An analysis of crossbow data

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1) Summary:

We calculate the effective mass, efficiency, and crossbow energy of the eleven crossbows.

We find that impact is proportional to velocity squared; or in other words that it is proportional to the kinetic energy of the bolts.

We find that the kinetic energy of the bolts accounts for 73% of the statistical variance in the impact data.

We find that the data has a time dependency. The kinetic energy of the bolts, plus the correction for the time dependency, together account for 84% of the statistical variance in the impact data.

We introduce a new physical concept, **specific impact**, which measures impact per unit of kinetic energy. Specific impact has the great analytical advantage that it is substantially independent of the crossbow.

We find that there is no statistically significant difference in specific impact between the bolts with egg Baldar blunts and the bolts with UHMW blunts. We combined the data for both kinds of bolt.

The kinetic energy of the combined bolts, plus the correction for the time dependency, together account for 89% of the statistical variance in the impact data.

We investigate the dependence of specific impact on the other characteristics of the crossbows, and find that there is no statistically significant difference for any of the other characteristics.

In particular, we find that specific impact is not dependent on crossbow poundage.

We speculate that the remaining 11% of the statistical variance in the impact data might be accounted for by bolt behaviour during flight, or by bolt behaviour on impact.

We calculate that the effect of drag during flight could be large enough to account for most of the remaining statistical variance in the impact data.

We find that the inch pound value is a good predictor of impact. Surprisingly, we find that the product of inch pound value times crossbow efficiency is not as good a predictor of impact as the inch pound value alone. This is not as we expected, and we are unable to explain this.

While investigating the latter relationship, we notice that two crossbows have unusually low impacts, and wonder whether this might be the result of poor flight behaviour. We predict that if this were so, then the UHMW bolts from those two crossbows would have low impacts relative to egg Baldar bolts from the same crossbows. We find this to be the case. This leads us to notice that the impacts of the UHMW bolts from five crossbows are significantly lower than the impacts from the other UHMW bolts. This in turn leads us to speculate that the UHMW bolts from these five crossbows might have poor flight behaviour.

We investigate the implications of this speculative possibility, and find that if the impacts of the UHMW bolts from these five crossbows were increased to adjust for their speculative poor flight behaviour, we would be able to account for 94% of the statistical variance in the impact data.

The arrow from the sample hand bow was defined to have an impact of 4.0 for these tests. We calculate that the sample arrow might have had an impact of 5.5 on this scale. The difference between these two values might be explained if the Markland blunt used for the arrow has flight or impact characteristics significantly different from either of the blunts used with the crossbow bolts.

2) The data:

The data analysed here were gathered by THL Siegfried Sebastian Faust on 2003-April-12 with the assistance of Baron Konrad der Ruhige Bär, Lord Llewellyn gan Barfog, Lord Eoghan O'Ruadhain, and Lord Aeddan Ivor. The original data, except for some weights provided later, and a correction of the poundage of crossbow C from 92 to 102 pounds, were at <http://crossbows.biz/xbowtest>. The site has since disappeared so the corrected data are given in the Appendix (section 22).

This paper represents over 200 hours of analysis with the aid of spreadsheets, graphs, curve fitting software, and arrow ballistics software. As I did not at first know what kind of analysis to do, there were a number of false starts and dead ends.

3) Initial data checks:

- The reported impacts for the 12 shots for each bolt type from each individual crossbow were analysed using the Weisberg t-test for outliers (Seely 2003). Nine impacts with significant t-values ($0.01<P<0.05$) were examined in conjunction with the recorded comments, and one was identified as anomalous ($P<0.001$), and was excluded from further calculations.

- Similarly, seven velocities were examined, and two data points were identified as anomalous ($P<0.001$), and were excluded from further calculations.

- The four individuals who acted as targets reported an average impact of 4.6, and all individuals are within 5% of this average. Therefore inter-judge consistency is good.

4) Crossbow effective mass and crossbow efficiency:

A bow or crossbow can be considered to have an **effective mass** and an **efficiency**. The efficiency varies with the mass of the arrow or bolt See section 20, "Equations", at the end of this paper.

The mass of an egg Baldar bolt was given as about 2.75 ounces (77.96 grams), and the mass of a UHMW bolt was given as about 962.7 grains (62.38 grams).

We calculate the effective mass of each crossbow by using the average velocity and mass for an egg Baldar bolt and the average velocity and mass for a UHMW bolt. Using the effective mass, we calculate the efficiency of each crossbow, once when used with the egg Baldar bolts and once when used with the UHMW bolts. See Table 1.

Crossbow	Effective mass (grams)	Efficiency (egg Baldar bolts)	Efficiency (UHMW bolts)
A	35	69%	64%
B	31	71%	67%
C	4	96%	95%
D	30	72%	67%
E	10	88%	86%
F	3	97%	96%
G	31	71%	67%
H	30	72%	67%
J	5	94%	92%
K	15	83%	80%
L	12	87%	84%

Table 1

The calculation of crossbow effective mass and efficiency is quite sensitive to bolt mass and velocity, so having the most accurate values possible for both is important.

For example, crossbow A has a pair of calculated efficiencies of 69% and 64%. The uncertainty about bolt mass in the data means that the actual efficiencies could be as high as the pair 76% and 73%, or as low as the pair 64% and 58%. The values in Table 1 should therefore be treated as approximate.

For each crossbow one can then calculate the **crossbow energy**, the total amount of energy released by the crossbow during firing. The values for crossbow energy are used in later analysis. See section 20, "Equations", at the end of this paper.

5) Adjusting reported impact:

The impacts were reported on an arithmetic scale with values from 1 to 7. If these values were used directly, this would be the same as saying that the heaviest impact has 7 times more 'thwack' than the lightest impact, and that the heaviest impact has 1.75 times more 'thwack' than the standard impact.

This is probably not a realistic scale. Based on comparison with many other physical scenarios, including Sir Pieter van Doorn's measurements of sword blows (see section 19, "References"), a geometric scale would probably be closer to reality. Many biological responses are geometric functions of the stimulus. So we will convert the impacts to a geometric scale.

The choice of the geometric ratio to use is somewhat arbitrary. Sir Pieter van Doorn found that a heavy sword blow had twice the momentum of a standard sword blow, which in turn had twice the momentum of a light sword blow. There are other physical scenarios which show a ratio of 2, and so that is the ratio that I have chosen to use. This ratio was chosen on purely subjective grounds before any of the calculations that follow were done, and is not the result of 'fiddling' to obtain any particular result.

The reported impact of 4 corresponds to a standard blow, the reported impact of 2 corresponds to a light blow as defined by Sir Pieter, and the reported impact of 6 corresponds to a heavy blow as defined by Sir Pieter.

We will convert a reported impact of 4 to 100, a reported impact of 2 to 50, and a reported impact of 6 to 200. Because this is a geometric scale, reported impacts 1, 3, 5, and 7 will then differ from their neighbours by the square root of 2.

With this **adjusted impact scale** the heaviest impact now has 8 times more 'thwack' than the lightest impact, and the heaviest impact has 2.83 times more 'thwack' than the standard impact.

6) Analysis based on the adjusted impact scale:

A preliminary set of calculations and graphs were done comparing the unadjusted and adjusted impact scales. These calculations indicated that the adjusted impact scale was probably a better model to choose than the unadjusted impact scale.

All subsequent analysis is based on the adjusted impact scale. All calculations and graphs use average velocities and average impacts. Many calculations and graphs are repeated three times, once for egg Baldar bolts, once for UHMW bolts, and once for all bolts combined (i.e. impact for a particular crossbow averaged across all bolts).

7) Adjusted impact as a function of velocity:

One theory of missile impact is that reported impact will be proportional to the **momentum** of the missile. For example, SCA heavy weapon killing blows to the helmet were found by Sir Pieter van Doorn to be proportional to momentum. Another theory is that reported impact will be proportional to the **kinetic energy**. For example, biomechanics predicts that bruising will be proportional to kinetic energy.

As a comparison, in the field of terminal ballistics for naval guns, armour penetration (i.e. damage to armour) is proportional to velocity raised to an exponent that ranges between 1 (momentum) and 2 (kinetic energy). There are different exponents, each appropriate for a particular combination of armour type, armour thickness, shell type, shell mass, and shell velocity. Each exponent was determined empirically (by firing thousands of shells at thousands of samples of armour).

Because of the unpredictability of the exponent in a closely related field, we determine the exponent for bolt impact empirically rather than proposing momentum or kinetic energy as an hypothesis.

We now determine the exponent of velocity that best matches the data. To do this we divide each average impact by the mass of the bolt times the matching average velocity raised to an exponent that steps from 1.0 to 2.5. We graph each set of normalised calculated values (labelled "Impact / fv") for egg Baldar bolts, for UHMW bolts, and for all bolts. The graph for which the statistical variance is a minimum represents the exponent that best matches the data.

Here, as an example, is the set of graphs for all bolts combined, zoomed in on the region of interest. Each series within the set corresponds to velocity raised to a different exponent.

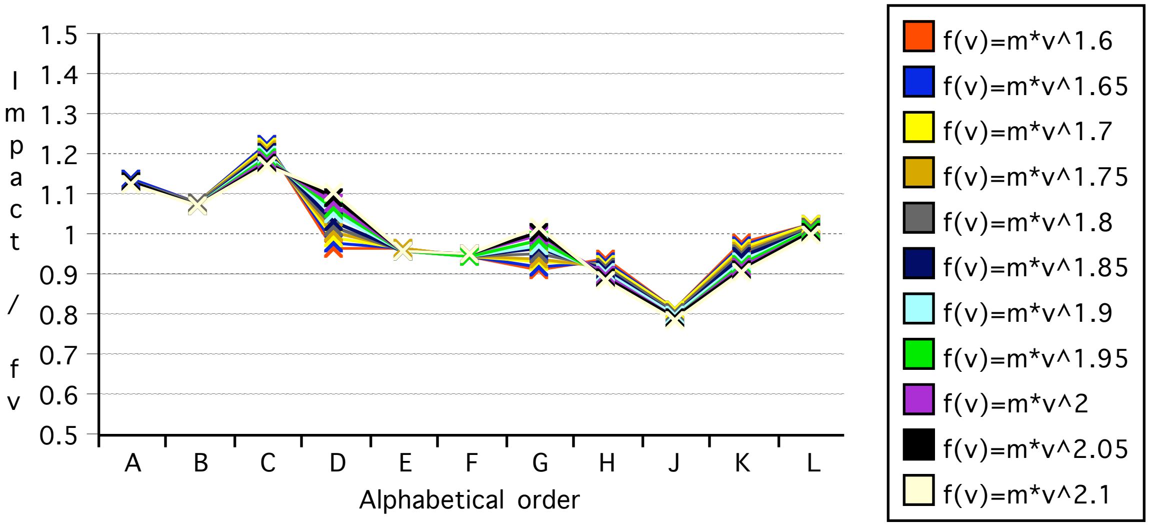

Figure 1

I will now indulge in a bit of time travel, and talk about something that I discovered much later in the analysis, and introduce it to you now so that you won't have to travel the same road several times, as I did. It is a short parable of scientific discovery.

I had done most of the analysis described later, including sorting the data points according to various characteristics. As part of doing those calculations the graph set starts out 'unsorted', which is to say in crossbow alphabetical order, A to L. I had seen, but not noticed, that in its 'unsorted' state the graph set has a significant trend. When sorted by another characteristic, that trend vanished.

It was not until later that the penny dropped. Trend. Significant. Alphabetical order. Time order? Could something be changing as the day progressed? Discovery! The crossbows were indeed shot in alphabetical order.

8) Adjusted impact as a function of time:

Refer to Figure 1 above. There is a significant downward trend in this graph set (t-test, 0.001<P<0.01). This tells us that the impacts were reported as getting lighter as the day progressed.

It is probably not possible to determine from these data whether the targets were becoming habituated to the impacts (my personal guess); whether the perceived impact was being affected by rising or falling temperature; whether the chronograph was gradually reporting higher velocities; whether the comparison arrow from the bow had an increasing perceived impact as the day progressed; or whether some other factor was at work.

I had already determined during my early analysis of the other characteristics that none of them was responsible for this downward trend. Regardless of the cause, it is necessary to correct for this downward trend.

I applied a simple linear **time correction** to the "Impact / fv" values. To determine the value to use for the time correction I took the single graph that corresponded to the exponent with the minimum statistical variance for the egg Baldar bolts (1.92) and did a least squares fit to a straight line to determine the slope of the line. I did the same for the UHMW bolts (1.75) and for all bolts (1.82). Because the egg Baldar and UHMW bolts were interleaved it is reasonable to assume that the time correction should be the same for both, so I averaged the three slopes.

I applied this average time correction, adding zero for crossbow A, a correction of about 0.23 for crossbow L, and a proportional correction for the intervening crossbows.

I repeated the process until the three graphs were all as close to horizontal as possible (minimum statistical variance). This took one repetition, with a correction for crossbow L of about 0.29.

Here again is the set of graphs for all bolts combined, after applying the time correction.

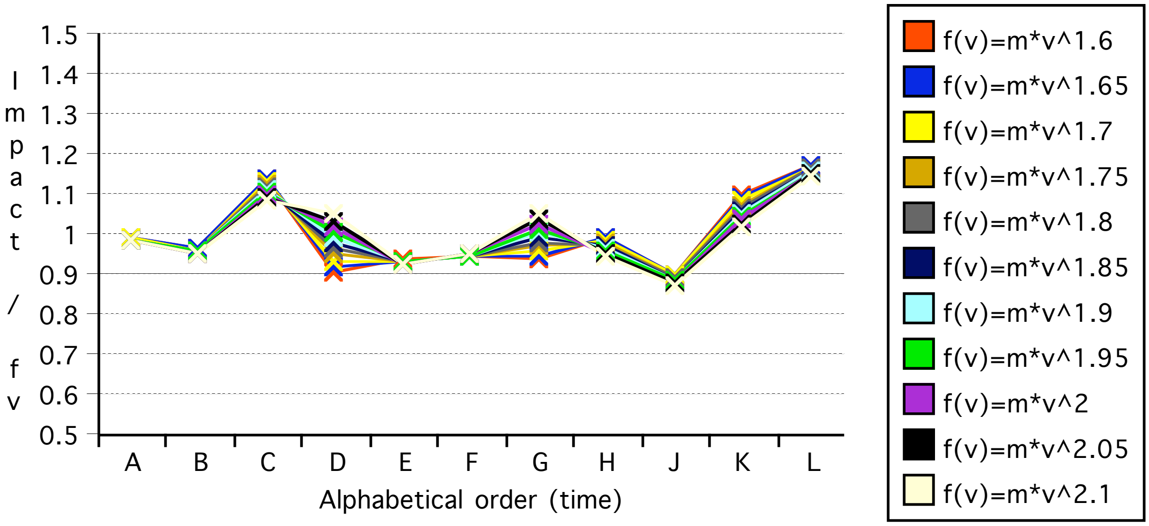

Figure 2

Just in case the time correction was an artefact of the geometric ratio chosen for the impact scale (see Section 5, "Adjusting reported impact"), I also tested the sensitivity of the time correction to several other geometric ratios, and found no effect.

9) Revisiting adjusted impact as a function of velocity:

With the time correction applied to the "Impact / fv" values, we can now plot the statistical variance for all three graph sets. Here, for example, is the graph of the statistical variance for all bolts combined, as a function of the exponent.

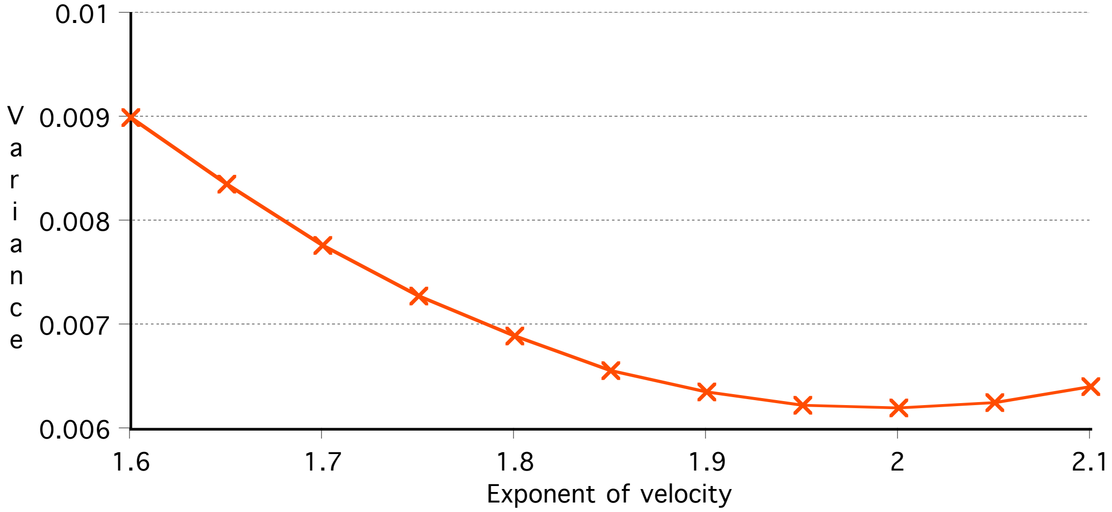

Figure 3

From each graph of statistical variance we can estimate the exponent of the velocity that would correspond to the minimum statistical variance. Here is a table of the results, obtained by further zooming in on the critical regions with a step size of 0.01.

	egg Baldar	UHMW	All
Estimated exponent of velocity	2.09	1.91	1.99

Table 2

This tells us that impact is very close to proportional to the average measured kinetic energy of the bolt. In other words, the kinetic energy of the bolt is a good predictor of impact.

- The measured kinetic energy accounts for an average of 73% of the statistical variance in the adjusted impact data (67% of the statistical variance for the egg Baldar bolts, 73% of the statistical variance for the UHMW bolts, and 78% of the statistical variance for all bolts).

- The measured kinetic energy, plus the time correction, accounts for an average of 84% of the statistical variance in the adjusted impact data (87% of the statistical variance for the egg Baldar bolts, 75% of the statistical variance for the UHMW bolts, and 89% of the statistical variance for all bolts).

We will compare the average impact with other known characteristics, to see what we can learn.

To do this we divide the average impact by the average measured kinetic energy of the bolt, and normalise, a procedure very similar to what we did to get "Impact / fv" in section 7, "Adjusted impact as a function of velocity". This quantity we will call the **specific impact**, because it can be used to measure how much 'thwack' the bolt delivers per unit of kinetic energy.

It is important to remember that specific impact, being based on the average measured kinetic energy of the bolts, depends on effects that show up **after** the bolt has passed through the chronograph. This means that it should be largely independent of the power and efficiency of the crossbow.

10) Specific impact as a function of blunt design:

There is one factor whose effect on specific impact is now easy to determine, and that is blunt design.

Comparing the average specific impact for the egg Baldar bolts with the average specific impact for the UHMW bolts, we find that the UHMW bolts used in this testing deliver 4.9% more 'thwack' per unit of kinetic energy than the egg Baldar bolts.

As UHMW bolts were shot second for every crossbow, they need a small time correction themselves, half of the approximately 3% time correction between two adjacent crossbows. With this correction applied, the UHMW bolts probably deliver 6.3% more 'thwack' per unit of kinetic energy than the egg Baldar bolts at a range of 20 feet.

I presume that this is an approximate measure of the 'area-and-hardness' of this particular design of UHMW blunt as compared with the 'area-and-hardness' of this batch of egg Baldar blunts.

I compared the specific impacts of the two types of bolt and the difference is not statistically significant (paired t-test, $0.1 < P < 0.5$). This means that the difference could be just an coincidence.

It also means that we can combine the data for both types of bolt, and use the specific impacts for all bolts (the set of graphs for all bolts combined in sections 7 and 8) in subsequent analysis.

- The measured kinetic energy plus the time correction plus combining both types of bolt accounts for 89% of the statistical variance in the adjusted impact data.

Here is the graph of specific impact for all bolts. The numbers on the vertical axis measure the specific impact of a bolt compared to the average. The points in this graph are in alphabetical order of crossbow (time order). The graph is 'horizontal', with 'random' wiggles up and down.

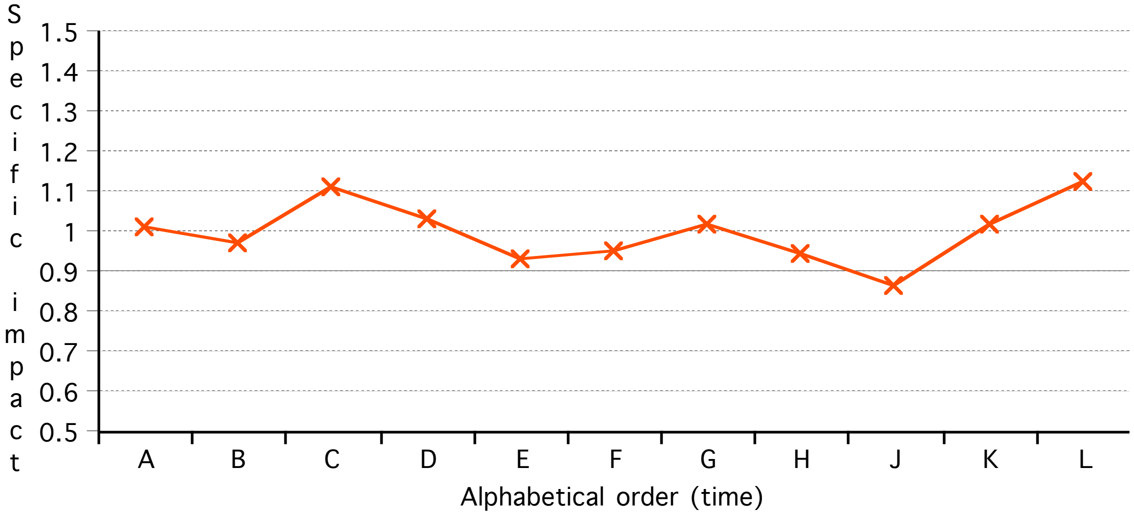

Figure 4

11% of the statistical variance in the adjusted impact data is still unaccounted for. In Figure 4 we can see that the bolts from crossbows J and L might be slightly anomalous, but I don't have a suggestion for why this might be so.

I wish to stress again that the variability visible in this graph has nothing directly to do with the crossbows. It depends either on what happens in flight after the bolt has cleared the chronograph, or on what happens at the moment of impact. None of the specific impact values is more than two standard deviations from the average, which means that the variability visible in this graph is statistically expected.

11) Specific impact as a function of other characteristics:

The graph of specific impact (see Figure 4) can be used to see whether any of the other crossbow characteristics could account for some of the remaining statistical variance. If the data points are sorted by one of the other characteristics, and if the new graph shows a trend up or down with a slope significantly different from the horizontal, then that characteristic may be having some kind of effect on the specific impact.

There are fourteen characteristics (data gathered by Siegfried) that can be analysed in this way. We find that none of the slopes is statistically different from the horizontal (t-test, 0.5<P or 0.1<P<0.5).

Here, as an example, is the graph with the greatest slope, the graph for string thickness.

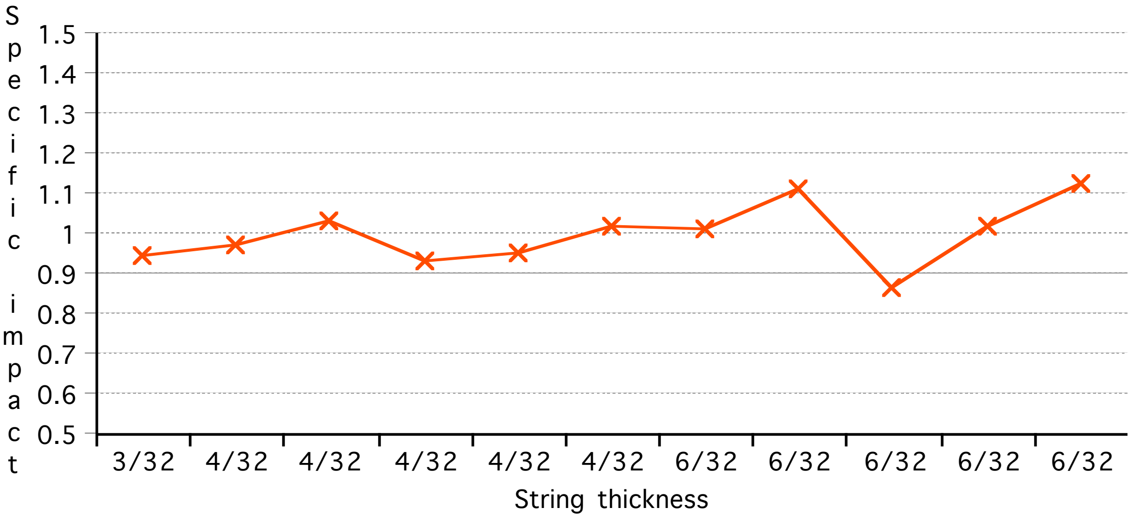

Figure 5

Some people in the SCA have suggested that crossbow poundage might have an effect on specific impact. The data give no support for the suggestion. Here is the graph for crossbow poundage.

Figure 6

If crossbow poundage affected specific impact, the graph would show a clear trend upwards or downwards. The slope of the graph is very close to zero (horizontal).

There are five characteristics that are not numeric and which must be analysed differently. We group the specific impact data points according to the values of the non-numeric characteristic. For example, the values for prod style are: recurve (three crossbows), straight (five crossbows), and reflex (three crossbows).

We analyse whether the specific impact for any of the groups of data points differs from the entire sample of eleven bows. None of the groups for any of the five characteristics is statistically different from the entire sample (t-test, 0.5<P or 0.1<P<0.5).

Here, as an example, is a graph for the characteristic whose groups differed most, a graph for prod style.

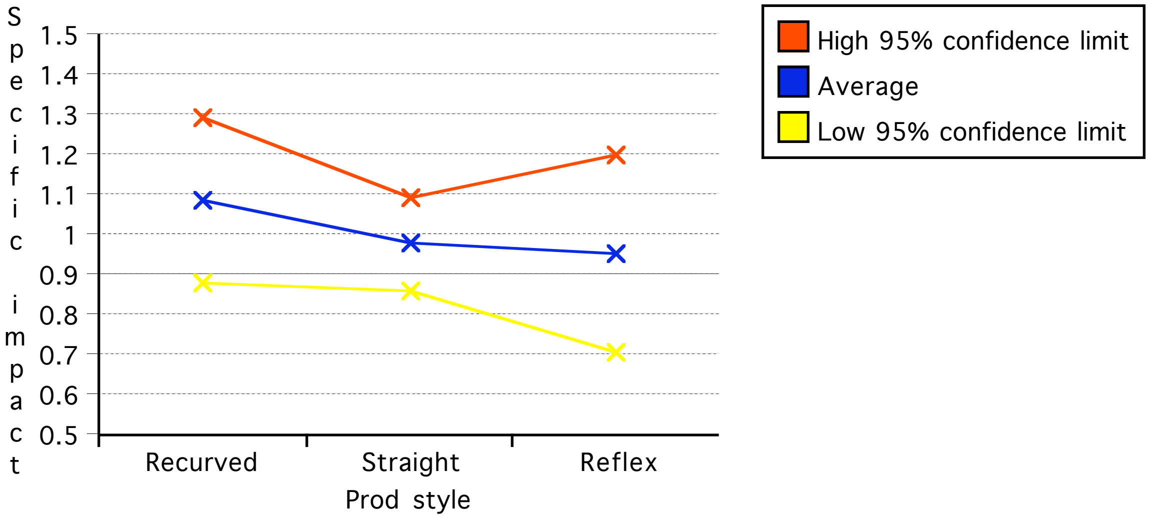

Figure 7

We can see that while the graph of the average shows a downward trend, the differences are not statistically significant, which means that they could have occurred by chance.

To recap, none of the other characteristics that were gathered is able to account for any of the remaining 11% of the statistical variance in the adjusted impact data.

12) Flight effects:

It is worth repeating that the statistical variance not yet accounted for has nothing directly to do with the crossbows. It depends either on what happens in flight after the bolt has cleared the chronograph, or on what happens at the moment of impact.

One effect that might happen during flight is discussed in this section. Three effects that might happen at the moment of impact are discussed in section 13, "Impact effects".

During flight some bolts might experience higher drag than others, perhaps as a result of fishtailing (oscillating significantly), after leaving the chronograph at a range of 6 feet and before striking the target at a range of 20 feet.

Estimated values for the coefficients of drag for bolts with these blunt types were determined by me some years ago, using my external ballistics software to analyse measured velocities, maximum ranges, and flight times for a variety of missiles with various blunt types. It is those (unpublished) values for the coefficients of drag that are used here.

Using the same external ballistics software we determine the loss of energy due to drag during the flight from a range of 6 feet to a range of 20 feet, for both types of bolt.

Here is a table showing the percentage loss of kinetic energy as the result of drag for both types of bolt, with normal drag and with triple the drag.

Loss of energy to drag	egg Baldar	UHMW
Coefficient of drag	0.5	1.5
Normal drag flight	2%	13%
Triple drag flight	7%	34%

Table 3

The ratio of the loss of kinetic energy between normal drag and triple drag is 5% for the egg Baldar blunts, and 24% for the UHMW blunts. The effect of poor flight is stronger for the UHMW bolt for two reasons: firstly because it has a higher coefficient of drag to begin with; and secondly because it is lighter, and thus is affected more by drag. If the bolts don't fly so badly as to triple their drag, then the effects will be intermediate.

The effect of drag is enough to account for some or all of the remaining statistical variance.

For example, if exactly one crossbow launched its bolts badly, so that they continued to fishtail all the way out to 20 feet, then for that one crossbow the average velocity would be reduced and so the average specific impact would be lower than expected. If exactly the right collection of crossbows had exactly the right amount of increased drag, then it is theoretically possible, with 24% of the energy of the UHMW bolts to play with, for most of the remaining variance to be accounted for. We do not have data for determining which bolts might have flown badly, nor how badly.

13) Impact effects:

This section discusses three possible effects that could happen at the moment of impact, and that could affect the reported impact.

The **first possible effect** is that if some bolts strike perpendicularly, and other bolts strike at an angle, those that strike at an angle will have some of their kinetic energy converted to rotational or sideways kinetic energy, and will therefore have less kinetic energy to convert into perceived impact.

It is not possible to calculate this effect exactly due to the unpredictable physics of the impact. We can make estimates. The lower estimate assumes that the blunt sticks upon impact, and that the sideways component is converted into rotation. The higher estimate assumes that the blunt skids upon impact, and that the sideways component is converted into sideways motion.

If the bolt strikes at an angle of 5 degrees, the amount of kinetic energy converted during the initial phase of the impact (before rebound) could be between 0.25% and 0.75%. If the bolt strikes at an angle of 10 degrees, an angle which might just be noticed by one of the participants during testing, the amount of kinetic energy converted could be between 1% and 3%.

These low percentages suggest that the loss of kinetic energy to rotational kinetic energy during the impact is not likely to be a very significant effect for angles up to 10 degrees.

The **second possible effect** is that impact at an angle might change the effective area of impact of the blunt. This might tend to decrease the effective area of impact as the angle of the bolt increases, thereby increasing the perceived impact. This is opposite to the effect of the transformation of kinetic energy into rotational or sideways kinetic energy.

It is not possible to calculate this effect due to the unpredictable physics of the impact, nor can we make an estimate.

The **third possible effect** is that the individuals acting as targets could have had a collective tendency to favour one crossbow over another. It is not possible to quantify this possibility.

14) Impact and inch pound values:

The inch pound value for a crossbow, which is the length of the power stroke in inches times the draw weight in pounds, is an approximate measure of how much energy it takes to draw a crossbow. It should be a moderately good predictor of impact for crossbows of similar efficiency. How good is the inch pound value as a predictor of impact for these crossbows?

Here is a graph of average impact for all bolts combined divided by the inch pound value for each crossbow, normalised so that the average value is 1.0. No time correction has been applied.

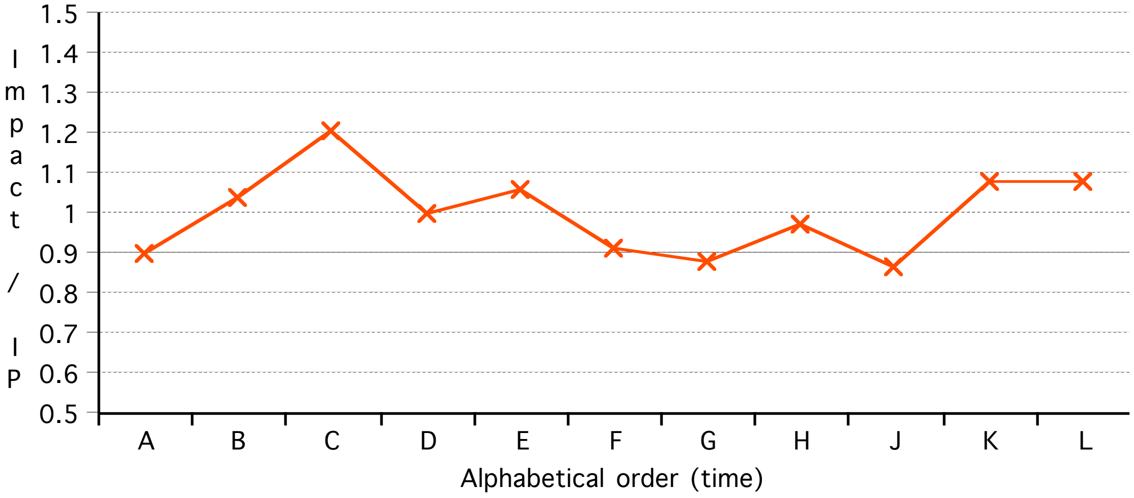

Figure 8

Interestingly, the inch pound value accounts for 81% of the statistical variance in the adjusted impact data. This is almost as good as the 89% accounted for by our detailed analysis (see sections 9 and 10).

The inch pound value times the efficiency of each bow should ideally be a better predictor of impact. Here is a graph of average impact for all bolts combined divided by the inch pound value times the efficiency for each crossbow, normalised so that the average value is 1.0. No time correction has been applied.

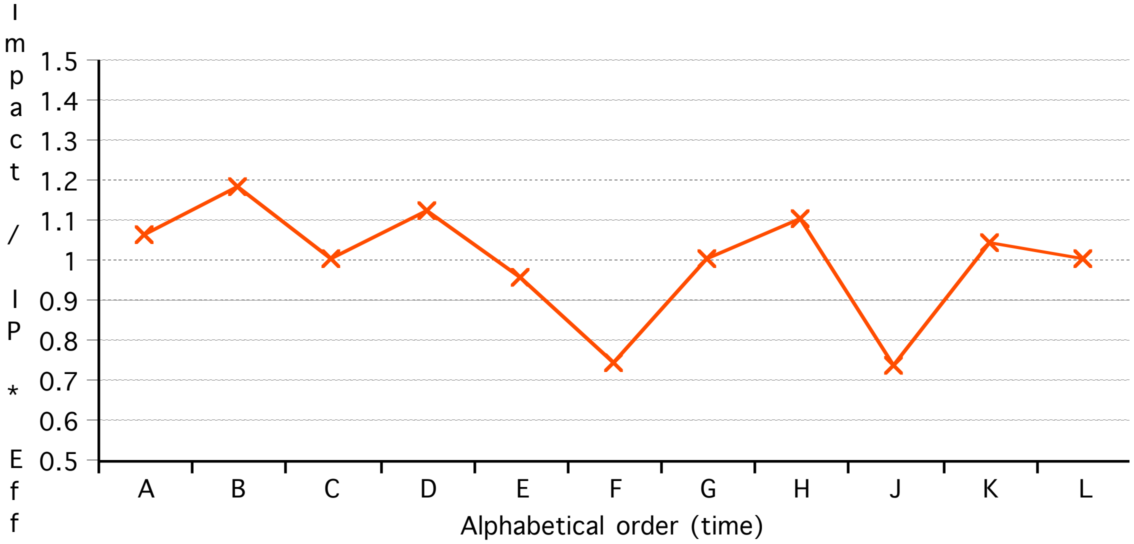

Figure 9

Surprisingly, the inch pound value times the efficiency is not as good a predictor of impact as the inch pound value on its own, and accounts for only 65% of the statistical variance in the adjusted impact data. I can't explain this, though there are two possible factors that could account for this anomalous behaviour.

The first is that the measured poundages for some of the crossbows could be in error. The measured poundage for crossbow C is known to be uncertain, and there could be other uncertainties.

The second is that the bolts from some crossbows may have flown very poorly.

If bolts, especially UHMW bolts, fly poorly from a crossbow this will lower the average specific impact for that crossbow. The values for crossbows F and J in Figure 9 seem unusually low.

If the low values for crossbows F and J were the result of poor flight behaviour, then because of the different drag behaviours of egg Baldar bolts and UHMW bolts (see Table 3 in section 12, "Flight effects") the poor flight behaviour should show up for crossbows F and J as lower impacts for UHMW bolts compared with egg Baldar bolts. And indeed we find that this could be the case (see section 15, "Flight effects revisited (a speculative examination)").

> **Historical Note**
>
> The inch pound value for crossbows was proposed by me in the spring of 1986 as a safety guide, as an upper limit. Because it does not take into account crossbow efficiency, it was not proposed as a good predictor of impact for an individual crossbow. See section 19, "References".
>
> The intention was that if a high efficiency crossbow with a particular inch pound value was acceptable (SCA marshallate definition), then any crossbow with the same inch pound value but lower efficiency would also be acceptable (SCA marshallate definition).
>
> In a similar way, the measurement of "30 pounds at 28 inches" for a hand bow cannot predict the impact of an individual bow, but does say that any bow meeting that AMO specification will be acceptable (SCA marshallate definition).

15) Flight effects revisited (a speculative examination):

Let us now see if we have any evidence of poor flight behaviour for crossbows F and J, as suggested in section 14, "Impact and inch pound values".

Here is a graph comparing the specific impact of egg Baldar bolts and UHMW bolts.

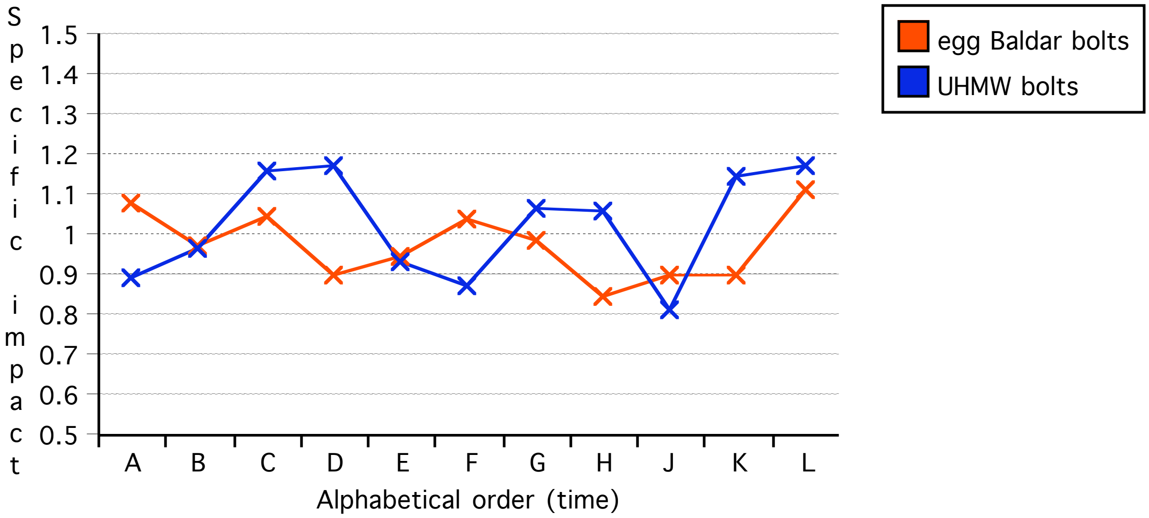

Figure 10

While on average the UHMW bolts have a higher specific impact than the egg Baldar bolts (see section 10, "Specific impact as a function of blunt design"), we note from Figure 10 that for three crossbows (A, F, and J) the UHMW bolts have a lower specific impact. The lower values for crossbows F and J support the speculative suggestion made in section 14, "Impact and inch pound values", and therefore warrant further investigation.

We note also that the UHMW bolts seem to fall into two groups. The first group, crossbows C, D, G, H, K, and L, has an average specific impact of 1.13. The second group, crossbows A, B, E, F, and J, has an average specific impact of 0.91. Both groups are significantly different from the average for all UHMW bolts (t-test, $0.001<P<0.01$). Because the egg Baldar bolt and UHMW bolt values are paired, each pair being fired from the same crossbow, one might expect a more consistent relationship.

This suggests the speculation that the UHMW bolts from crossbows in the second group might fly worse than those from crossbows in the first group. As we have seen in section 12, "Flight effects", poor flight behaviour would reduce the impact of UHMW bolts more than that of egg Baldar blunts.

The difference in average specific impact between the two groups of UHMW bolts at 20 feet is 24%, which is within the range of possibilities that would be allowed for by the values in Table 3. The effect of drag on the egg Baldar bolts would be much less, only a few percent, and consequently we might not be able to tell from Figure 10 which if any egg Baldar bolts flew poorly.

There is a problem in that there seems to be no middle ground in Figure 10 between the two groups. The values for the first group are high (suggesting good flight), the values for the second group are low (suggesting poor flight), and intermediate values are absent. I don't know of any reason for there being no intermediate values, and this suggests caution in accepting this speculative explanation.

What would Figure 10 look like if we adjusted the specific impacts of the five crossbows in the second group (crossbow A, B, E, F, and J) upwards by 24%, the ratio between the two groups? Here is the graph.

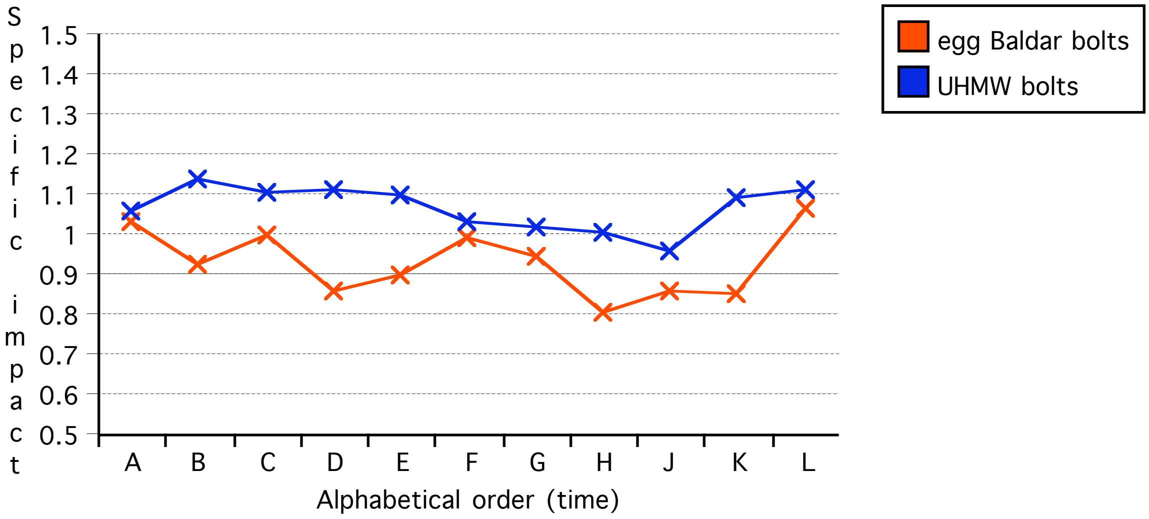

Figure 11

The line for UHMW bolts is now suspiciously smooth for crossbows B through J, which further suggests caution in accepting this speculative explanation.

On the other hand, there is now a downward trend in the UHMW bolt line in Figure 11 (except for crossbows A, K, and L), a trend which might explain an anomaly that I had noticed earlier while determining the time correction in section 8, "Adjusted impact as a function of time". When examined separately, the time correction for the UHMW bolts was less than the time correction for the egg Baldar bolts. Figure 11 suggests that there might be an additional time correction necessary for UHMW bolts, a time correction previously obscured by the flight behaviour effects.

16) Revisiting adjusted impact as a function of time and velocity (a speculative examination continued):

We can now repeat the process of sections 8 and 9, and determine what the time correction and the exponent of velocity would be if we were to adjust for the flight behaviour of some of the UHMW bolts as suggested in section 15, "Flight effects revisited (a speculative examination)". The revised time correction for crossbow L would be 0.32. Here is the revised table of estimated exponents of velocity.

	egg Baldar	UHMW	All
Estimated exponent of velocity	2.12	2.03	2.08

Table 4

The conclusion in section 9, "Revisiting adjusted impact as a function of velocity", was that the exponent of velocity was 2.0. Is that value different from the values for the two independent data points, those for egg Baldar bolts and for UHMW bolts? No, the difference is not statistically significant (t-test, $0.5<P$). Accordingly we are still justified in considering that the kinetic energy of the bolt is a good predictor of impact.

- The measured kinetic energy plus the time correction plus combining both types of bolt plus adjusting for the speculative UHMW bolt flight behaviour would account for 95% of the statistical variance in the adjusted impact data.

If we then repeat the process of section 10, comparing specific impacts, we find that the UHMW bolts might deliver 15% more 'thwack' per unit of kinetic energy than the egg Baldar bolts at a range of 20 feet. The difference between the specific impacts of the two types of bolt would then be statistically significant (paired t-test, $P< 0.001$).

What effect would the speculative adjustment of some UHMW bolts for flight behaviour have on the analysis of impact and inch pound values in section 14, "Impact and inch pound values"?

Here is a graph of average impact for all bolts combined, adjusted for UHMW flight behaviour, divided by the inch pound value for each crossbow, normalised.

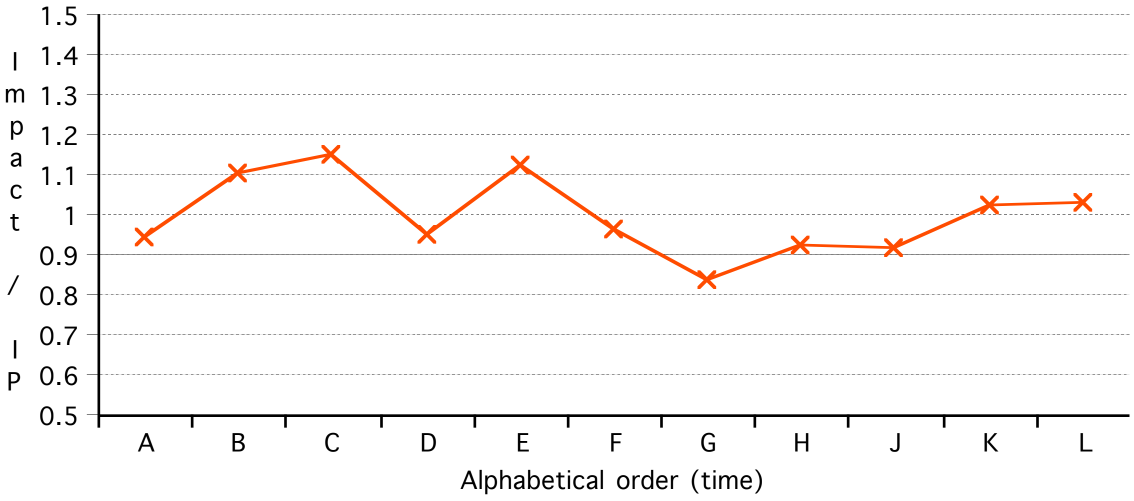

Figure 12

The inch pound value would now account for 83% of the statistical variance in the adjusted impact data, an improvement of 2%.

Here is a graph of average impact for all bolts combined, adjusted for UHMW flight behaviour, divided by the inch pound value times the efficiency for each crossbow, normalised.

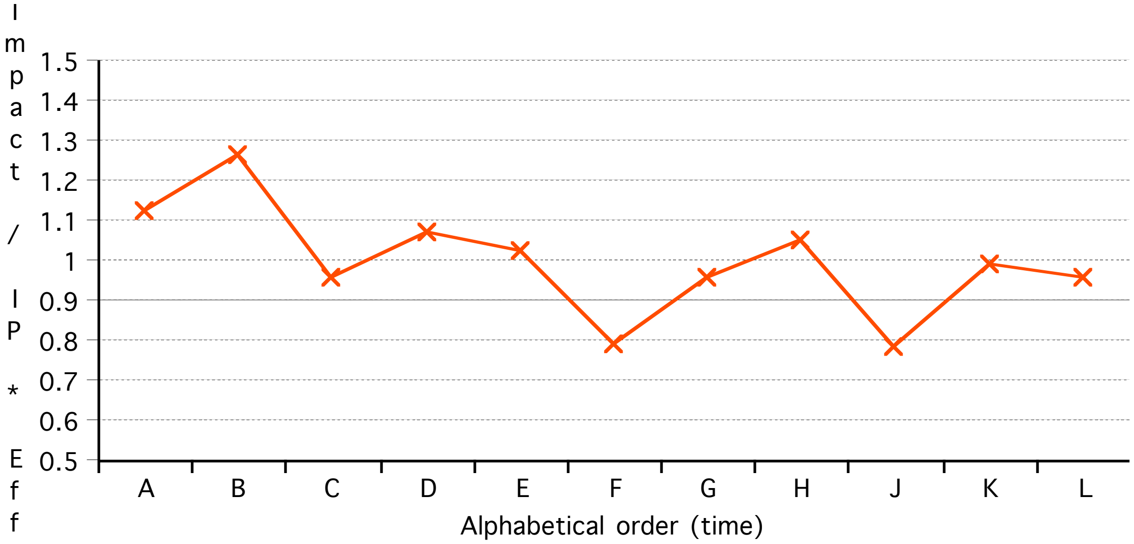

Figure 13

The inch pound value times the efficiency would now account for 66% of the statistical variance in the adjusted impact data, an improvement of 1%.

17) A comparison with the sample bow:

The sample bow (i.e. not a crossbow) is described as being 27 pounds at 28 inches, with a brace height of 6.5 inches and a bow depth of 0.5 inches, firing a Markland blunt on a 1/4 inch fibreglass shaft, and with an APD. The arrow weighed 3.3 ounces (93.55 grams).

The reason for using a sample bow as a standard for comparison is that in the SCA the impact of an arrow fired from a bow is thought to be understood and acceptable.

The power stroke for this bow is 21 inches, so the inch pound value for this bow is 567. Not enough data are available to calculate the effective mass of this bow, so we will assume a mid-range effective mass (for bows) of 12 grams and see where this takes us.

For this arrow and this effective mass, the bow would have an efficiency of 86% and would launch the arrow with a velocity of 23.1 m/s (75.7 fps).

If this arrow had a specific impact equal to the average time corrected specific impact of the test bolts, then we could predict that it would have an impact on the adjusted impact scale of 169. This would be equivalent to an impact of 5.5 on the original unadjusted impact scale.

Compared to an arrow fired from a maximum energy SCA legal bow, which would by definition have an impact of 200 on the adjusted scale, the arrow from the sample bow would be predicted to have an impact on the adjusted scale of 172. It may be just a coincidence that the adjusted impact is almost equal when calculated using these two completely independent methods.

These calculations do not explain the difference between the unadjusted impact of 4 that the targets were instructed to assign to the arrow, and the unadjusted impact of 5.5 that we have just calculated.

There might be many explanations for this difference. The Markland blunt might be significantly 'softer' than either the egg Baldar or the UHMW blunts; the Markland blunt might have a significantly larger impact area; or the Markland arrow might have significantly higher drag.

There is a small effect that is a function of the length of the shaft and the velocity of sound within the shaft which might increase bolt impact by 0%-10% relative to the impact from an arrow with the same kinetic energy and the same blunt. This effect is not large enough on its own to account for all of the reported difference, but could make a contribution to it.

There is the possibility that the increased flex of an arrow shaft may somehow dissipate more energy during impact than the lesser flex of a bolt shaft, though the small amount of energy that it takes to simply flex the arrow shaft (much less than 1% of the total kinetic energy) is not enough on its own to account for any of the difference.

As a comparison, the overall average unadjusted impact measured for the crossbows was 4.6. We can use the average inch pound value (compared to an 'ideal' 630) times the average efficiency (compared to an 'ideal' 90%) to predict a theoretical overall average unadjusted impact for the crossbows of 4.8.

18) Directions for possible future testing and analysis:

A direct comparison using a number of bolts from a number of crossbows, and a number of arrows from a number of bows, using Siegfried's technique as described in section 22, "Appendix", would allow us to compare bolts and arrows in a way that is not currently possible.

Velocity measurements taken by shooting through two chronographs in succession, one situated at point blank range as in Siegfried's testing, and one situated at a range of 20 feet, would allow us to determine whether or not drag does in fact account for any significant proportion of the remaining statistical variance in the impact data.

There is one final anomaly to discuss. In Figures 4 and 10 the specific impacts of bolts from crossbow L seem high. Also, the specific impacts of UHMW bolts from crossbow K also seem high. These are the last three bolt / crossbow combinations shot. Either the impacts were being reported higher for these combinations, or the velocities were being measured lower. Despite following several analytical leads, I have been unable to find any evidence supporting either possibility. The anomaly remains a puzzle.

19) References:

There are a number of sources that cover the physics and mathematics of bows. The one used here is the appendix from:

Hardy, Robert. *Longbow*. 3rd ed. Bois d'arc: London, 1992.

I am also indebted to three other sources:

Prescott, John R (Professor Emeritus). Personal communications. 2004-2005.

Seely, R.J. et al. "Demonstrating the Consistency of Small Data Sets". BioPharm International (2003 May). Online: http://www.biopharm-mag.com/biopharm/article/articleDetail.jsp?id=58166

van Doorn, Sir Pieter. "A Survey of Blow Calibration Standards in the Combat of the Society for Creative Anachronism". Private publication. 1991.

I reference a short article of my own:

Prescott, James. "The 630 inch-pound rule for crossbows." Private publication. 1992.
(http://www.telusplanet.net/public/prescotj/data/archery/inchpound.html)

20) Equations:

Momentum is $I = mv$

Kinetic energy is $E = \frac{1}{2}mv^2$

If the kinetic energy in the bolt is e, the mass of the bolt is m, the effective mass (sometimes called the virtual weight) of the crossbow is M, and the work done drawing the crossbow is W, then

$$e = \left(\frac{m}{m + M}\right)W$$

Since we know the velocity (v) and mass (m) of two different bolts, and since W is constant and M is constant (to a first approximation), we can solve equations (1) and (2) below for the effective mass M, giving equation (3).

$$\frac{1}{2}m_1v_1^2 = \left(\frac{m_1}{m_1 + M}\right)W \qquad (1)$$

$$\frac{1}{2}m_2v_2^2 = \left(\frac{m_2}{m_2 + M}\right)W \qquad (2)$$

$$M = \frac{m_2v_2^2 - m_1v_1^2}{v_1^2 - v_2^2} \qquad (3)$$

The efficiency of a crossbow for a particular bolt is then simply

$$\left(\frac{m}{m + M}\right)$$

The crossbow energy E, the total amount of energy released by the crossbow during firing, is then

$$E = \frac{1}{2}(m + M)v^2$$

The crossbow energy will be the same for both bolts.

When a bolt strikes its target at an angle, its velocity along its direction of travel can be resolved into two components, one along the shaft of the bolt and one at right angles to the shaft of the bolt. The component along the shaft of the bolt contributes to the perceived impact. The component at right angles to the shaft of the bolt, acting through the centre of rotational inertia, contributes to rotation of the shaft about the point of impact, and does not contribute to the perceived impact.

James Prescott, Calgary, 2003-June-11
Minor amendments 2004-January-16
Major revision 2004-June-12
Minor revision 2005-November-02

21) Additional notes for the Appendix:

Here are some additional notes regarding the measurements, extracted from emails written by Siegfried.

"Egg Baldars resist radar *grin*. Something about their shape makes them hard for the prochrono to pick up on. The UHMW, no matter the speed, ALWAYS registered. I never had one that didn't. The Baldars would consistantly/annoyingly not register, and require reshoots many times to get it to register."

"The order of the shooting, was by the crossbows letters. In more specifics, the first three crossbows were rotated through each person (in order), so A at A, B at A, C at A, repeat against target B & C. Then, crossbows D through L (all the rest) were shot at target A (he had to leave early). Then D-G were shot at targets B & C. At this point, Target D showed up. Target D was then shot with A-G to bring him 'up to speed'. Crossbows H-L were then shot at B, C, and D in that order."

22) Appendix (data originally at <http://crossbows.biz/xbowtest>):

- The Procedure
- The Initial Thoughts
- The Matrixed Results
- The Raw Data

Major thanks to Baron Konrad, Lord Lywellyn, Lord Aedden, and Lord Eoghan for letting me shoot them, alot, with high powered crossbows. Also thanks to Lord Gorm, Lord Eoghan, Lord Aedden, Baron Konrad, and THL Nikolai for loaning crossbows to the cause.

The Procedures

The following is a complete documentation of the procedures used for conducting this test

The Ammo

The ammo used in this test was made exactly identical, and with easily findable materials, so that it could be reproduced by anyway, anywhere, easily. Each type of ammo (Baldar/UHMW) was preproduced for 10 bolts worth, making 20 bolts total in the test. Some of the construction methods were exactly the same for both of them. Both had 1/4" fiberglass shafts, as bought from Northstar Archery. They were cut to be 20" long, to accomodate crossbows with long shelves. All had Siloflex APDs, as produced again by Northstar Archery. These are 160 PSI APDs, with a routed channel, straight cut. The mounting details will follow. Finally, all were covered, as required, with a longitudinal piece of strapping tape, 3M brand, 1" wide.

The Mounting: APDs

- Materials:

- Strapping Tape, 3M brand, 1" wide
- APD from Northstar Archery

- Method:

- APD was placed on shaft, EXACTLY 1/2" from end
- An 8" piece of strapping tape was used for the 'through' wrap
- A 13" piece of stapping tape was used to do the 'around' wrap

The Mounting: Baldar

- Materials:

- Egg Baldar, unmodified
- Strapping Tape, 3M brand, 1" wide
- Electrical Tape, Duck Brand, 3/4" wide
- Gel Super Glue, 3M brand

- Method:

- 2 drops of Super Glue were placed inside the Baldar
- Baldar was placed onto shaft, and fired at half/draw from a 30# bow to seat it (The APD works like a nock for this)
- An 8" piece of Electical Tape was used to wrap the base
- An 8" piece of Strapping Tape - half width, was used to go over the blunt and onto the shaft
- A 4" piece of Strapping Tape was used to anchor the previous piece.

The Mounting: UHMW

- Materials:

- Tapered UHMW Blunt, as manufacturered by Sun Lu-shan
- Strapping Tape, 3M brand, 1" wide
- Blue Closed Cell Foam Camping Mat, 3/8" thick, Wal-Mart

- Method:

- Blunt was placed onto shaft
- 2, 8" pieces of Strapping Tape - half width, were 'X'd across the top of the blunt, and down the shaft
- A 4" piece of strapping tape was used to anchor these
- 2 disks of blue foam were cut from the camping pad, using a 1.5" hole saw, running backwards, in a power drill. Making slightly larger than 1.25" disks (around 1 3/8").
- These disks were placed on top of the blunt.
- 4, 8" pieces of Strapping Tape - half width, were 'Compass Star'd across the top of the foam, and down the shaft, to almost completely cover the foam. The foam was minimally compressed during this stage.
- A 4" piece of strapping tape was used to anchor these.
- A 6" piece of strapping tape was wrapped around the side of the foam & blunt to compress/contain the foam sideways.

The Crossbow Data Gathering

The night before the testing, I took all measurements of the crossbows, except for draw weight, and recorded all the data. All data was recorded to 1/16" accuracy, except for string thickness, which went down to 1/32" accuracy out of necessity. All measurements are in inches. On the day of the testing, I measured each crossbows draw weight with a bow scale, and checked my bow scales accuracy with another person's bow scale. (They measured the same by about a pound, so I went with mine). It was determined that 3 of the crossbows there that day were over legal limits, but that this was acceptable, and perhaps even desirable for the testing, (plus we didn't want to play with the string length/etc to try to get them legal at the last minute after already doing all the measuring). Theorectically, these ones should definately be hitting 'too hard'

The Shooting

When it came time to shoot, everything was handled as follows. A pavise was set up between the fighter, and myself, with the chronograph on a tripod behind the pavise. It was designed so that the fighter was 20ft away from where I stood to fire the crossbow, 5ft beyond minimum, and a common broken field/bridge battle shooting distance. The chrono was strategically placed to be far enough that the bolt would have left the bow from even the longest crossbow I was shooting. Every shot was sent through the chrono, to then impact the fighter. The fighter would call the shot on a 1-7 scale of 'ouchiness'. The FPS, and the scale, would be recorded. If there was any problem with the chrono, or the shot in general, it would be redone (to the fighter's chagrin). It was discovered that Baldar Eggs are hard to chronograph, and often would not read.

All shots had to land on the 'torso' to count. A couple hit arm, helm, or crotch (sorry!) and were redone. The reason for this, is that I was trying to 'mix up' where the shots would land, partially, to keep the fighter from getting sore in any one spot, and also to get them registering across the torso in different areas. Each fighter was shot three times with each ammo, from each bow. Making 6 shots from each bow at them. Before each round of shooting, they would be shot by the 'sample case'. This was a 27lb fiberglass recurve at 28", and has a 6.5" brace height. The ammo used were 1/4" fiberglass shafted, Siloflex APD, Markland headed arrows. (It's what I had laying around)

The impact testers were instructed to take the shots from the bow as a '4', an average hit, and then to rate each hit on the following scale:

1. Feather hit, "I barely felt it at all"
2. Light hit, "So light that I might not notice it in battle"
3. Soft hit, "A little light, but no problem feeling it."
4. Average hit, "What I expect."
5. Solid hit, "Solid, but no problem"
6. Hard hit, "Ooof, Not excessive, but I wouldn't every shot that way."
7. Excessive hit, "If you hit me with that again! I'll ..."

Thoughts/Anecdotes/Initial response to testing

Ok, following is just a list of things that were noticed in the testing, and immediately afterwards:

- Make sure to adjust your point of aim when switching from a 586"# crossbow to a 346"# crossbow, lest you shoot a friend in the cup.
- The crossbow that everyone was 'afriad of' after a few shots from it (K), was not the highest poundage, or in-lb crossbow on the field. Nor was it rated the highest in average impact rating. It did however, score a number of 7's
- The crossbow with the highest poundage, which noone was 'afriad of', actually in the end had the highest impact rating, even though it never had a 7, and noone complained about it (versus others)
- Pure poundage alone as a limiting factor, as Trimaris/etc has been doing, is obviously flawed, as a 43# crossbow was rated as the 3rd hardest hitting
- In general, all the crossbows were hitting harder than the test arrow. Only the two VERY underpowered bows didn't, and they were only rated slightly on the lighter side on the average.
- In general, bolts catching the edge of plates of armor, or off the armor, caused ouchies. There was a very big difference. It was noted by a numer of the targets, that the bolts were hitting holes in their armor that a sword couldn't. Because they were hitting gaps between plates/etc where a sword would have contacted across the two plates, and this bolt instead went right between them.

ORDER OF SHOOTING:

The order of shooting was Baldars then UHMWs within each bow/target combination.
Person A crossbows A, B, C

Person B crossbows A, B, C
Person C crossbows A, B, C
Person A crossbows D, E, F, G, H, J, K, L
Person B crossbows D, E, F, G
Person C crossbows D, E, F, G
Person D crossbows A, B, C, D, E, F, G
Person B crossbows H, J, K, L
Person C crossbows H, J, K, L
Person D crossbows H, J, K, L

Thwack-Level results (Sorted by Crossbow)

Crossbow	**Draw Weight**	**in-lb**	**Average Baldar FPS**	**Average UHMW FPS**	**Average Overall FPS**	**Average Thwack Baldar**	**Average Thwack UHMW**	**Average Thwack Overall**
A	76	717.25	79.92	86.08	83.00	5.42	4.92	5.17
B	73	597.6875	80.25	86.67	83.46	5.08	4.92	5.00
C	92	586.5	84.75	94.00	89.38	5.50	5.83	5.67
D	43	346.6875	59.67	64.50	62.08	3.00	3.58	3.29
E	65	524.0625	79.42	87.50	83.46	4.75	4.58	4.67
F	64	560	76.17	84.25	80.21	4.67	4.17	4.42
G	48	396	62.42	67.42	64.92	3.33	3.33	3.33
H	46	635.375	87.58	94.67	91.13	4.67	5.08	4.88
J	76	584.25	83.17	92.25	87.71	4.58	4.25	4.42
K	71	656.75	91.83	100.58	96.21	5.00	5.58	5.29
L	64	572	81.92	90.08	86.00	4.92	5.00	4.96

Thwack-Level results (Sorted by Draw Weight)

Crossbow	**Draw Weight**	**in-lb**	**Average Baldar FPS**	**Average UHMW FPS**	**Average Overall FPS**	**Average Thwack Baldar**	**Average Thwack UHMW**	**Average Thwack Overall**
C	92	586.5	84.75	94.00	89.38	5.50	5.83	5.67
A	76	717.25	79.92	86.08	83.00	5.42	4.92	5.17
J	76	584.25	83.17	92.25	87.71	4.58	4.25	4.42
B	73	597.6875	80.25	86.67	83.46	5.08	4.92	5.00
K	71	656.75	91.83	100.58	96.21	5.00	5.58	5.29
E	65	524.0625	79.42	87.50	83.46	4.75	4.58	4.67
L	64	572	81.92	90.08	86.00	4.92	5.00	4.96
F	64	560	76.17	84.25	80.21	4.67	4.17	4.42
G	48	396	62.42	67.42	64.92	3.33	3.33	3.33
H	46	635.375	87.58	94.67	91.13	4.67	5.08	4.88
D	43	346.6875	59.67	64.50	62.08	3.00	3.58	3.29

Thwack-Level results (Sorted by Inch-Pounds)

Crossbow

	Draw Weight	**in-lb**	**Average Baldar FPS**	**Average UHMW FPS**	**Average Overall FPS**	**Average Thwack Baldar**	**Average Thwack UHMW**	**Average Thwack Overall**
A	76	717.25	79.92	86.08	83.00	5.42	4.92	5.17
K	71	656.75	91.83	100.58	96.21	5.00	5.58	5.29
H	46	635.375	87.58	94.67	91.13	4.67	5.08	4.88
B	73	597.6875	80.25	86.67	83.46	5.08	4.92	5.00
C	92	586.5	84.75	94.00	89.38	5.50	5.83	5.67
J	76	584.25	83.17	92.25	87.71	4.58	4.25	4.42
L	64	572	81.92	90.08	86.00	4.92	5.00	4.96
F	64	560	76.17	84.25	80.21	4.67	4.17	4.42
E	65	524.0625	79.42	87.50	83.46	4.75	4.58	4.67
G	48	396	62.42	67.42	64.92	3.33	3.33	3.33
D	43	346.6875	59.67	64.50	62.08	3.00	3.58	3.29

Thwack-Level results (Sorted by Average Baldar FPS)

Crossbow	**Draw Weight**	**in-lb**	**Average Baldar FPS**	**Average UHMW FPS**	**Average Overall FPS**	**Average Thwack Baldar**	**Average Thwack UHMW**	**Average Thwack Overall**
K	71	656.75	91.83	100.58	96.21	5.00	5.58	5.29
H	46	635.375	87.58	94.67	91.13	4.67	5.08	4.88
C	92	586.5	84.75	94.00	89.38	5.50	5.83	5.67
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L	64	572	81.92	90.08	86.00	4.92	5.00	4.96
B	73	597.6875	80.25	86.67	83.46	5.08	4.92	5.00
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F	64	560	76.17	84.25	80.21	4.67	4.17	4.42
G	48	396	62.42	67.42	64.92	3.33	3.33	3.33
D	43	346.6875	59.67	64.50	62.08	3.00	3.58	3.29

Thwack-Level results (Sorted by Average UHMW FPS)

Crossbow	**Draw Weight**	**in-lb**	**Average Baldar FPS**	**Average UHMW FPS**	**Average Overall FPS**	**Average Thwack Baldar**	**Average Thwack UHMW**	**Average Thwack Overall**
K	71	656.75	91.83	100.58	96.21	5.00	5.58	5.29
H	46	635.375	87.58	94.67	91.13	4.67	5.08	4.88
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B	73	597.6875	80.25	86.67	83.46	5.08	4.92	5.00
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F	64	560	76.17	84.25	80.21	4.67	4.17	4.42
G	48	396	62.42	67.42	64.92	3.33	3.33	3.33
D	43	346.6875	59.67	64.50	62.08	3.00	3.58	3.29

Thwack-Level results (Sorted by Average Overall FPS)

Crossbow	**Draw Weight**	**in-lb**	**Average Baldar FPS**	**Average UHMW FPS**	**Average Overall FPS**	**Average Thwack Baldar**	**Average Thwack UHMW**	**Average Thwack Overall**
K	71	656.75	91.83	100.58	96.21	5.00	5.58	5.29
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E	65	524.0625	79.42	87.50	83.46	4.75	4.58	4.67
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F	64	560	76.17	84.25	80.21	4.67	4.17	4.42
G	48	396	62.42	67.42	64.92	3.33	3.33	3.33
D	43	346.6875	59.67	64.50	62.08	3.00	3.58	3.29

Thwack-Level results (Sorted by Average Baldar Thwack)

Crossbow	**Draw Weight**	**in-lb**	**Average Baldar FPS**	**Average UHMW FPS**	**Average Overall FPS**	**Average Thwack Baldar**	**Average Thwack UHMW**	**Average Thwack Overall**
C	92	586.5	84.75	94.00	89.38	5.50	5.83	5.67
A	76	717.25	79.92	86.08	83.00	5.42	4.92	5.17
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G	48	396	62.42	67.42	64.92	3.33	3.33	3.33
D	43	346.6875	59.67	64.50	62.08	3.00	3.58	3.29

Thwack-Level results (Sorted by Average UHMW Thwack)

Crossbow	**Draw Weight**	**in-lb**

			Average Baldar FPS	Average UHMW FPS	Average Overall FPS	Average Thwack Baldar	Average Thwack UHMW	Average Thwack Overall
C	92	586.5	84.75	94.00	89.38	5.50	5.83	5.67
K	71	656.75	91.83	100.58	96.21	5.00	5.58	5.29
H	46	635.375	87.58	94.67	91.13	4.67	5.08	4.88
L	64	572	81.92	90.08	86.00	4.92	5.00	4.96
B	73	597.6875	80.25	86.67	83.46	5.08	4.92	5.00
A	76	717.25	79.92	86.08	83.00	5.42	4.92	5.17
E	65	524.0625	79.42	87.50	83.46	4.75	4.58	4.67
J	76	584.25	83.17	92.25	87.71	4.58	4.25	4.42
F	64	560	76.17	84.25	80.21	4.67	4.17	4.42
D	43	346.6875	59.67	64.50	62.08	3.00	3.58	3.29
G	48	396	62.42	67.42	64.92	3.33	3.33	3.33

Thwack-Level results (Sorted by Average Overall Thwack)

Crossbow	**Draw Weight**	**in-lb**	**Average Baldar FPS**	**Average UHMW FPS**	**Average Overall FPS**	**Average Thwack Baldar**	**Average Thwack UHMW**	**Average Thwack Overall**
C	92	586.5	84.75	94.00	89.38	5.50	5.83	5.67
K	71	656.75	91.83	100.58	96.21	5.00	5.58	5.29
A	76	717.25	79.92	86.08	83.00	5.42	4.92	5.17
B	73	597.6875	80.25	86.67	83.46	5.08	4.92	5.00
L	64	572	81.92	90.08	86.00	4.92	5.00	4.96
H	46	635.375	87.58	94.67	91.13	4.67	5.08	4.88
E	65	524.0625	79.42	87.50	83.46	4.75	4.58	4.67
J	76	584.25	83.17	92.25	87.71	4.58	4.25	4.42
F	64	560	76.17	84.25	80.21	4.67	4.17	4.42
G	48	396	62.42	67.42	64.92	3.33	3.33	3.33
D	43	346.6875	59.67	64.50	62.08	3.00	3.58	3.29

Crossbow Data

Id	**Owner**	**Maker**	**Weight**	**Brace Height**	**Power Stroke**	**in-lbs**	**Release**
A	Eoghan	Meric	76	2 3/16	9 7/16	717.25	Nut
B	Siegfried	Siegfried	73	3 1/4	8 3/16	597.6875	Lever Notch
C	Siegfried	Siegfried	92	3 9/16	6 3/8	586.5	Lever Notch
D	Gorm	???	43	3 11/16	8 1/16	346.6875	Lever Notch
E	Siegfried	Siegfried	65	2 15/16	8 1/16	524.0625	Lever Notch
F	Siegfried	Siegfried	64	3	8 3/4	560	Lever Notch
G	Gorm	???	48	3 5/8	8 1/4	396	Lever Notch
H	Siegfried	(Pennsic Kit)	46	4	13 13/16	635.375	Post Removal
J	Aeddan	Siegfried	76	3 9/16	7 11/16	584.25	Lever Notch
K	Konrad	Iolo	71	3 1/8	9 1/4	656.75	Nut
L	Nikolai	Iolo	64	3 1/8	8 15/16	572	Nut

Id	**Prod Material**	**Prod Style**	**Prod Length**	**Prod Thickness**	**Stock**
A	Steel	Recurved	24 3/4	1/8	

B	Steel (Gladius)	Reflex	27 5/8	3/16
C	Fiberglass (Hou-Shigh)	Recurved	27	3/8
D	Fiberglass	Straight	25 1/4	3/16
E	Fiberglass (Power-Tuff)	Straight	27 7/8	1/4
F	Fiberglass (Sheet)	Straight	23 1/8	1/4
G	Fiberglass	Straight	24 1/8	3/16
H	Fiberglass (Dual electric fence posts)	Straight	35 1/2	3/8
J	Steel (Gladius)	Reflex	27 5/8	3/16
K	Aluminum	Reflex	27 7/8	3/16
L	Aluminum	Recurved	27 5/8	3/16

Id	**Prod Thickness Tips**	**Prod Width Stock**	**Prod Width Tips**	**Shelf Drag**
A	1/8	1 5/8	11/16	3/8
B	3/16	1 3/16	1/2	1/2
C	1/4	15/16	3/4	1/8
D	3/16	1 3/16	1 3/16	11/16
E	1/4	1 1/4	1 1/4	9/16
F	1/4	1 3/16	1 3/16	5/8
G	3/16	1 3/16	1 3/16	5/8
H	3/8	3/4	3/4	5/16
J	3/16	1 1/8	1/2	1/16
K	3/16	1 5/8	3/4	5/16
L	3/16	1 5/8	5/8	0

Id	**String Material**	**String Thickness**	**String Length**
A	Dacron	3/16	27 3/4
B	Dacron	1/8	27
C	Dacron	3/16	25 1/2
D	Dacron	1/8	23 3/4
E	Dacron	1/8	27
F	Dacron	1/8	22 1/8
G	Dacron	1/8	22 5/8
H	Dacron	3/32	34 1/4
J	Dacron	3/16	26 3/4
K	Dacron	3/16	27
L	Artifical Sinew	3/16	26 3/4

Tester Data

Id	**Name**	**Weight**	**Armor**	**History**
A	Eoghan	255	Dark Victory Barrell Plastic Scale Armor, covered in leather, thick gambeson underneath	Combat Archer only - 2 years
B	Konrad	260	Thin Plastic, Lorica style, foam underneath	Heavy Fighter - 16 years
C	Aeddan	210	Plastic coat of plates, thin gambeson under, thick aketon over	Combat Archer 4 years, Heavy Fighter 2 yrs
D	Llywelyn	325	Steel coat of plates, attached to thin gambeson	Heavy Fighter - 27 years

Shot Data - Crossbow A

CId	**TId**	**Ammo**	**Impact**	**FPS**	**Comments**
A	A	B	5	81	
A	A	B	5	81	
A	A	B	5	80	
A	A	U	5	87	

A	A	U	5	86	
A	A	U	4	87	
A	B	B	5	80	
A	B	B	6	80	
A	B	B	4	80	
A	B	U	5	87	
A	B	U	5	86	
A	B	U	5	85	
A	C	B	6	80	
A	C	B	6	80	
A	C	B	7	79	
A	C	U	5	86	
A	C	U	5	85	
A	C	U	4	85	
A	D	B	5	80	
A	D	B	6	79	
A	D	B	5	79	
A	D	U	7	86	Hit off edge of steel plate
A	D	U	5	87	
A	D	U	4	86	

Shot Data – Crossbow B

CId	**TId**	**Ammo**	**Impact**	**FPS**	**Comments**
B	A	B	6	81	
B	A	B	6	82	
B	A	B	5	81	
B	A	U	5	87	
B	A	U	5	87	
B	A	U	5	86	
B	B	B	6	80	
B	B	B	5	80	
B	B	B	4	79	
B	B	U	5	87	
B	B	U	5	86	
B	B	U	5	87	
B	C	B	5	80	
B	C	B	5	80	
B	C	B	5	80	
B	C	U	5	86	
B	C	U	5	87	
B	C	U	5	87	
B	D	B	4	80	
B	D	B	5	80	
B	D	B	5	80	
B	D	U	5	86	
B	D	U	4	87	
B	D	U	5	87	

Shot Data – Crossbow C

CId	**TId**	**Ammo**	**Impact**	**FPS**	**Comments**
C	A	B	6	85	
C	A	B	6	85	
C	A	B	5	87	
C	A	U	6	93	
C	A	U	6	96	
C	A	U	6	94	

C	B	B	5	84	
C	B	B	6	85	
C	B	B	6	85	
C	B	U	6	93	
C	B	U	6	93	
C	B	U	6	94	
C	C	B	6	84	Bolt flipping slightly sideways
C	C	B	5	84	Bolt flipping slightly sideways
C	C	B	5	84	Bolt flipping slightly sideways
C	C	U	6	95	
C	C	U	5	94	
C	C	U	5	94	
C	D	B	5	85	
C	D	B	5	84	
C	D	B	6	85	
C	D	U	6	95	
C	D	U	6	94	
C	D	U	6	93	

Shot Data – Crossbow D

CId	**TId**	**Ammo**	**Impact**	**FPS**	**Comments**
D	A	B	3	60	
D	A	B	2	60	
D	A	B	3	60	
D	A	U	3	65	
D	A	U	3	65	
D	A	U	3	65	
D	B	B	3	60	
D	B	B	3	60	
D	B	B	2	60	
D	B	U	3	65	
D	B	U	3	65	
D	B	U	4	64	
D	C	B	3	60	
D	C	B	4	59	
D	C	B	3	60	
D	C	U	4	65	
D	C	U	4	64	
D	C	U	4	65	
D	D	B	3	59	
D	D	B	3	59	
D	D	B	4	59	
D	D	U	4	64	
D	D	U	4	64	
D	D	U	4	63	

Shot Data – Crossbow E

CId	**TId**	**Ammo**	**Impact**	**FPS**	**Comments**
E	A	B	4	81	
E	A	B	4	79	
E	A	B	4	80	
E	A	U	4	88	
E	A	U	4	89	
E	A	U	4	86	
E	B	B	5	79	
E	B	B	5	78	

E	B	B	5	80
E	B	U	5	88
E	B	U	5	88
E	B	U	6	87
E	C	B	5	79
E	C	B	5	79
E	C	B	5	80
E	C	U	4	87
E	C	U	4	86
E	C	U	4	88
E	D	B	5	80
E	D	B	5	79
E	D	B	5	79
E	D	U	5	88
E	D	U	5	86
E	D	U	5	89

Shot Data – Crossbow F

CId	**TId**	**Ammo**	**Impact**	**FPS**	**Comments**
F	A	B	5	77	
F	A	B	4	77	
F	A	B	4	77	
F	A	U	4	84	
F	A	U	4	85	
F	A	U	5	85	
F	B	B	5	77	
F	B	B	5	77	
F	B	B	6	75	
F	B	U	4	78	
F	B	U	4	85	
F	B	U	4	86	
F	C	B	5	77	
F	C	B	4	74	
F	C	B	5	76	
F	C	U	5	85	
F	C	U	4	85	
F	C	U	4	84	
F	D	B	5	75	
F	D	B	4	75	
F	D	B	4	77	
F	D	U	4	84	
F	D	U	4	85	
F	D	U	4	85	

Shot Data – Crossbow G

CId	**TId**	**Ammo**	**Impact**	**FPS**	**Comments**
G	A	B	3	62	
G	A	B	4	63	
G	A	B	3	63	
G	A	U	4	67	
G	A	U	4	68	
G	A	U	3	69	
G	B	B	3	63	
G	B	B	3	63	
G	B	B	3	62	
G	B	U	3	66	

G	B	U	4	67	
G	B	U	3	67	
G	C	B	3	62	
G	C	B	3	61	
G	C	B	3	62	
G	C	U	3	68	
G	C	U	3	66	
G	C	U	3	68	
G	D	B	4	63	
G	D	B	4	62	
G	D	B	4	63	
G	D	U	4	66	
G	D	U	4	68	
G	D	U	2	69	Hit on Belt Knot (Thick Woven Belt)

Shot Data – Crossbow H

CId	TId	Ammo	Impact	FPS	Comments
H	A	B	4	87	
H	A	B	5	87	
H	A	B	4	87	
H	A	U	5	96	
H	A	U	5	97	
H	A	U	5	96	
H	B	B	4	88	
H	B	B	6	88	
H	B	B	6	88	
H	B	U	7	96	
H	B	U	5	93	
H	B	U	7	97	Hit above breastplate, on gorget flap
H	C	B	5	88	
H	C	B	4	86	
H	C	B	6	88	Gap in armor
H	C	U	4	92	
H	C	U	5	91	
H	C	U	4	92	
H	D	B	4	88	
H	D	B	4	88	
H	D	B	4	88	
H	D	U	4	96	
H	D	U	5	93	
H	D	U	5	97	

Shot Data – Crossbow J

CId	TId	Ammo	Impact	FPS	Comments
J	A	B	4	83	
J	A	B	4	83	
J	A	B	4	83	
J	A	U	4	91	
J	A	U	4	92	
J	A	U	4	92	
J	B	B	5	84	
J	B	B	5	83	
J	B	B	5	84	
J	B	U	5	93	
J	B	U	4	92	
J	B	U	4	93	

J	C	B	5	83	
J	C	B	5	83	
J	C	B	5	82	
J	C	U	5	93	
J	C	U	4	92	Glanced 'a little'
J	C	U	5	92	
J	D	B	4	83	
J	D	B	5	84	
J	D	B	4	83	
J	D	U	4	91	
J	D	U	4	93	
J	D	U	4	93	

Shot Data – Crossbow K

CId	**TId**	**Ammo**	**Impact**	**FPS**	**Comments**
K	A	B	6	92	
K	A	B	4	92	
K	A	B	4	92	
K	A	U	6	101	
K	A	U	5	101	
K	A	U	6	100	
K	B	B	5	91	
K	B	B	6	92	
K	B	B	6	91	
K	B	U	6	100	
K	B	U	7	99	
K	B	U	6	102	
K	C	B	6	94	
K	C	B	5	91	
K	C	B	5	92	
K	C	U	6	101	
K	C	U	6	101	
K	C	U	6	99	
K	D	B	4	92	
K	D	B	4	91	
K	D	B	5	92	
K	D	U	4	102	
K	D	U	5	100	
K	D	U	4	101	

Shot Data – Crossbow L

CId	**TId**	**Ammo**	**Impact**	**FPS**	**Comments**
L	A	B	4	82	
L	A	B	4	82	
L	A	B	4	82	
L	A	U	5	91	
L	A	U	4	91	
L	A	U	5	91	
L	B	B	5	82	
L	B	B	5	82	
L	B	B	5	81	
L	B	U	5	89	
L	B	U	4	90	
L	B	U	5	91	
L	C	B	6	82	
L	C	B	6	81	

L	C	B	5	81	
L	C	U	5	89	
L	C	U	6	90	
L	C	U	6	90	
L	D	B	4	83	
L	D	B	6	83	Gap in armor
L	D	B	5	82	
L	D	U	5	91	
L	D	U	5	89	
L	D	U	5	89	