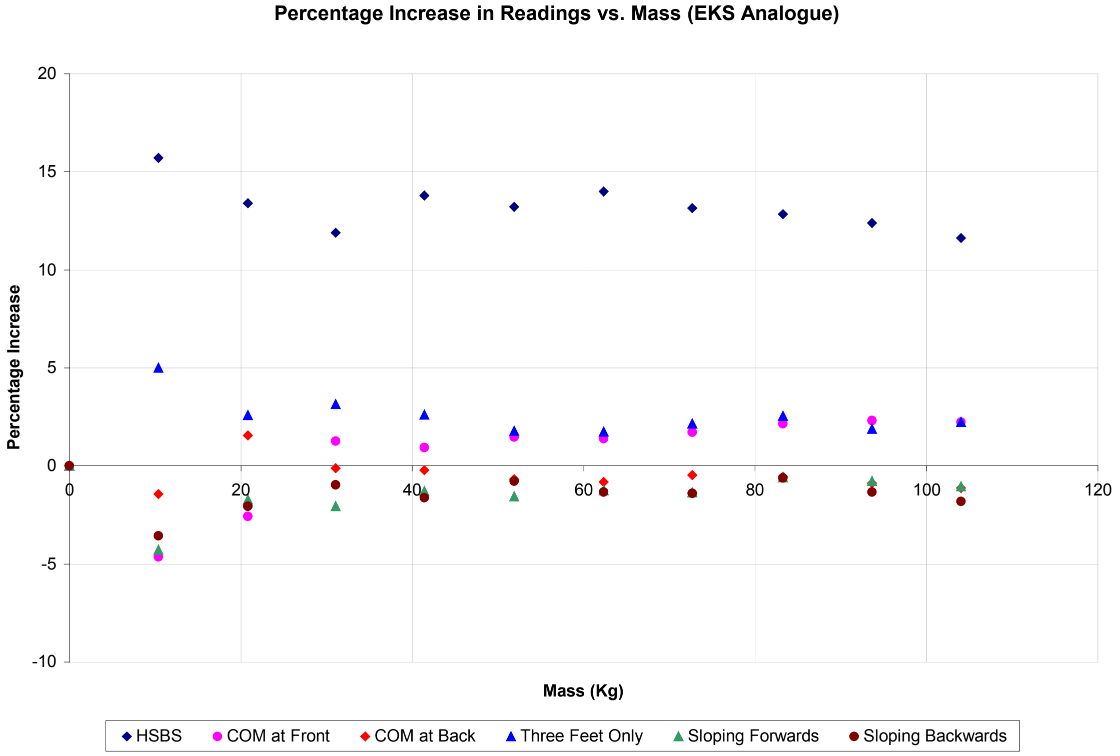
Digital Scale Reading vs. Mass



Percentage Increase in Readings vs. Mass (Digital Scales)

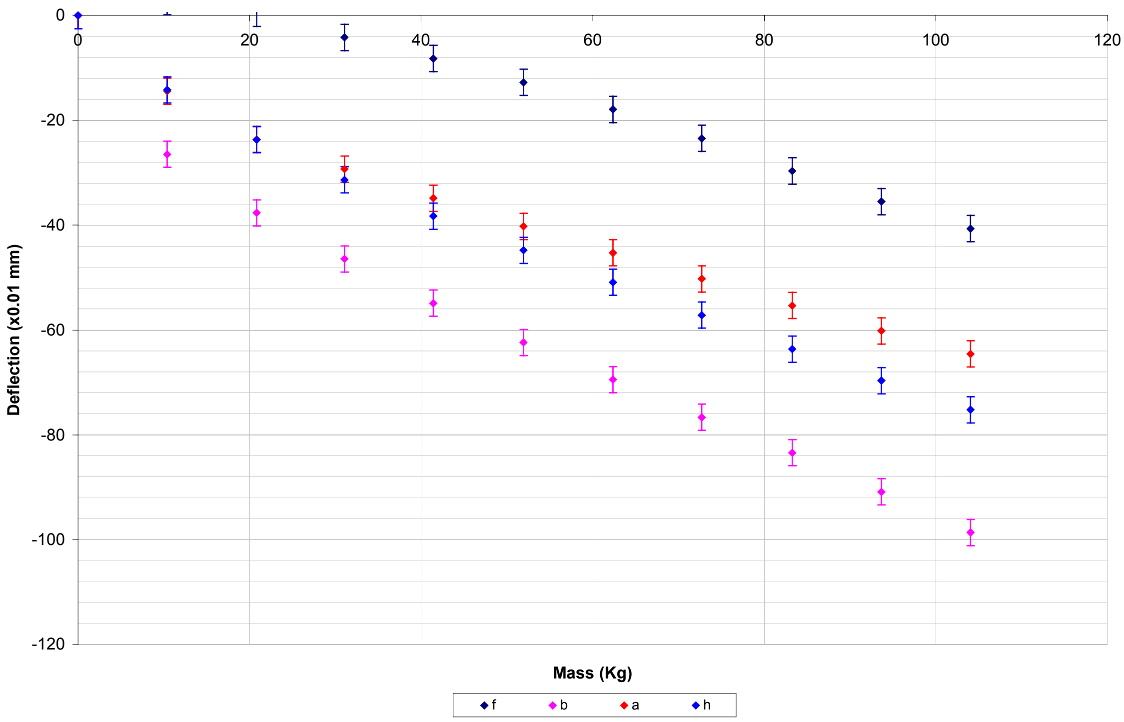
Section 3.5


Plot of Scale Reading vs. Mass for Various Factors (EKS Analogue)
Scale Reading (Kg)
0
20
40
60
80
100
120
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Mass (Kg)
Hard Surface
Hard surface; Base Supported
COM at Front
COM at Back
Three Feet Only
Sloping Forwards
Sloping Backwards

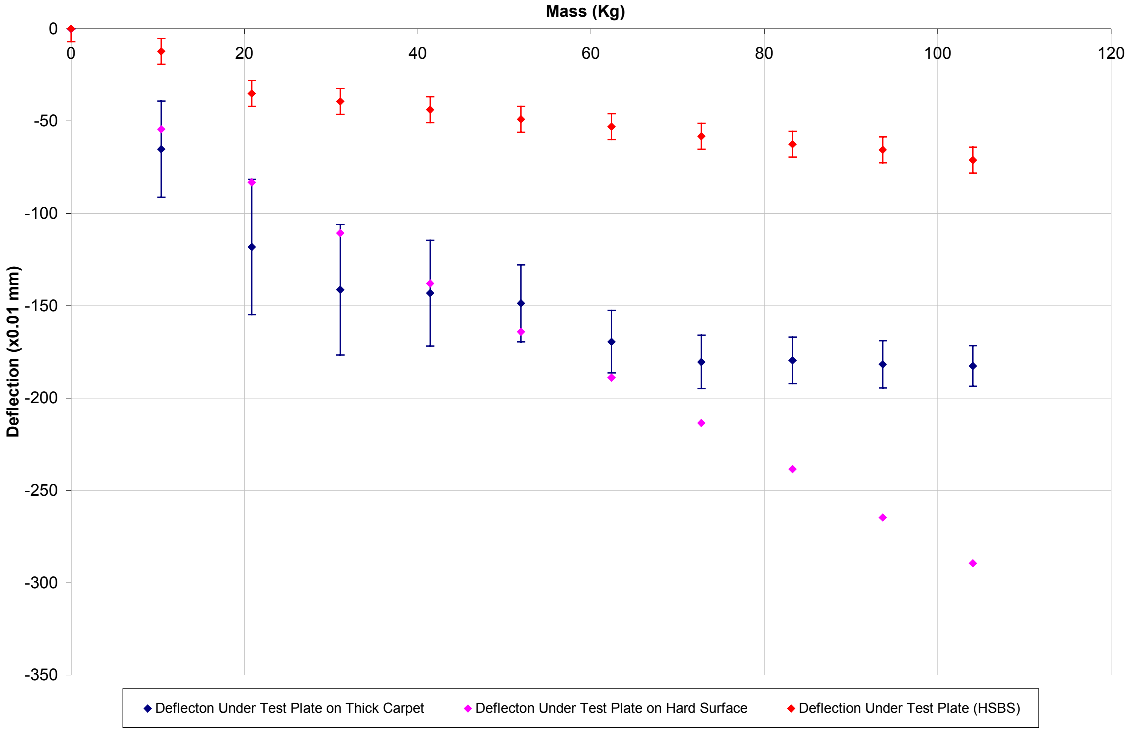

Percentage Increase in Readings vs. Mass (EKS Analogue)
Percentage Increase
20
15
10
5
0
-5
-10
0
20
40
60
80
100
120
Mass (Kg)
HSBS
COM at Front
COM at Back
Three Feet Only
Sloping Forwards
Sloping Backwards

Section 4.1

Plot of Base Bending vs. Mass, Hanson Digital Scale (Hard Surface)
Letters refer to figure 4.1.1.



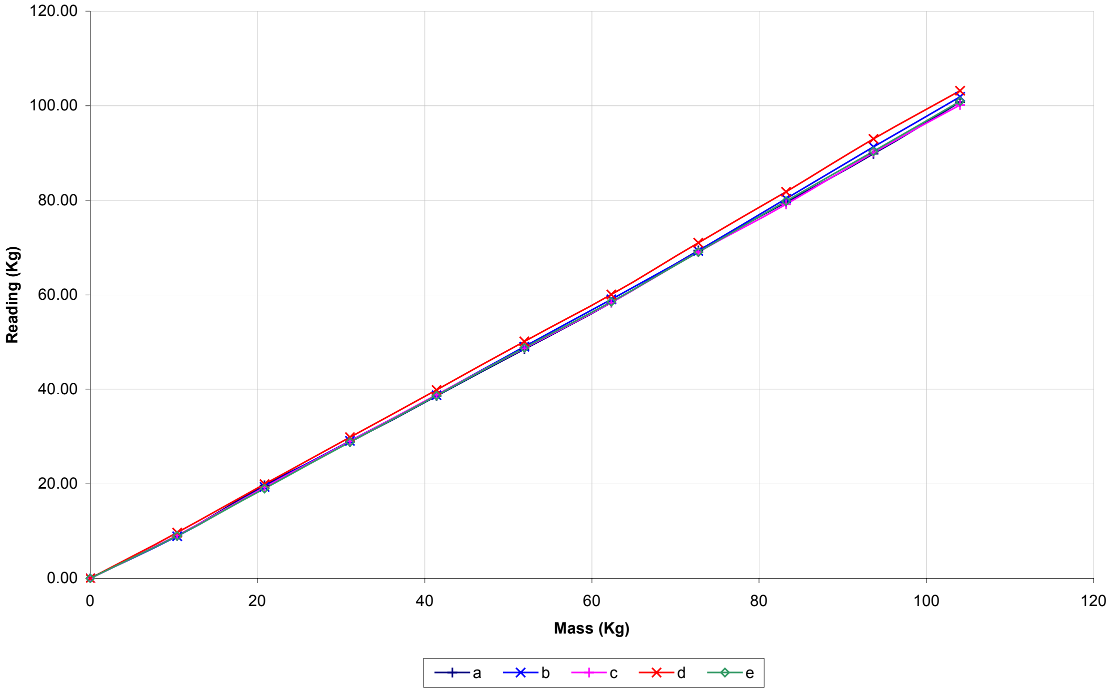
Base Deflection Under Test Plate vs. Mass (Hanson Analogue, Thick Carpet)



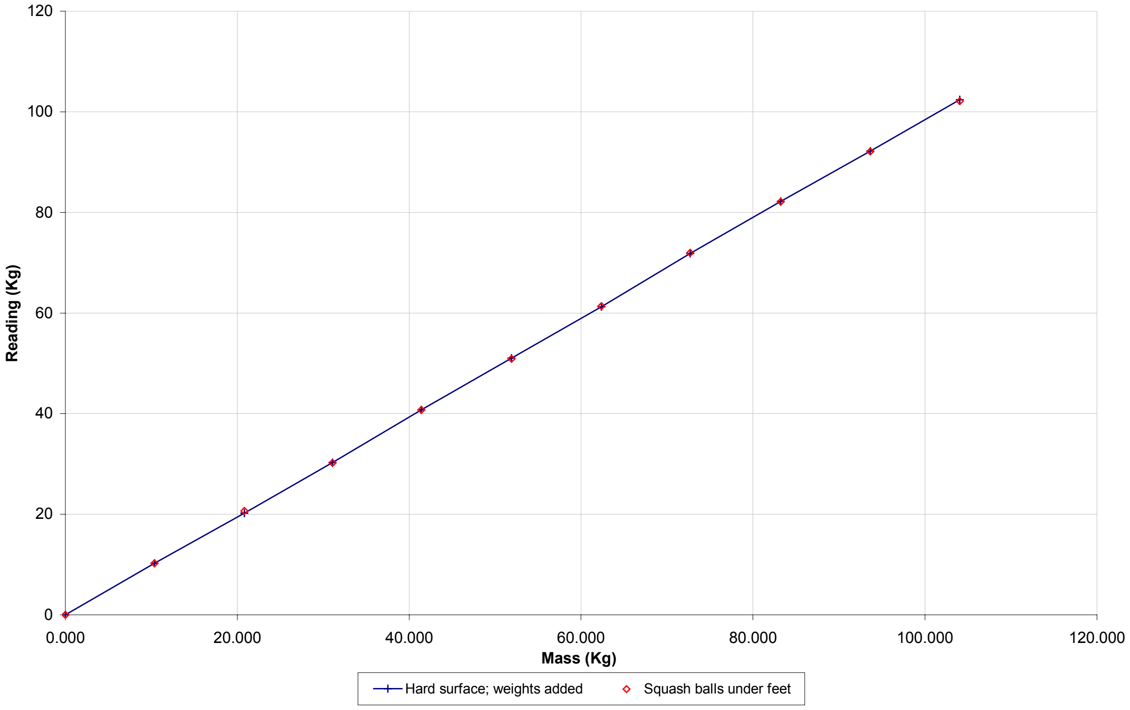
Section 4.2

Plot of Scale Reading vs. Mass (Hanson Analogue)

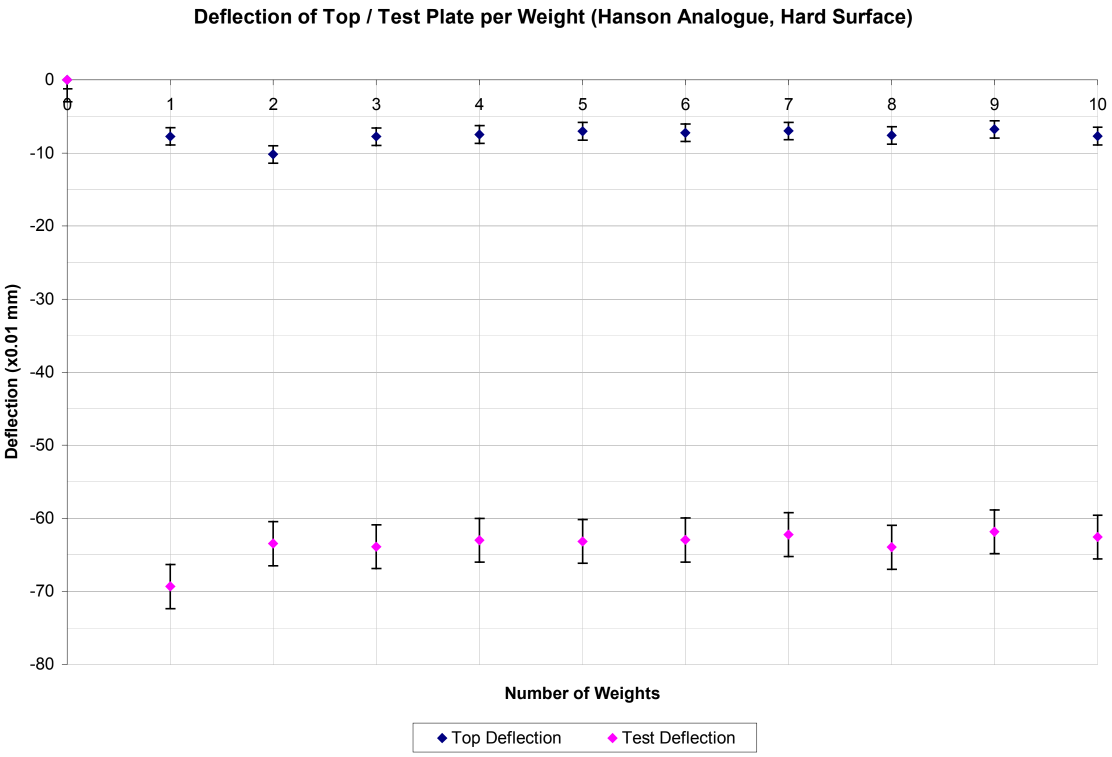
Letters refer to figure 4.2.2; trend e has support under all parts of the feet.

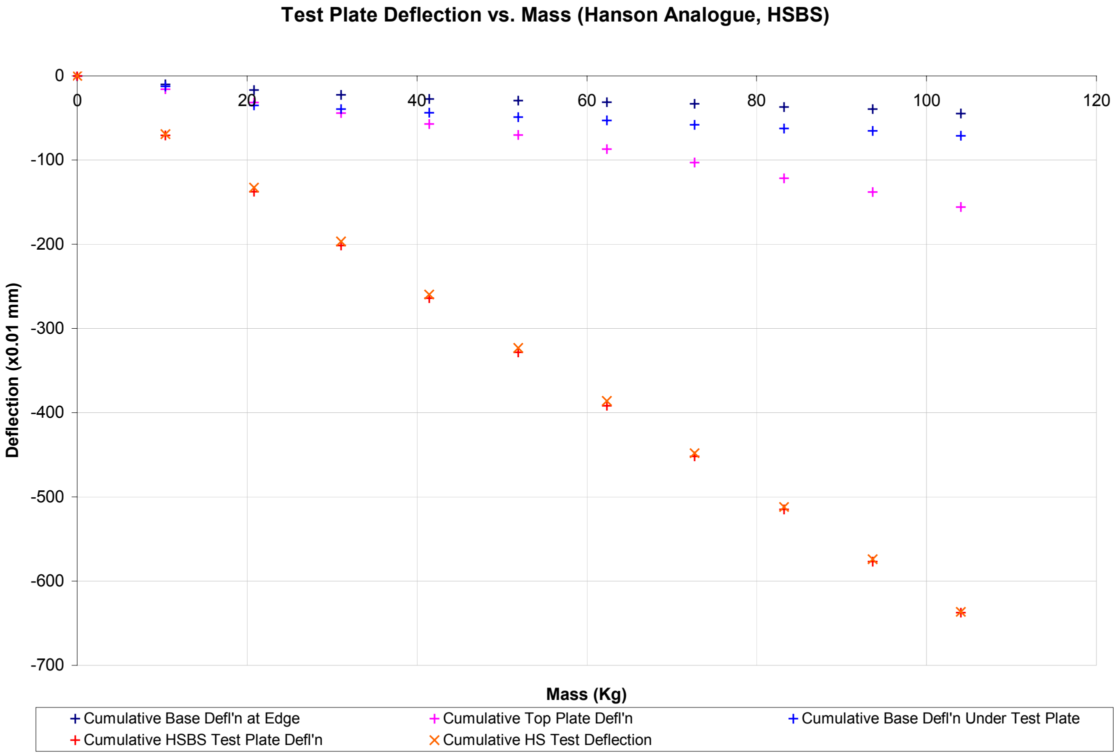


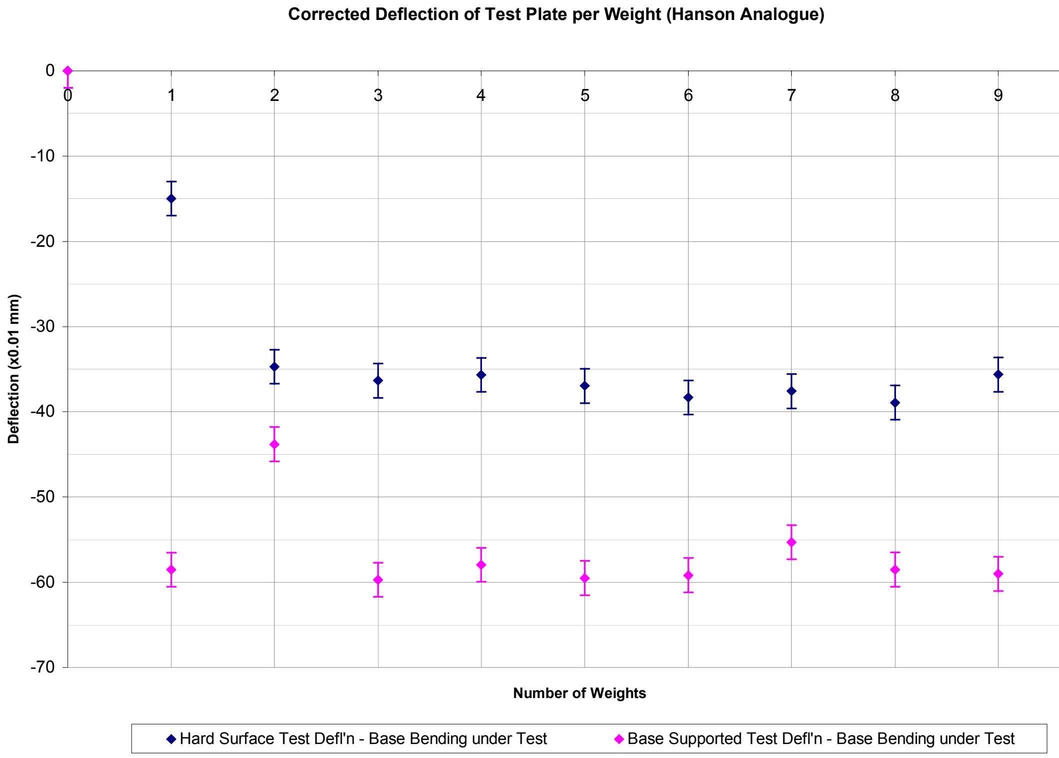
Scale Reading vs. Mass (Hanson Analogue, Squash Balls)



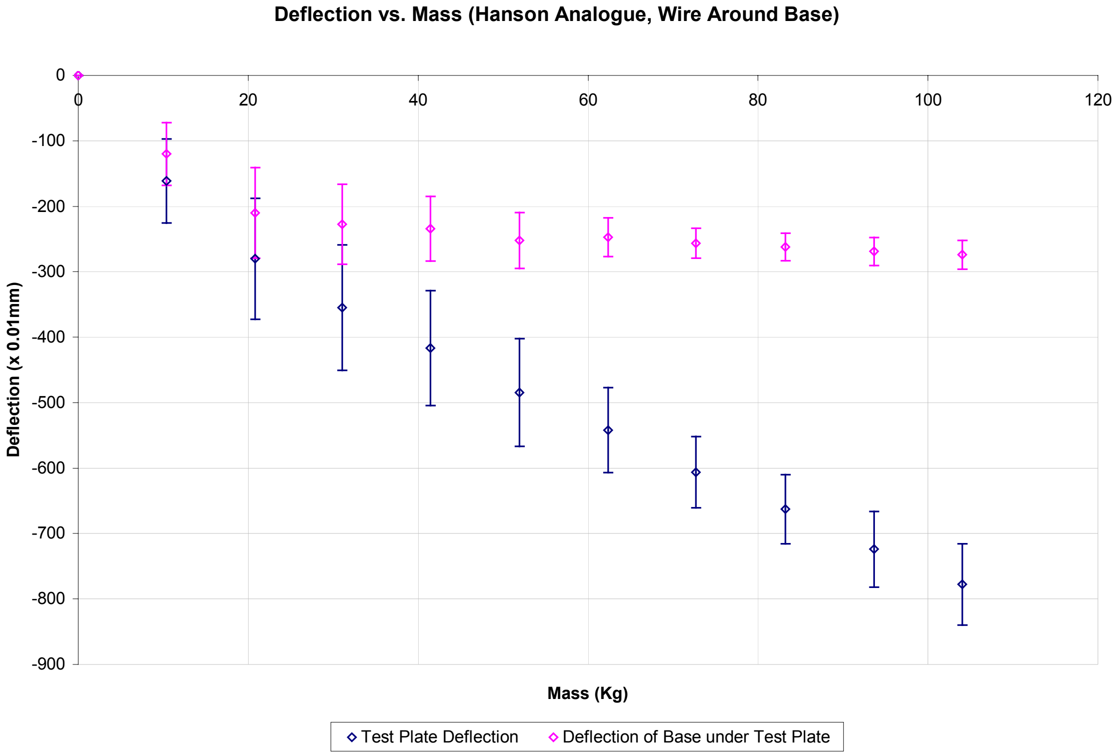
Section 4.3

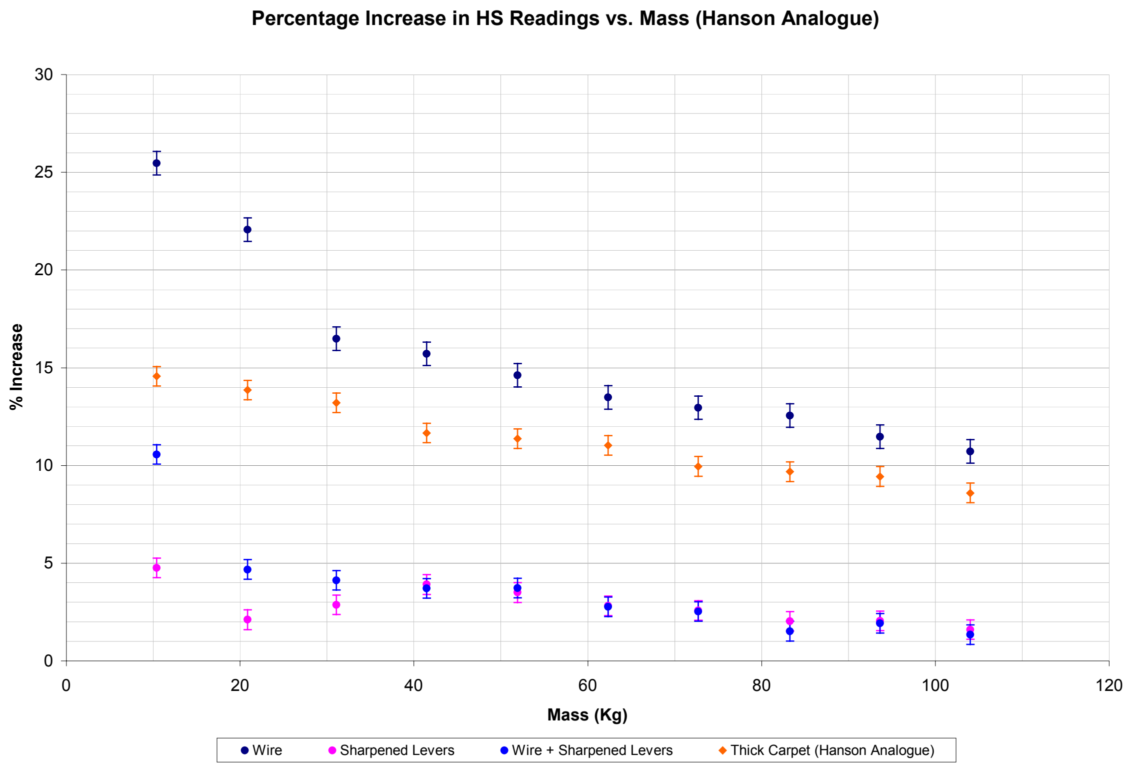

Deflection of Top / Test Plate per Weight (Hanson Analogue, Hard Surface)
Deflection (x0.01 mm)
0
-10
-20
-30
-40
-50
-60
-70
-80
0
1
2
3
4
5
6
7
8
9
10
Number of Weights
Top Deflection
Test Deflection

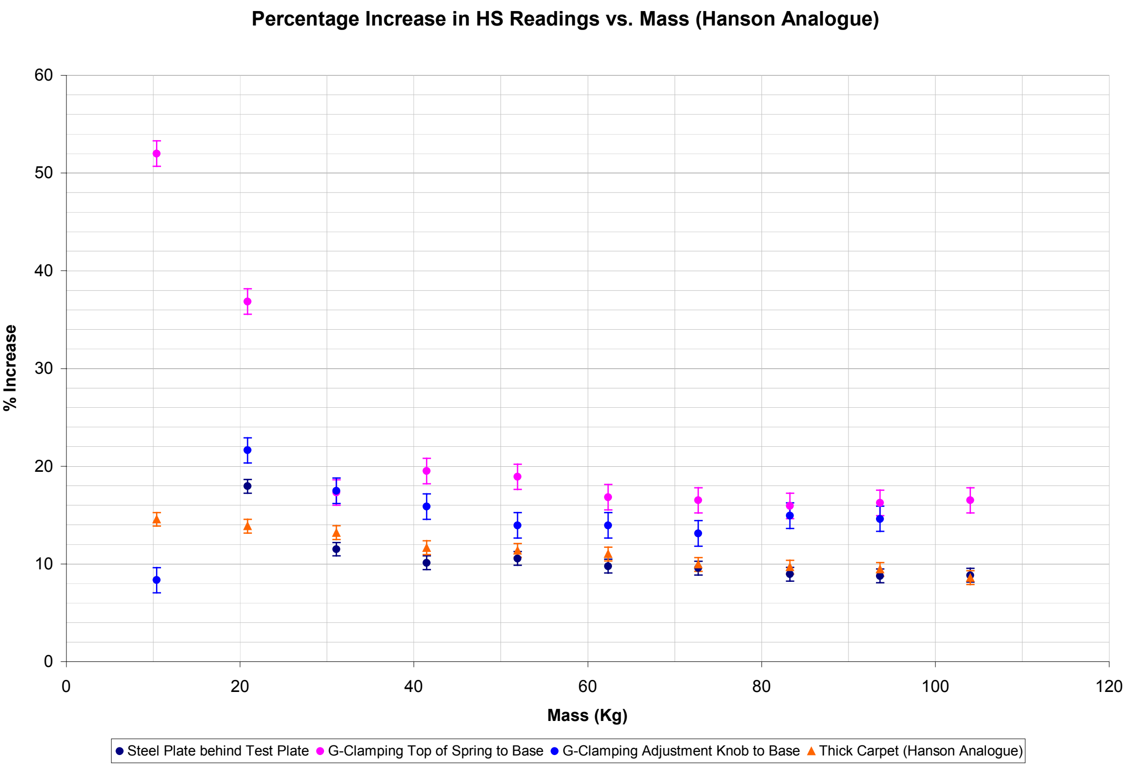

Test Plate Deflection vs. Mass (Hanson Analogue, HSBS)
Deflection (x0.01 mm)
0
-100
-200
-300
-400
-500
-600
-700
0
20
40
60
80
100
120
Mass (Kg)
Cumulative Base Defl'n at Edge
Cumulative Top Plate Defl'n
Cumulative Base Defl'n Under Test Plate
Cumulative HSBS Test Plate Defl'n
Cumulative HS Test Deflection


Corrected Deflection of Test Plate per Weight (Hanson Analogue)
0
-10
-20
-30
-40
-50
-60
-70
0
1
2
3
4
5
6
7
8
9
10
Deflection (x0.01 mm)
Number of Weights
◆ Hard Surface Test Defl'n - Base Bending under Test
◆ Base Supported Test Defl'n - Base Bending under Test

Section 5.1


Deflection vs. Mass (Hanson Analogue, Wire Around Base)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
0
20
40
60
80
100
120
Deflection (x 0.01mm)
Mass (Kg)
◇ Test Plate Deflection
◇ Deflection of Base under Test Plate


Percentage Increase in HS Readings vs. Mass (Hanson Analogue)

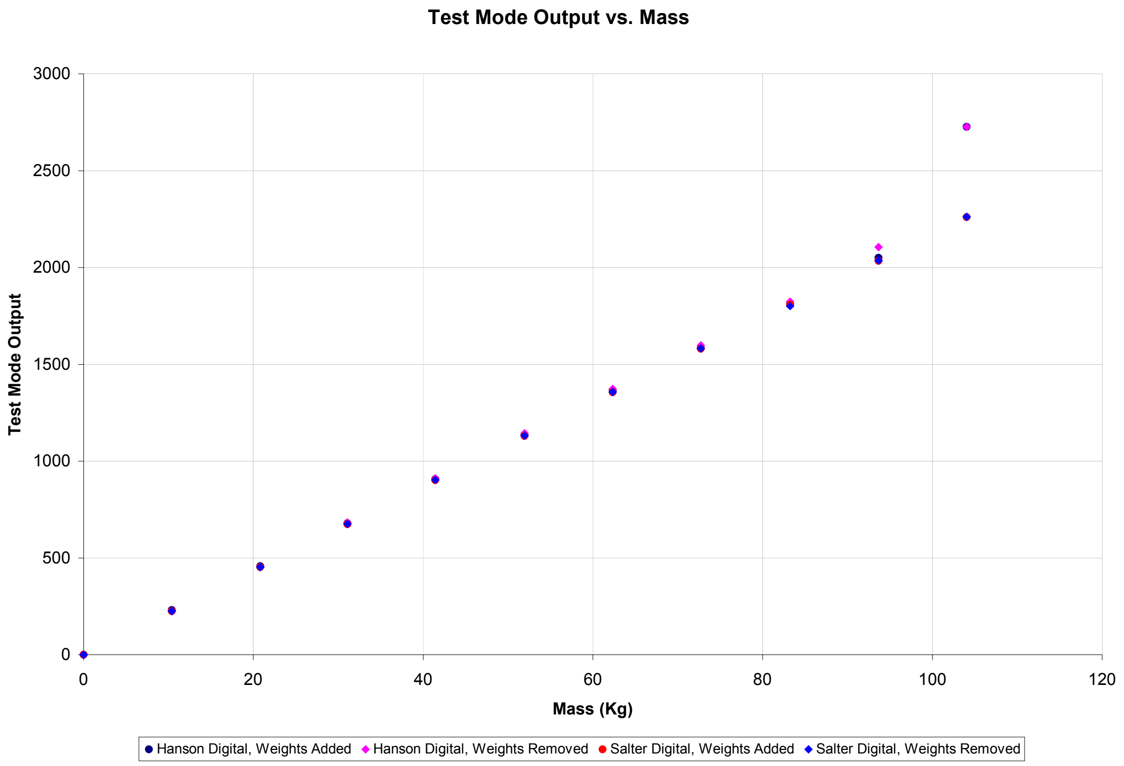

Percentage Increase in HS Readings vs. Mass (Hanson Analogue)

Appendix B: Digital Strain Gauge Scales

In normal operation, the scales would automatically zero themselves when turned on, before testing for a weight reading. Presumably this allows the scale to adapt to changes in the test beam position or strain gauge architecture caused by prolonged use. The scale would then wait five seconds, or longer if the reading had not stabilised, before “freezing” the output. The display would then flash, and the frozen reading would be displayed for a further few seconds. The scale would then automatically turn itself off. Thus, the experimental technique devised in section 3.2 had to be modified slightly. The readings were still taken in succession, but all weights were completely removed after each reading and then added (in order) in quick succession once the scale had zeroed itself for the next reading. The weights had to be moved in a short space of time, in order to prevent the scale freezing the reading before the correct weight had been added, which turned out to very good exercise at high weight readings!

The digital scales tested in this investigation both contained similar electronic circuit boards; both of the boards had two pins marked “test”. Short circuiting these pins placed the scale in *a test mode*. In this mode, the scales displayed a 4-digit number, which was assumed to be linearly proportional to the signal produced by the strain gauge. They no longer turned themselves off or froze the reading at any point, and the batteries had to be removed to turn the scales off again.

This test mode allowed the same method of weight application as that used for the analogue scales (section 3.2) and, if the above assumption is correct, allows a more detailed study of scale accuracy; the test mode output increased on average by 22.1±0.2 *test mode units* per Kg of mass added (4.42 units per 0.2Kg). The Hanson scale was electronically limited to an accuracy of 0.2Kg, and the Salter scale to an accuracy of 0.5Kg; if the test mode units are linearly proportional to weight on the top plate, this allows a study of the carpet effect that is four times (Hanson) or eleven times (Salter) more accurate than that in section 3.4. HS, HSBS and thick carpet readings were taken for both digital scales in test mode. A HS study of hysteresis in test mode readings was also conducted in the same manner as that in section 3.2. The results are shown in figures C1 and C2.



<u>Figure B1:</u> Plot of Test Mode Output with Increasing Mass. Measurement error is insignificant (±0.5).

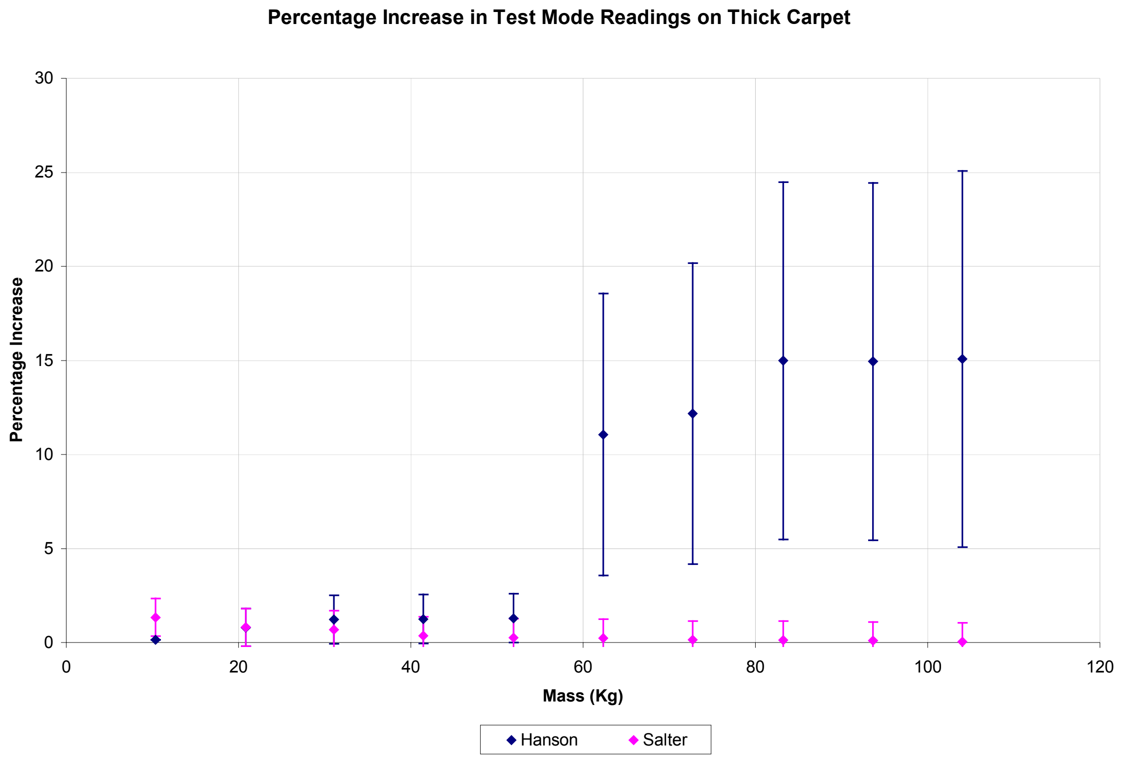


Figure B2: Percentage Increase in Test Mode Output on Thick Carpet

Interestingly, the test mode readings show a smaller level of hysteresis that that of the scale readings found in section 3.2. The test mode readings show a slightly larger percentage increase on thick carpet (0.41%) than that of the scale output (0.13%). This perhaps suggests that the test mode reading is not related linearly to the applied mass (which was assumed). This is further supported by the deviation of the Hanson test mode output from a linear trend at higher mass (both on carpet and a hard surface), which accompanies a marked increase in the carpet effect. This artefact was not shown by the Salter scale. It seems to be related to temporal instability in the high weight test mode readings.

Above 7 weights[18], addition of mass caused the output to rise sharply initially; however, the output continued to rise slowly for 2 – 3 minutes. Factors that could be causing this slow temporal response include base bending, strain gauge deformation, top plate settling and deformation of the sides of the scale. Thus, the accuracy of the Hanson scale tails off at high weight; this could be the reason for freezing the reading after it has roughly stabilised, and provides an explanation as to why the accuracy of the scale is electronically limited. Readings were taken 30 seconds after the addition of weight to ensure some measure of comparability at high weight. This temporal instability is the cause of the large error bars above 60Kg in figure C2.

Slow temporal response of readings was not visible for the Salter scale until the mass exceeded 80Kg, however; even then, the effect was much reduced. This may be linked to the much lower hysteresis level and larger dimensions of the Salter scale, suggesting that the roots of this effect also lies in base deformation. It is a more expensive scale, and so better accuracy might be expected. Thus, as concluded in the main report, it is a mystery why the Salter scale is electronically limited to a lower accuracy than the Hanson scale.

The results in figures C1 and C2 throw some doubt on the assumption that the test mode output is linearly proportional to the applied mass at high weight. Nonetheless, the scales seem to be more accurate than their imposed limit on a hard surface. The accurate return of the test mode output to its starting value after each experiment suggests that the strain gauge scale is a very stable and accurate measurement system. Instabilities at high mass, rather than on soft surfaces, appear to be the reason for the imposed accuracy limit.

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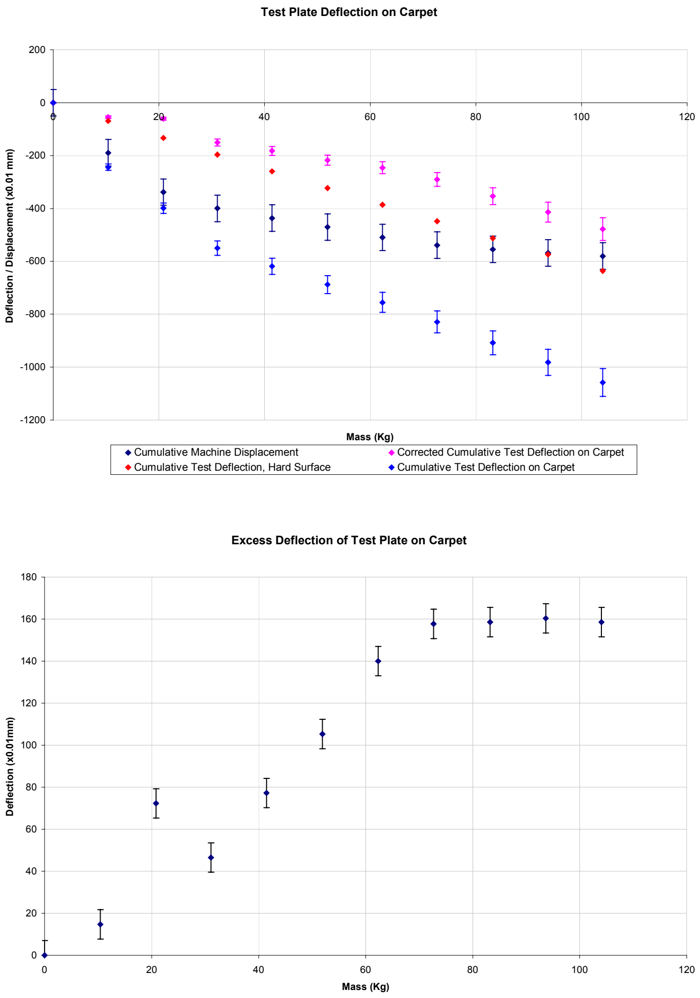
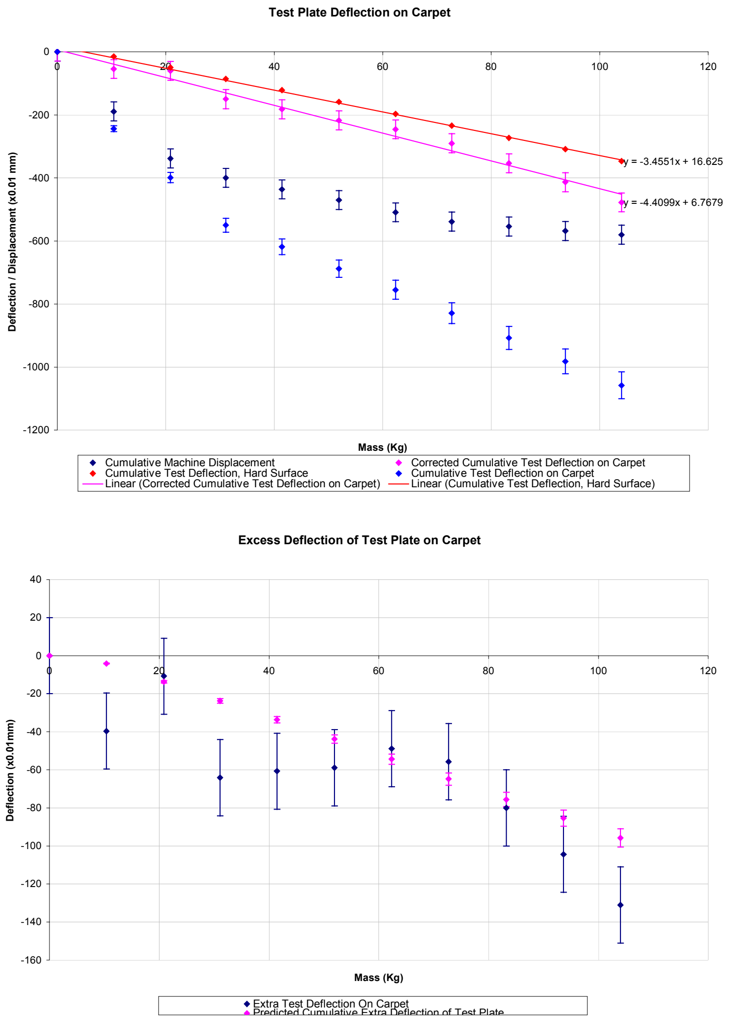
[18] This threshold decreased to 5 weights on thick carpet.

Appendix C: Detailed Analysis of Test Plate Movement

Figure C1 shows a set of results assuming that the central channel does not move as the base bends. This is possible, since the base bending may affect the scale mechanism in other ways; section 5 discusses this in detail. Figure C2 shows the same results with base bending under the test spring subtracted, which assumes that the channel (and thus test spring) displays a systematic downwards movement as the base bends.

The results reveal that is extremely important to discern which case is correct, since the conclusion of section 4.3 depends entirely on this. Figure C1 shows a positive (upwards) excess test plate deflection, which suggests that the carpet effect is due to *upwards movement of the test spring*[19]; however, figure C2 shows negative excess test plate deflection, suggesting that *excess downwards movement of the test plate* is the cause of the increase in readings on carpet.





<u>Figure C1 (left):</u> Results Assuming No Test Spring Movement (Two Plots). Error is dominated by sinking of the scale into carpet, and will be larger than that shown at low mass (figure 4.1).

<u>Figure C2 (right):</u> Results Assuming Test Spring Moves with the Base of the Scale (Two Plots). Base deflection under the test plate has been subtracted from observed test plate movement. Error in test plate deflection is larger than that in figure C1 due to the double influence of the sinking error.

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[19] since a positive excess deflection of the test plate would mean a reduced reading unless it was actually due to an upwards movement of the spring (to which the test plate is attached). Assuming that the force applied by the levers remains the same, the extension of the spring remains the same: so the test plate must follow the spring upwards.

The cumulative deflection of the test plate is the total deflection from the zero mass position. Corrected cumulative deflection refers to the cumulative deflection *minus the mean displacement of the whole scale* due to sinking into the carpet. In figure C1, the corrected cumulative test plate deflection on carpet (magenta) is less than that on a hard surface (red). This leads to the positive excess deflection, which reaches a plateau (of +1.61±0.07mm) at high weight. This is unexpected, since the readings on carpet continue to increase (relative to hard surface values) at high mass, and provides the first clue that figure C2 holds a better interpretation.

The first plot in figure C2 has corrected cumulative deflection on carpet (magenta) greater than the hard surface trend (red), and thus gives a negative excess test plate deflection (second plot). This excess is given in blue, and compared against a predicted trend (magenta). The predicted trend has been calculated using the two trend lines in the first plot; it is given by the ratio of the gradients multiplied by the hard surface values of test deflection. The observed results do not fit the predicted trend within experimental error (except in the middle of the mass range), suggesting that there might be other factors besides base bending contributing to the test spring movement; section 5 presents factors which are likely to be significant. Nonetheless, the observed and predicted trends bear significant resemblance, providing further support to the theory that the test spring moves as the base bends underneath it.

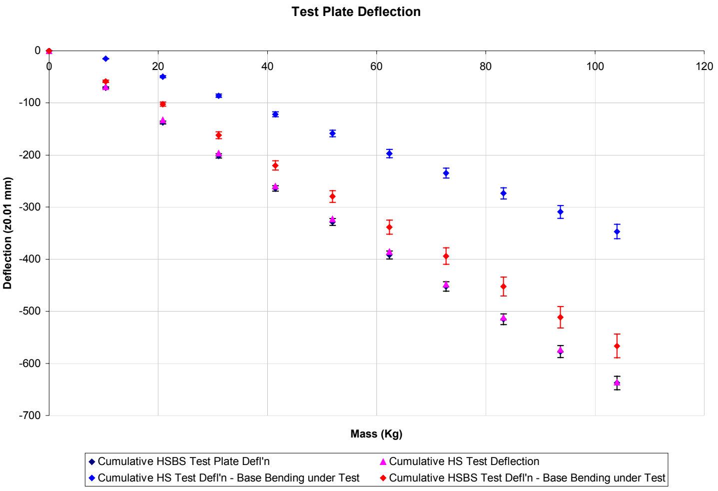


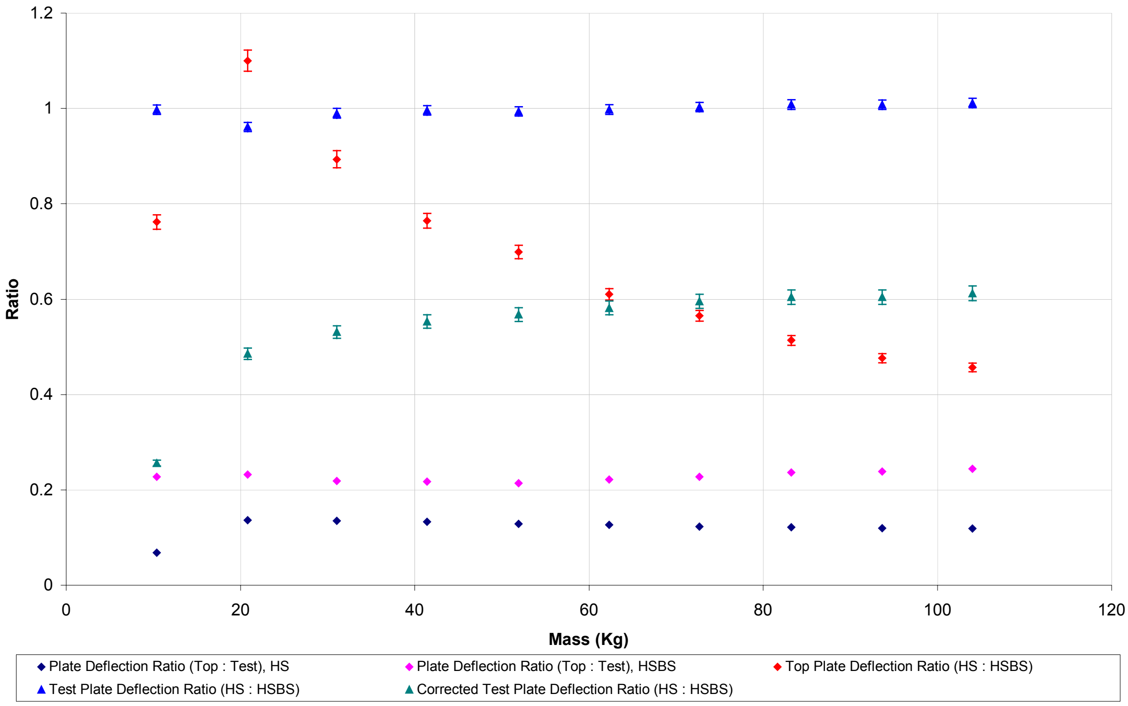
Figure C3: **Test plate deflection on a hard surface with the base of the scale supported. Cumulative measurement error is shown.**

In fact, the strongest evidence that the spring moves as the base bends stems from the discovery in section 3.5 that HSBS readings can be used to study the carpet effect without the inconvenience of soft surfaces. The Hanson analogue scale was again used to determine the HSBS test plate deflection. This allows more accurate readings, as they need not be corrected for scale movement.

The result is shown in figure C3; the advantages of much smaller experimental error can clearly be seen. The uncorrected HSBS and HS test plate deflection results are identical to well within experimental error. If these were the correct values, HSBS or thick carpet would surely have no effect on scale readings. When the results were corrected for base deflection, however, they became easily distinguishable. This was done by subtraction of HSBS base deflection from the HSBS results, and subtraction of HS base deflection from the HS results; these values of base deflection are included on a plot in Appendix A. It seems that the test spring must move if a supported base or thick carpet is to affect the scale readings, and it makes sense that this movement should follow the base bending. Correction for base bending makes HSBS test plate deflection substantially greater than HS deflection.

Top plate movement was also measured using a DTI, in order to assess the ratio of top plate and test plate movements. If the moment of the levers is constant across the mass range (which should be the case if the levers are not moved by deformation of the base of the scale), the ratio should be constant across the weight range.

Figure C4: Ratios of Top and Test Plate Delfection



The results (figure C4) show that the ratios of top plate and test plate movement are remarkably constant across the weight range; perhaps unsurprisingly, the HS ratio is more constant than the HSBS ratio. The measurement error for these ratios corresponds to about the height of a point on the plot; thus, discounting the 10Kg reading (which, as previous sections have shown, has a large error due to settling of the scale mechanism) the results describe a horizontal line to within experimental error for both ratios. This shows that the lever moment remains constant across the weight range for both set-ups; the top plate always moves as a fraction of the test plate movement. For a hard surface, this fraction is 0.127±0.006.

However, the fraction appears to change for HSBS; the ratio changes to 0.228±0.009. The difference in these two ratios is 0.101±0.006. This means that the HSBS top plate movement is a larger fraction of the test plate movement, suggesting an expected 10.1±0.6% increase in HSBS scale readings for the *Hanson analogue scale* over HS values. This compares with the observed 12.48±0.25% increase.

The un-corrected test plate deflection ratio is equal to 1 within experimental error, implying no difference in HS and HSBS movement. The corrected ratio has the HSBS and HS base bending subtracted from the corresponding test plate measurements. This gives a value which increases with applied mass, reaching a plateau at 0.61±0.08%. This would imply ~40% increase in readings on HSBS, which is much greater than that observed. This suggests that there might be other factors influencing the increase in HSBS and carpet readings (see section 5). However, it could also mean that the correction applied is incorrect.

Note that the top plate deflection ratio is far from constant, which suggests that the relative moment of the HS and HSBS lever systems is constantly changing as the mass increases. This disagrees with the other results, and with the observed increase in readings (appendix A, section 3) which were fairly constant across the weight range. If the increase was caused by a change in moment of the lever system, this change would be expected to be approximately constant, as shown by the plate deflection ratios. The best explanation for the changing HSBS top plate movement may be deformation in the base and sides of the scale causing excess vertical movement of the top plate *which does not constitute extra vertical movement of the test plate*.

Appendix D: Internal Dimensions of the Scales

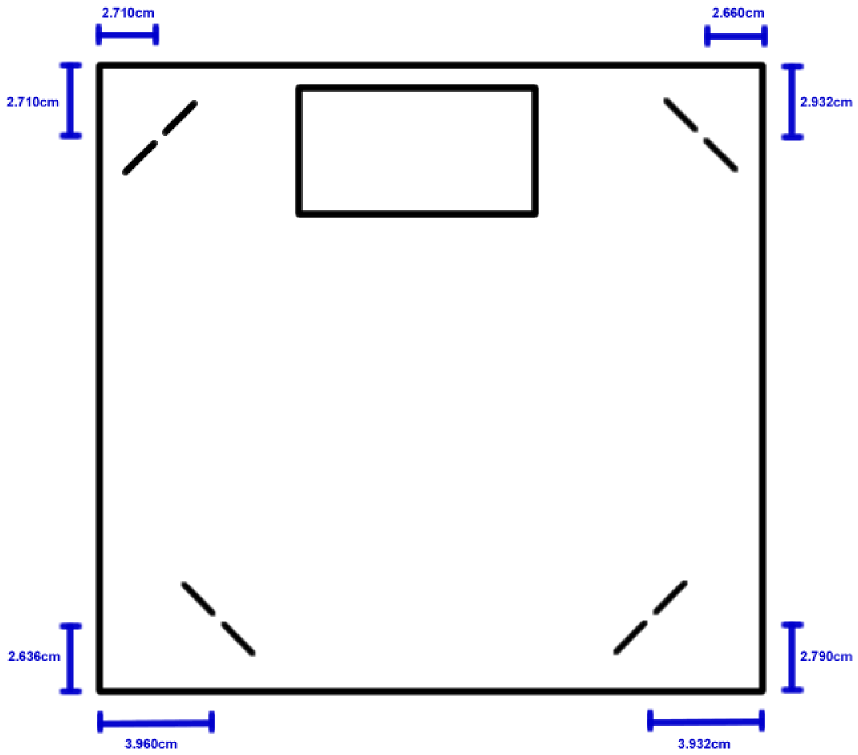


Figure D1: Dimensions of the Underside of the Top Plate (Hanson Analogue)

Figure D2: Dimensions of the Lowered Corners of the Base Plate (Hanson Analogue)

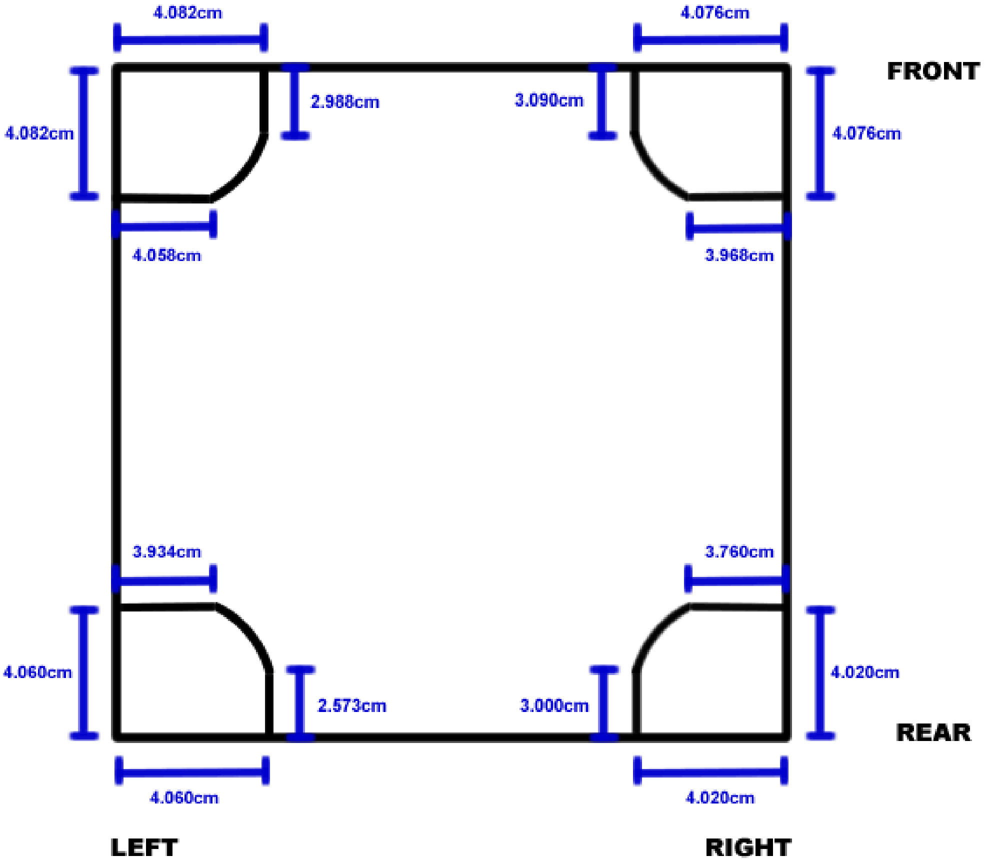


Figure D1 shows the dimensions of the underside of the top plate. The mounting points which couple the top plate to the levers are represented as the four broken lines. Figure D2 shows the dimensions of the lowered sections of the metal base plate; these lowered sections were the only parts of the base that contacted with a hard surface (the Hanson analogue scale was supplied without plastic feet). The measurement error for both figures is ±0.002cm.

A significant inconsistency is visible in all of the measurements; presumably this is due to a low manufacturing tolerance which minimises production costs. In fact, the measurements are largely symmetrical to within ±1mm, which (considering the size of the scales) is a fairly small error. The experimental results confirmed that this error causes very little effect when the centre of mass is moved or the scale is titled.

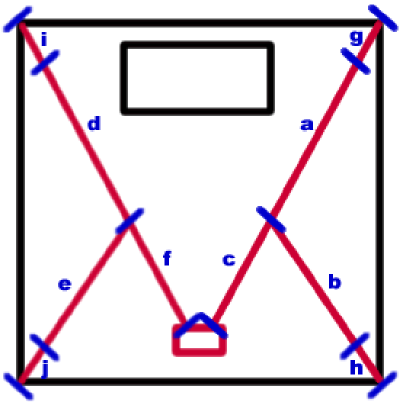


Figure D3: **Schematic showing the lever system of the scales.**

Figure D3 shows the lever system schematically, with various distances labelled. Measurements are given in figure D4:

Scale	a	b	c	d	e	f	g	h	i	j
Hanson Analogue	10.60	11.01	10.21	10.62	11.02	9.58	1.668	1.818	1.648	1.762
Hanson Digital	9.32	10.39	9.49	9.33	10.39	9.46	1.284	1.608	1.280	1.598
Salter Digital	12.16	11.88	10.07	12.17	11.88	10.09	2.060	2.110	2.055	2.118

Figure D4: **Table giving lever measurements. Letters refer to figure D3. Error is ±0.01 (a-f), ±0.005 (g-j).**

It is interesting that the measurements are more consistent in the digital scales; this suggests that they are subject to a higher manufacturing tolerance. The fraction of weight on the top plate delivered to the test plate is:

$$\frac{f}{F}=\frac{xyi}{(i+d+f)}+\frac{x(1-y)g}{(g+a+c)}+\frac{(1-x)yj}{(j+e+f)}+\frac{(1-x)(1-y)h}{(h+b+c)}$$

F is the weight on the scale and f is the force on the test plate. x is a fraction describing bias of weight to the front of the scale, and y is the corresponding fraction giving bias of weight to the left. For a perfectly central COM, $x = y = 0.5$. Changing these fractions in a spreadsheet produced surprisingly little change in the total force delivered to the test plate until the COM was almost completely biased to one corner of the scale (a physically unrealistic situation). This theoretical conclusion was supported by the experimental data collected in section 3.5. The measured distances in the table above gave the following moments for the lever systems ($x, y = 0.5$):

Scale	f/F
Hanson Analogue	0.0768±0.0004 (1/13.0)
Hanson Digital	0.0694±0.0009 (1/14.4)
Salter Digital	0.0863±0.0012 (1/11.6)

Both digital scales had a test beam of length 8.160±0.020cm.