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Spring Rod Deflection Test Report

Test subject: **Springfree Trampoline Model SF90**

Date of Test: **3 July 2009**

Date of Report: **20 Aug 2009**

Test Summary: **Tests were carried out to determine the likely force exerted on human finger by two closing spring rods on a SF90 Springfree trampoline.**

Trampoline Description

The Springfree trampoline's SoftEdge design consists of fiberglass rods laid over at an angle of 30° around the trampoline edge. The fiberglass rods are placed in sockets in the frame and to connect with the mat, the top ends of the rods have to be bent inwards towards the centre. The plastic cleats around the mat edge keep the rods in place. The force needed to bend the rods inwards is the force that keeps tension in the mat.

Test Conditions

Temperature:	≈10°C
Moisture Content:	The trampoline was tested in the received condition – it was assumed to have a moisture content that would not vary significantly with environment.
Trampoline setup:	The trampoline was tested without enclosure net, sitting on concrete floor.

Test Equipment

IOC Test Ball

The International Olympic Committee test ball was used in this test to simulate a body impacting onto the mat of the trampoline. Please see Appendix A1 for drawings and relevant information regarding the IOC test ball.

The test ball can be assembled in three mass configurations, 30, 60 and 90kg. For the spring rod deflection test, only the 30 and 60kg configurations were used.

It was understood that although the IOC test ball was able to adequately simulate the weight of a user, it did not represent the motion and impact characteristics of the user well enough. Because the IOC ball is such a concentrated mass, the energy it possesses at the instance of impact would be somewhat larger than that of a human body when dropped from the same height. This was not of concern to the results since the more concentrated mass of the IOC ball would provide a worst case scenario by overstating loads on fingers, and will give more consistent results than a human jumper.

Measurement Device

A simple mechanical coupling system was designed to model a human finger wrapped around a spring rod. This incorporated a standard S-beam load cell for the force measurement (Figure 2.1).

The design consisted of two aluminium levers pivoted through their centres (see Figure 2.1). A 250kg S-beam load cell was coupled to the larger end of the lever assembly. The circular notch in the lower lever was designed so that the whole assembly can sit over a spring rod and be clamped onto it.

The clamping end of the coupling mechanism approximately simulated the size and shape of an adult finger wrapping around a spring rod.

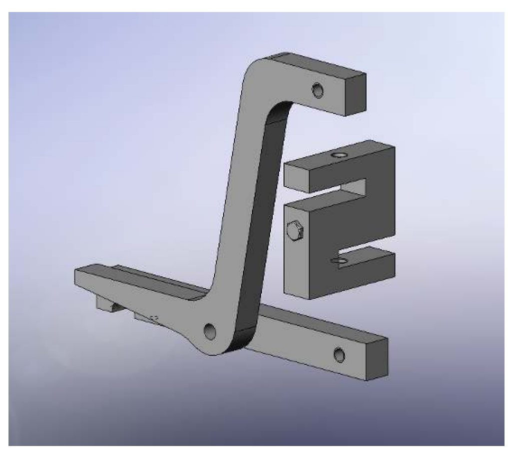

Figure 2.1 Load Cell Coupling Mechanism

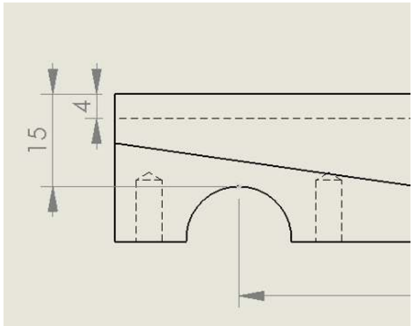

Figure 2.2 Load Cell Coupling Mechanism – Clamping end dimensions

The levers were able to accurately transmit the compressive force from the spring rods to the load cell that was on the other side of the pivot. The loading data was most accurate when the spring rods contact the levers in a normal arrangement. This gave an indication of the likely force a human finger will experience when placed in between the rods.

Please refer to Appendix A2 for detail drawings of the load cell coupling mechanism.

Data Acquisition Equipment

An instrumentation amplifier was used to amplify the signal from the S-beam load cell and a Compact DAQ module (Figure 2.3) was used to interface the amplifier to the PC.

A 4V excitation voltage was provided to the load cell by the instrumentation amplifier. The amplifier also took in the analogue output voltage produced by the load cell before amplifying it to an adequate level. The amplified signal was then fed into the DAQ module, which sampled the signal at 50kHz. The DAQ module then delivered this digitised signal to the LabView application in the computer via a USB connection.

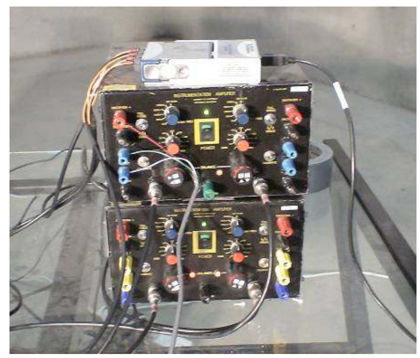

Figure 2.3 DAQ System

Test Setup

Figure 2.4 below shows the setup for the spring rod deflection test.

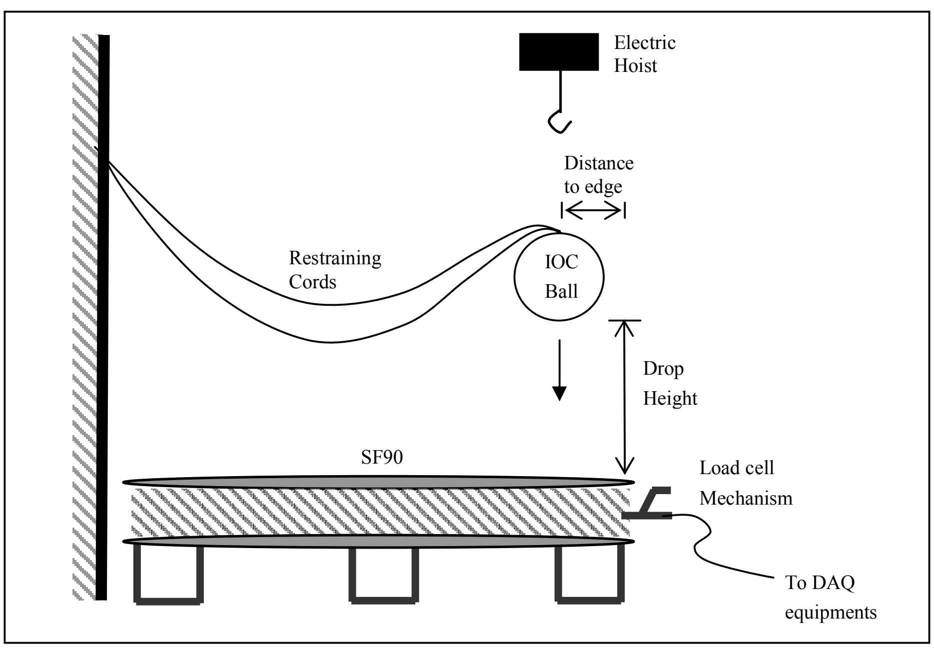

Figure 2.4 Test Setup

The SF90 Springfree trampoline was positioned under an electric hoist, which was used to adjust the height of the IOC test ball before release. The IOC test ball was restrained by three cords for safety considerations. Two of the restraining cords were attached to the wall to prevent the ball falling off the immediate edge of the trampoline. Another cord (not shown in diagram) was tied to the frame of the trampoline, near the load cell position, to prevent the ball bouncing into the wall.

A quick release mechanism was used to release the IOC test ball. Please see Appendix A3 for drawings of this mechanism.

The attachment scheme of the load cell mechanism had undergone a number of refinements during preliminary testing. Details regarding these refinements are discussed in Appendix A4. The final attachment scheme involved clamping the load cell mechanism onto the worst case scenario spring rod. The worst case scenario spring rod is the rod below the cleat that is most in line with the weave of the mat and the impact position of the IOC test ball. The load cell mechanism was tightly fastened so that it could not slip around the spring rod.

Test Method

The IOC test ball was dropped from a range of heights, at a range of distances into the SF90 Springfree trampoline. Force measurements were taken at both above cleat and mid-rod (17cm down top rod end) positions with the load cell mechanism. In particular, the above cleat position was considered the worst case scenario since at this position the spring rods undergo the most deflection.

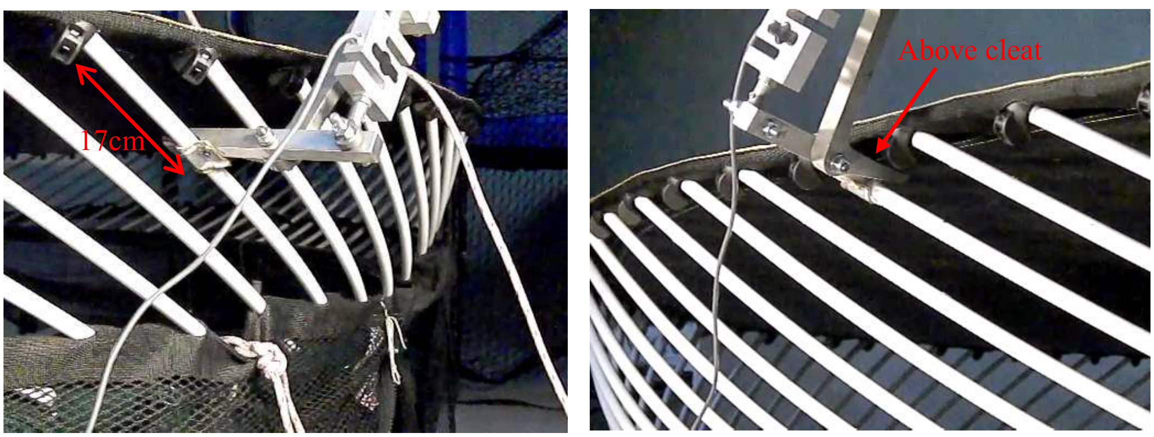

Figure 2.5 Load Cell Positions – Left: 17cm down rod end, Right: above cleat

The feasible drop height range of the test ball is different for each intended impact position. The maximum drop height that can be exercised at the edge of the trampoline (test ball just inside trampoline) was 0.5m (to the bottom of the test ball) with the 60kg test ball configuration. This is not only because it is unrealistic for a user to jump higher than 0.5m at the edge, but also because dropping the ball any higher would result in it hitting the trampoline frame. Table 2.1 shows the range of intended impact distance from trampoline edge and the range of drop heights used in testing.

Distance From Trampoline Edge (m)	**Drop Height Range**	
	60 kg	**30kg**
0.2	0.3m – 0.5m	0.3m
0.3	0.3m – 0.6m	0.3m – 0.4m
0.4	0.3m – 0.7m	0.3m – 0.5m
0.5	0.3m – 0.8m	0.3m – 0.6m

0.6	0.3m – 0.9m	0.3m – 0.7m
1.0	0.3m – 1.3m	0.3m – 1.1m

Table 2.1 Test Ranges

The impact location of the test ball was established by aligning a piece of string that was blue-tacked onto the bottom of the test ball. This was lined up with a marked intended impact point on the trampoline. See Figure 2.6.

The height of the test ball above the trampoline mat was measured using a laser tape measure. The electric hoist was used to lift up the IOC test ball as well as adjusting its height.

The orientation of the load cell mechanism was adjusted before every drop to the same angle, such that the rod above it would strike the top surface of the sensing lever normally.

To release the test ball, the string attached to the quick release mechanism was pulled. The data acquisition software simultaneously began recording the force level detected by the load cell.

The force level over the entire sampling period was saved as a text file by LabView. The test was repeated three times for each of the test conditions.

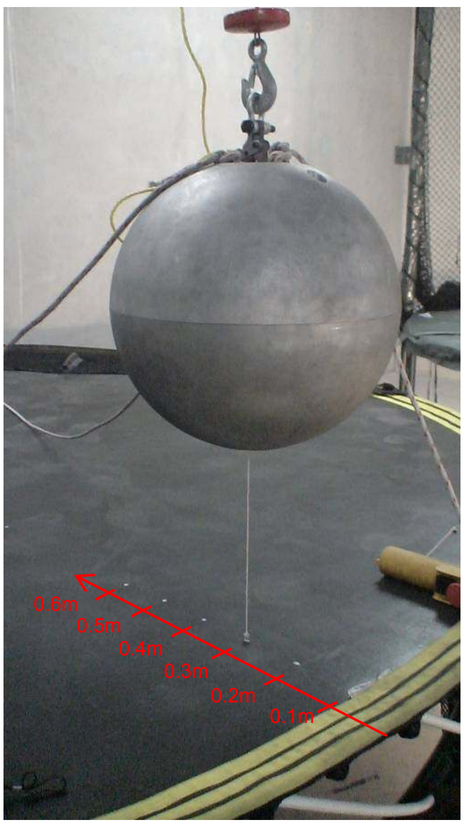

Figure 2.6 Impact location determination method

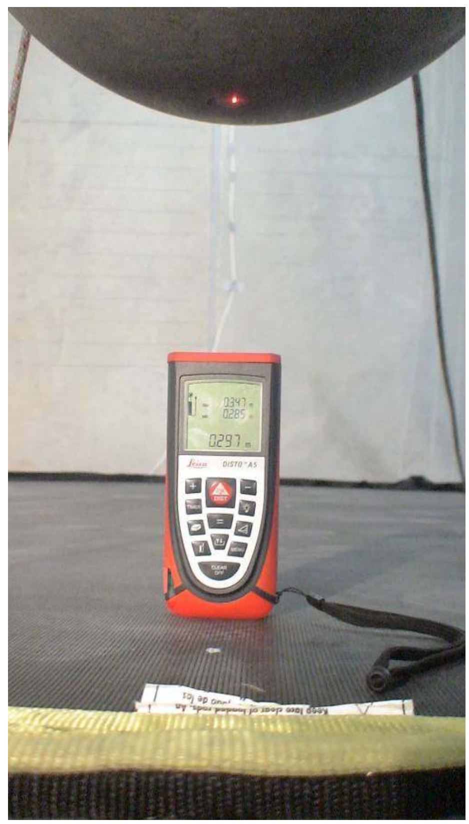

Figure 2.7 Drop Height Measurement

Load Cell Calibration

Strain gauge type load cells are generally subject to or affected by a hysteresis error [1]. In order to identify this error, the load cell mechanism was carefully calibrated by applying known masses to it; computer readouts were recorded for both the loading and unloading process.

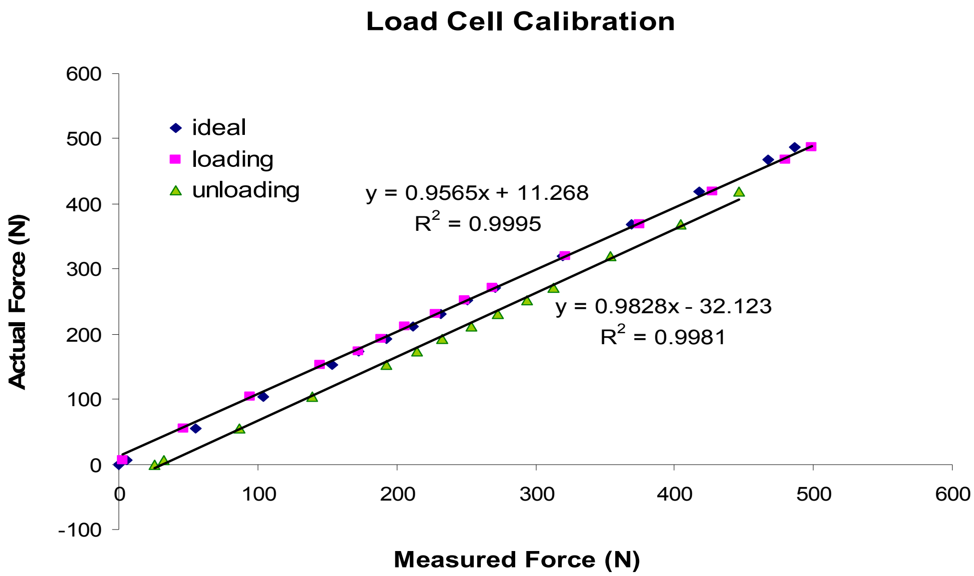

Figure 2.8 Load Cell Calibration Graph

Calibration showed that the load cell mechanism was indeed prone to hysteresis error. While the loading curve closely matched the ideal 1:1 sensitivity curve, the unloading curve was offset by a constant of 32N. A small amount of sensitivity error was also present, as shown by the trend line equations, which were used later to correct test results in post processing.

Results and Post-Processing

The raw data produced by the LabView application were in the form of text files containing the force and time information recorded during each test run. These allowed force traces similar to that shown in Figure 2.9 to be plotted.

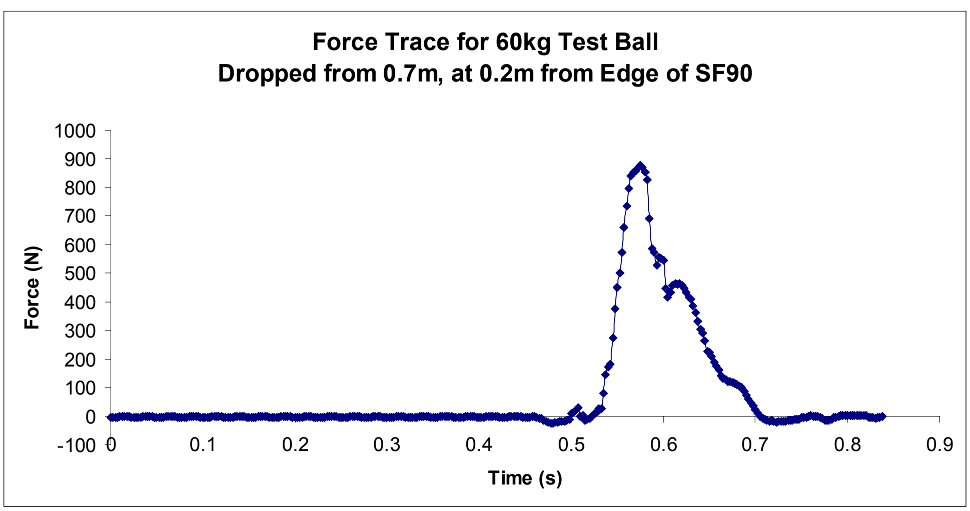

Figure 2.9 Typical Force Trace

From these force traces, the maximum force during each test drop was identified and recorded. Maximum force data from repeated tests were then averaged. To account for the sensitivity error, the results were corrected using the equation $\mathbf{Force_{corrected} = 0.9565*(Force_{Measured}) + 11.268}$, which was the trendline equation for the positive loading curve in Figure 2.8. In the context of this experiment, because only the maximum force due to positive loading was of interest, the data could be appropriately corrected using the positive loading curve only, hysteresis effect was be safely neglected.

The corrected results are tabulated in Appendix A5.

The maximum force measured out of all test runs was 1385N (138.5kg). This was for the case of a 60kg test ball weight dropped at 0.1m from the edge of the trampoline, from a height of 0.5m, shown in Figure 10. The force measurement was taken at above cleat position.

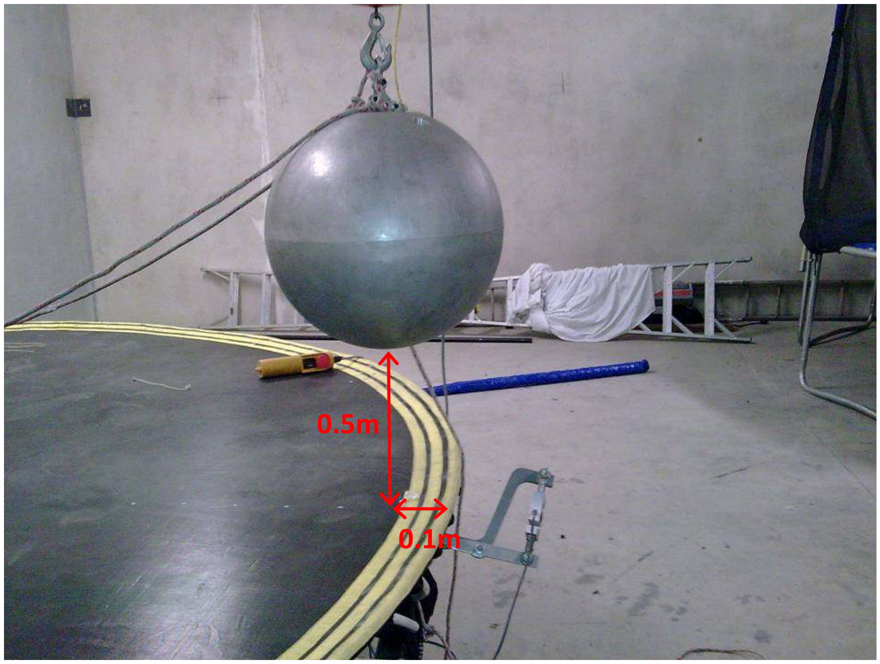

Figure 2.10 Worst case drop

When the test ball was at 0.1m from the trampoline edge, one quarter of its diameter was hanging over the edge of the trampoline. This was an unsafe operation due to the likelihood of the test ball impacting on the load cell mechanism, which was located very close to the trampoline edge. Therefore only a few drops at 0.1m had been carried out before the termination of any further testing at this position. The closest test position to the trampoline edge thereafter was 0.2m. In reality, because of the hour-glass shape of Springfree enclosure net, the closest to the edge any jumper is able to jump at would be in fact around 0.2m.

Analysis and Discussion

The following graphs present the predicted force on a bystander's finger against the distance away from the trampoline edge a jumper is jumping at. The different series in the graphs are for the different jump heights of the jumper. Each graph represents a different combination of jumper weight and finger location scenarios as described by the graph titles.

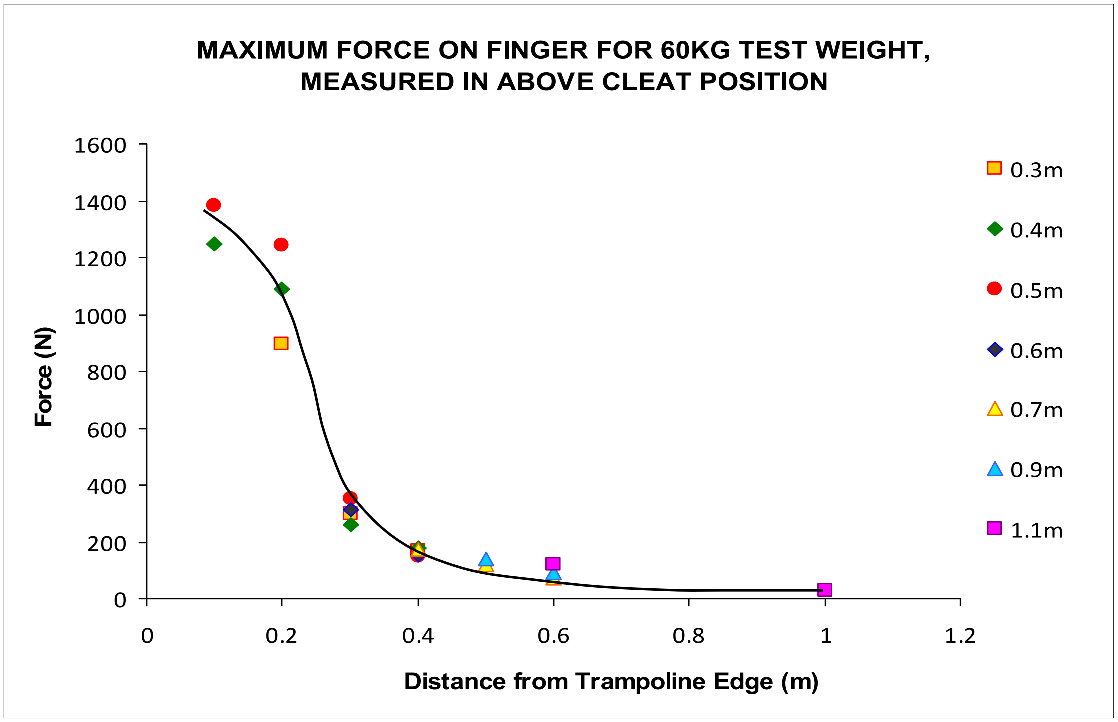

Figure 2.11

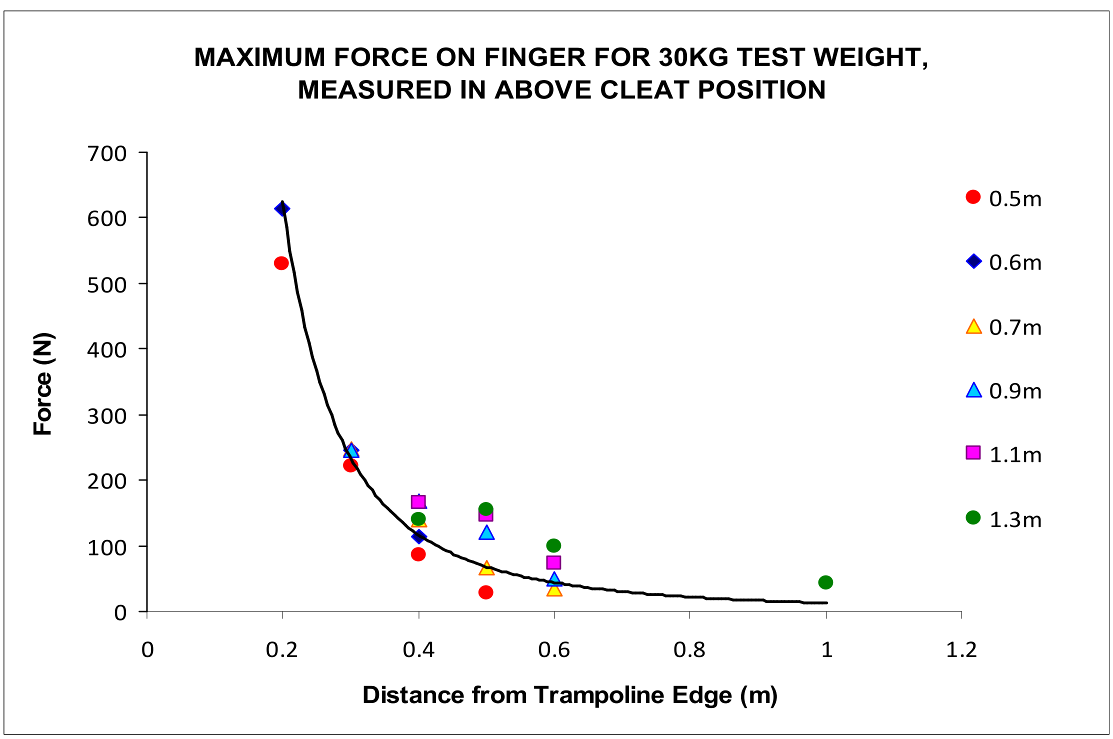

Figure 2.12

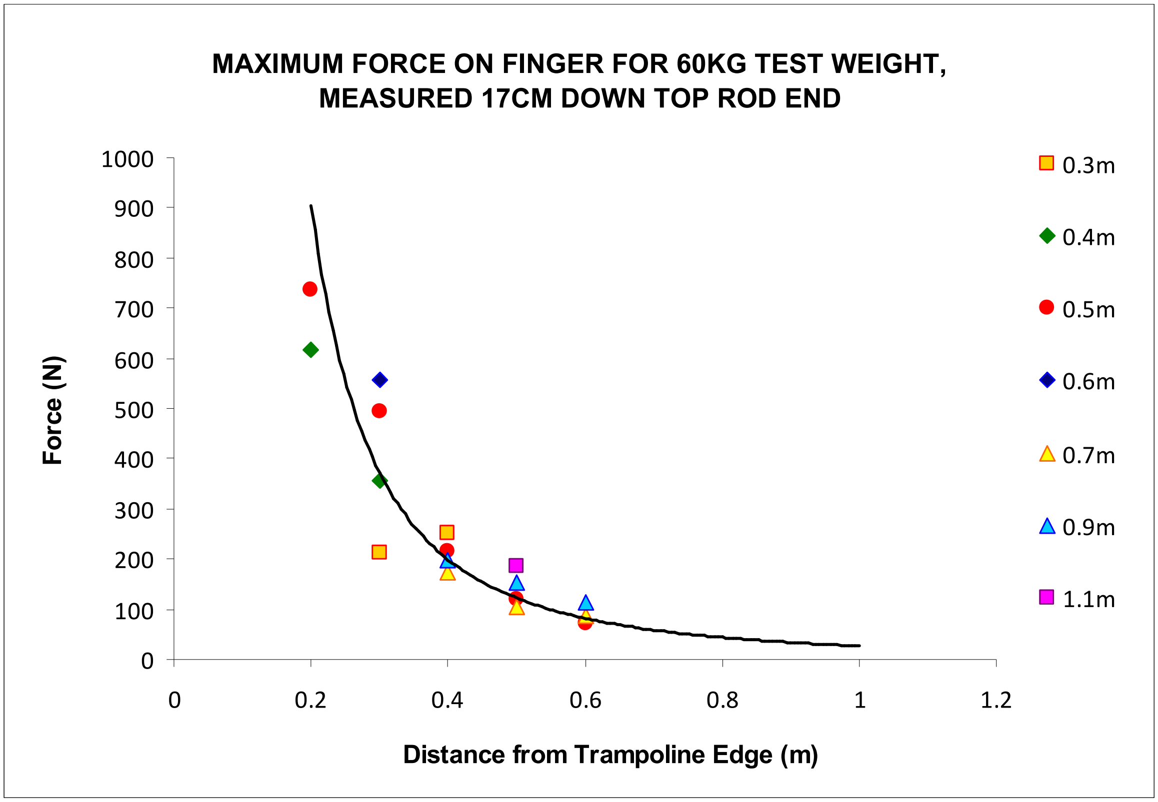

Figure 2.13

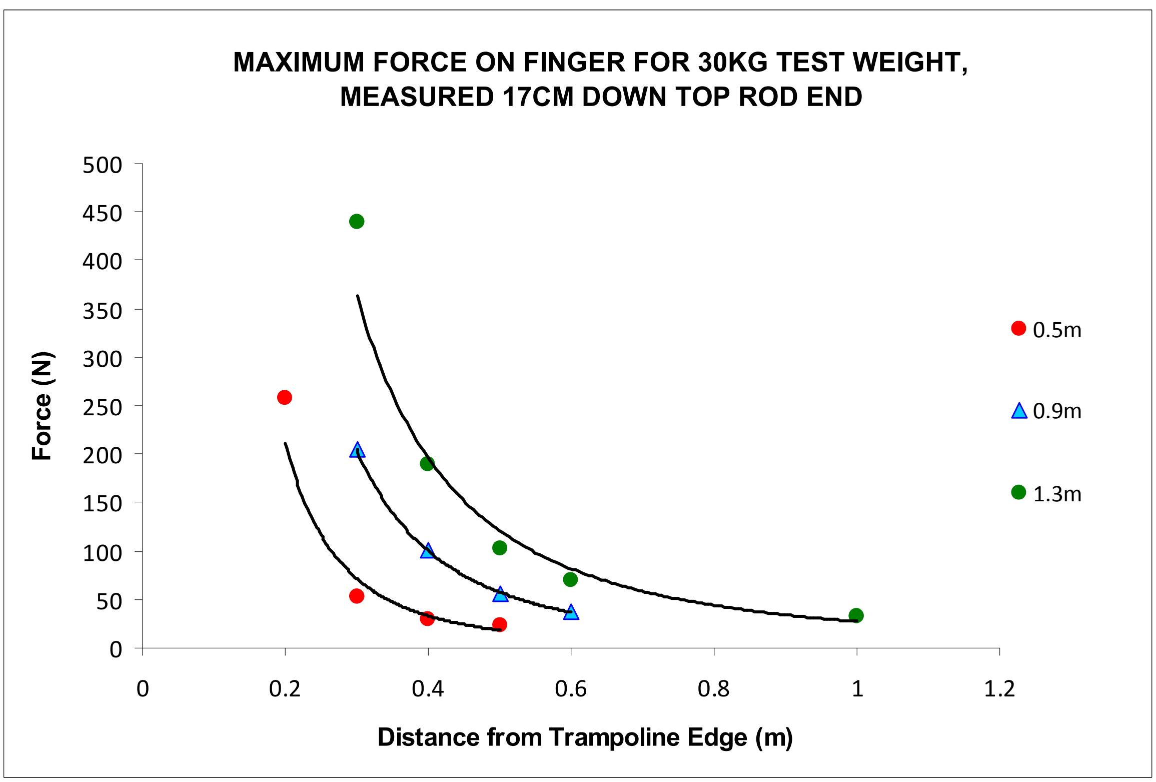

Figure 2.14

Effect of Jumping Location

The force experienced by a finger in between two spring rods is closely related to the distance away from the trampoline edge the jumper is jumping at. The closer to the edge the jumper is, the greater the force a finger is likely to experience. As the jumper moves away from the edge of the trampoline, the force on the finger rapidly drops off. It can be seen from all of the figures above that there is always an at least 50% reduction in the force, when moving the test ball impact point from 0.2m to 0.3m from the edge. Past 0.4m from the edge, the force measured remains relatively constant and low, and past 0.8m from the edge, virtually no force was detected.

The reason for the described trend is obvious: when the jumper is close to the edge of the trampoline the impact force of the jumper is distributed over a small portion of all the spring rods. Therefore the spring rods closest to the side of the jumper will tend to deflect more and cause a greater force on a finger. In contrast, when the jumper is jumping in the middle of the trampoline, his/her impact weight is distributed over the entire circle of spring rods, therefore the amount of deflection each spring rod undergoes will be insignificant, which was the reason that no force at all was detected by the load cell mechanism when the test ball was dropped far from the edge.

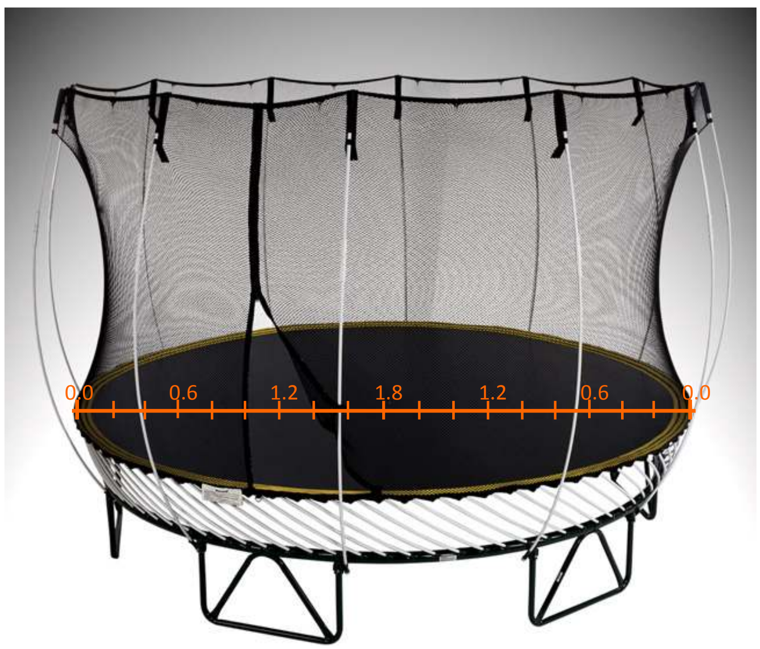

Figure 2.15 SF90 trampoline with scale shown across diameter

As mentioned earlier, the hour-glass shape of the Springfree enclosure net prevents jumpers from jumping closer than 0.2m to the trampoline edge. Figure 2.11 suggests that even if one intentionally landed on the edge, the maximum force on the bystander's finger would not grow without bound approaching the extremity of the trampoline edge.

Effect of Jump Height

In general the higher the jumper jumps, the greater the potential energy he/she possesses and therefore will land on the trampoline with a greater amount of momentum, causing higher closing forces in between the spring rods. However Figure 2.11 and 2.13 show that in the cases of measurement taken at above cleat position, it appears that apart from drops close to the edge, the drop height of the test ball made no significant contribution to the variation in the forces detected. On the other hand in Figure 2.14, which is for the case of 30kg drop weight with measurement taken at 17cm down rod position, each of the three drop height series has its own distinct trendline. In this graph, the trendlines only converge after 0.8m from the trampoline edge.

This phenomenon is due to the way the spring rods deflect after the jumper's impact. While the bottom of the rods has little movement during deflection, the top of the rods always closes right up to similar extent, regardless of how high the jumper jumps from.

Effect of Measurement Location

The location of the load cell mechanism (finger) also contributes to the magnitude of the force applied by the closing spring rods. In cases where the test ball is dropped close to the edge, the forces measured with the load cell mechanism attached in above cleat position are noticeably higher than those measured with the load cell 17cm down rod end. For example, at 0.2m the force obtained with 60kg test ball released from 0.5m is 1243N (124.3kg) if the measurement was taken in the above cleat position, whereas for the mid-rod position case, the force is only 737N (73kg). This further shows that the worst case scenario for a finger to be placed is indeed at above cleat position.

Effect of Jumper Weight

It can be seen from the scales of the graphs that for both the above cleat case and mid-rod case that the magnitude of the forces obtained with the 60kg drop weight is about double of that obtained with the 30kg drop weight. This is expected as doubling the weight doubles the energy with which the jumper impacts the mat.

Likely Force Prediction

The likely jump height of both adult and child are different at different positions in the trampoline. For example, at the centre of the trampoline under normal use, an average adult weighing 60kg is able to achieve a maximum jump height of 1.5m, while at the edge of the trampoline, the same jumper will not be able to any higher than 0.5m. Table 2.2 shows the likely maximum jump height of both adults and children at various test positions on the SF90 trampoline.

Distance From Edge (m)	Likely Jump Height (m)	
	Adult	Kid
0.2	0.5	0.3
0.3	0.6	0.4
0.4	0.7	0.5
0.5	0.8	0.6
0.6	0.9	0.7
0.7	1.0	0.8
0.8	1.1	0.9
0.9	1.2	1.0
1.0	1.3	1.1

Table 2.2 Likely jump heights

Figure 2.16 and 2.17 below show the most likely force on a bystander's finger for the likely jump heights the jumper is able to achieve at various points on the trampline.

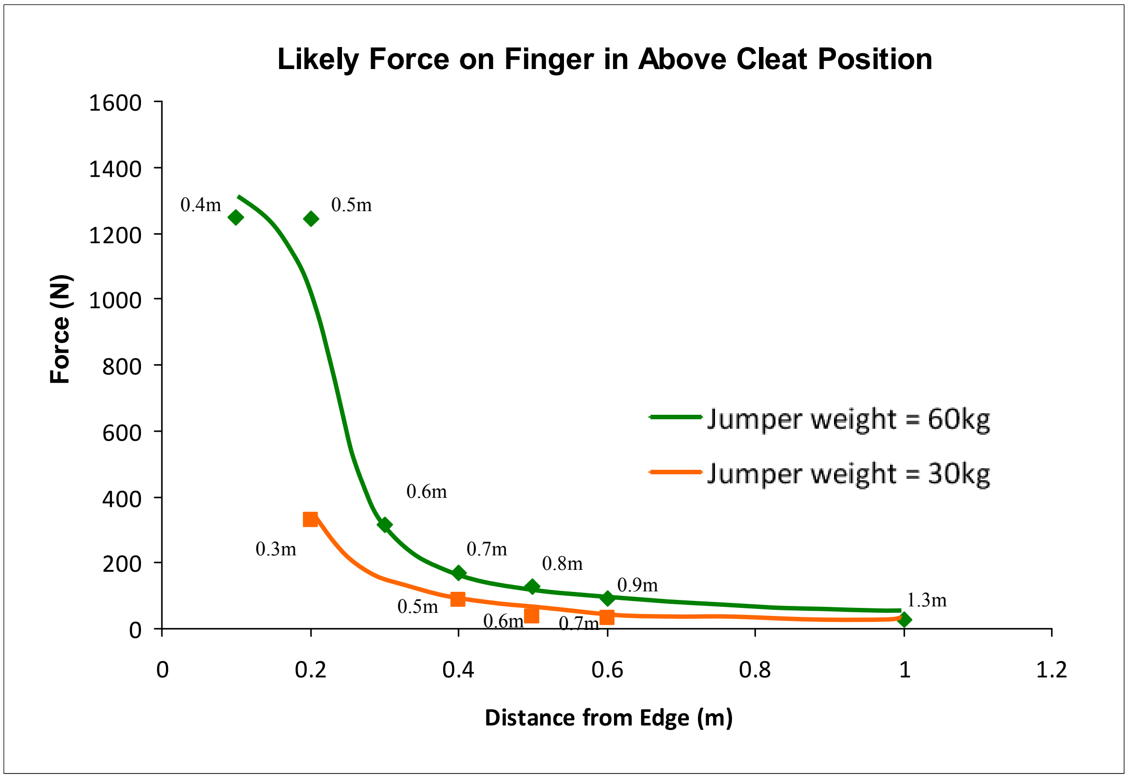

Figure 2.16

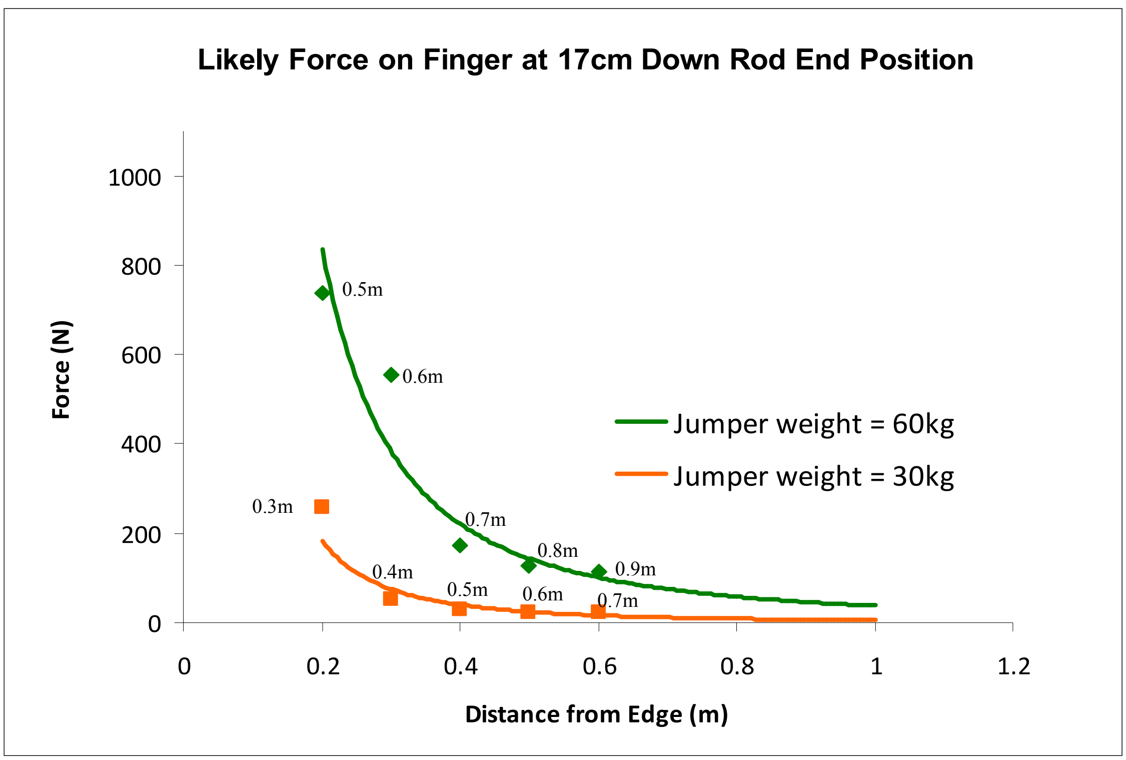

Figure 2.17

Finger Strength Calculations

Research into human bone properties found that:

- The compressive transverse strength of human adult femur bones is 131MPa. [2]
- The shear strength of human adult femur bones is 65 – 71MPa. [2]
- Children's bones are generally more flexible than adult bones. This means that they tend to tolerate a larger amount of deflection before breaking. [5]

No data on children bone strengths were found, therefore they are conservatively assumed to be the same as those of adults in the following calculations.

Compressive Force Calculation

Compressive force is applied to a finger when two closing spring rods are directly above and below the finger.

The impression on the finger by a spring rod can be approximated by an ellipse of the shape shown in Figure 2.18. The cross section area of a human phalange is approximated to be circular.

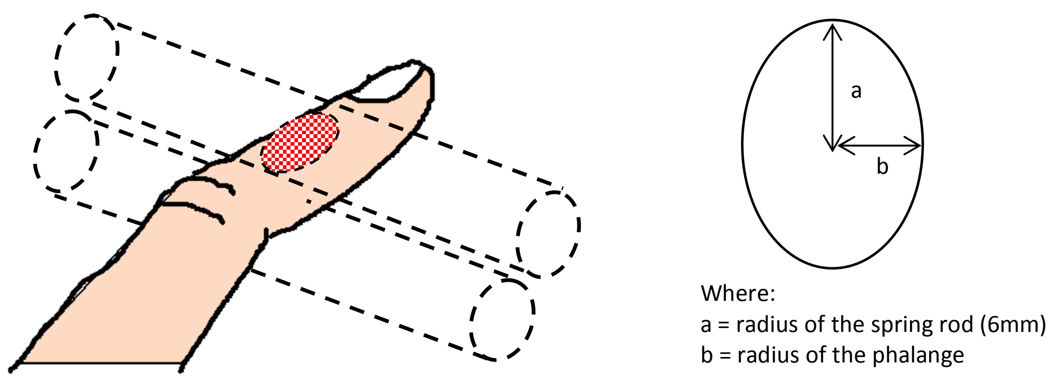

Figure 2.18 Impression on finger made by spring rod

An average adult typically has a phalange size of around 8mm in diameter. The minimum compressive force required to break an adult's finger is estimated by the compressive strength the bone multiplied by the contact area between the rod and the phalange. The area of an ellipse is given by $A = \pi \cdot a \cdot b$, therefore the compressive force required to break an adult's finger is:

$$F_{adult,compress} = 131MPa \cdot \pi \cdot 0.004m \cdot 0.006m = \underline{\underline{9877N}}$$

For a child with a phalange diameter of 6mm, the minimum compressive force required to break the child's finger is:

$$F_{child,compress} = 131MPa \cdot \pi \cdot 0.003m \cdot 0.006m = \underline{\underline{7408N}}$$

The calculations show that for both adults and children, the magnitude of compressive force required to break a human finger bone in the transverse direction is substantial.

Shear Force Calculation

Shear force is applied to a finger when the lines of action of the closing spring rods are misaligned as shown in Figure 2.19.

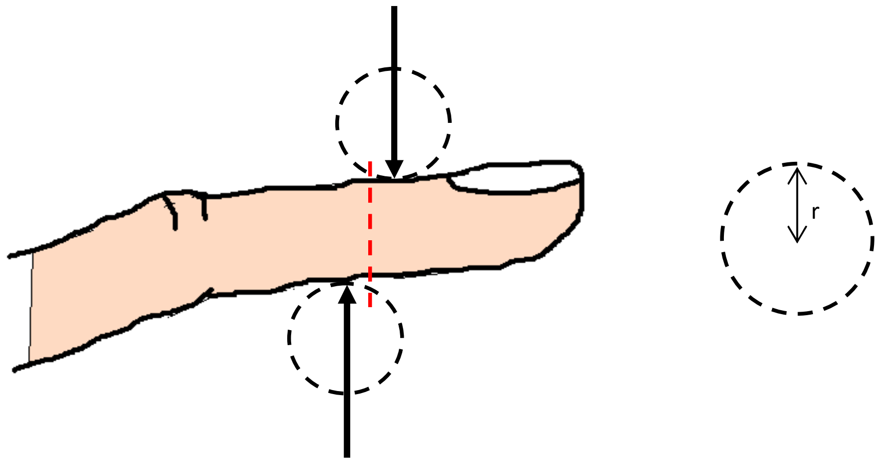

Figure 2.19 Shear force applied on finger

The shear force on a finger is found by multiplying the shear stress applied to the finger and the cross sectional area of the finger. In this case it is assumed that the human phalanges have circular cross section, with $Area = \pi \cdot r^2$. Using the same phalange dimensions as the previous calculations, the minimum shear forces needed to break an adult's and a child's fingers respectively are:

$$F_{adult,shear} = 65MPa \cdot \pi \cdot (0.004m)^2 = \underline{\underline{3267N}}$$

$$F_{child,shear} = 65MPa \times \pi \cdot (0.003m)^2 = \underline{\underline{1838N}}$$

The calculation shows that the magnitudes of shear forces required to break an adult's and a child's finger are both significantly lower than the compressive force thresholds.

Carrot Analogy

For comparison, the ultimate compressive strength of a carrot is found to be approximately 1.7MPa (13% of the strength of a human finger) [4].

Experiments were carried out to determine the breakage force for carrots with diameters of 25mm. Carrots were placed in between spring rods over a bathroom scale. Compressive force was gradually applied, and the magnitude of the force was monitored using the bathroom scale. The average force at which the carrots broke was found to be 30kg (300N).

The above results are useful information that gives a rough indication of the likely significance of the experimental results. Figure 20 and 21 below show graphically how the measured forces compare with the various threshold forces.

The graphs show that while the carrot breaking force can be easily exceeded in most situations, there is no tested case in which the forces obtained surpass the 1838N (183kg) threshold force required to break a child's finger by shear. The chosen scales of the graphs do not allow the other threshold breakage forces to be plotted. But since the shear force required to break a child's finger is the smallest threshold force amongst all cases, it is safe to state that **under normal circumstances**, it is unlikely for any bystander's finger to be broken by closing spring rods.

Note, normal circumstances do not include extreme uses of the trampoline, such as deliberately jumping close to the edge, jumping off higher objects onto the trampoline etc.

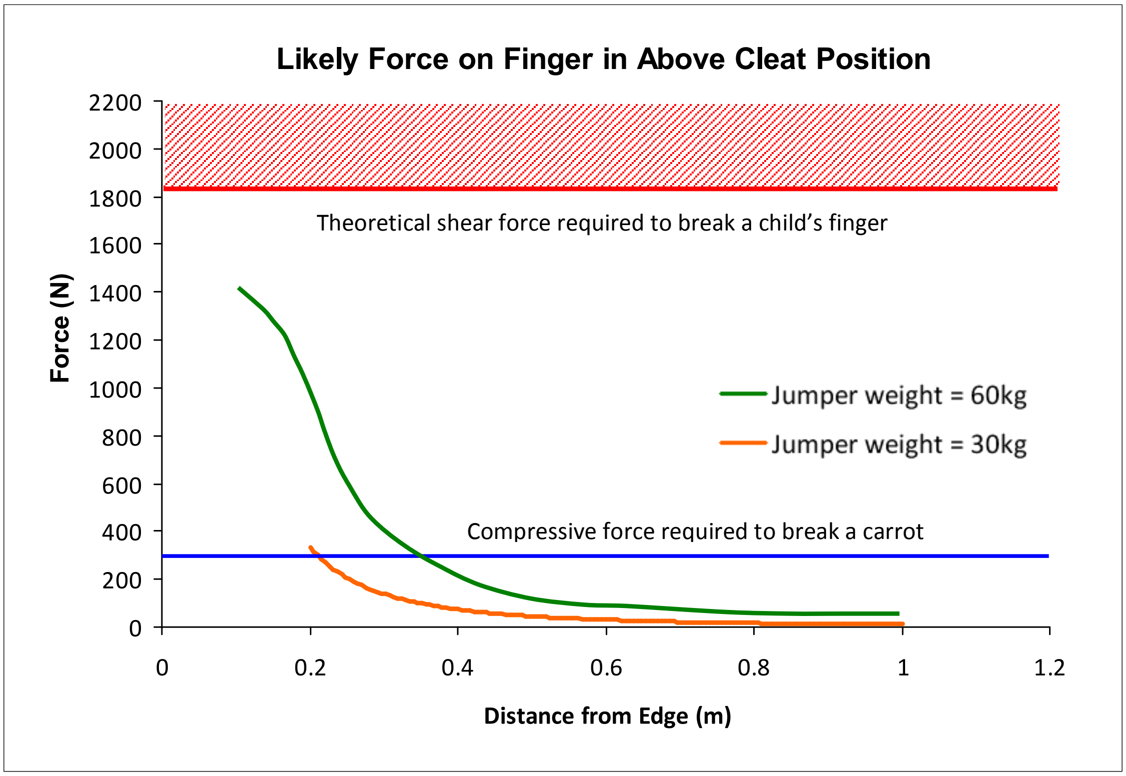

Figure 2.20

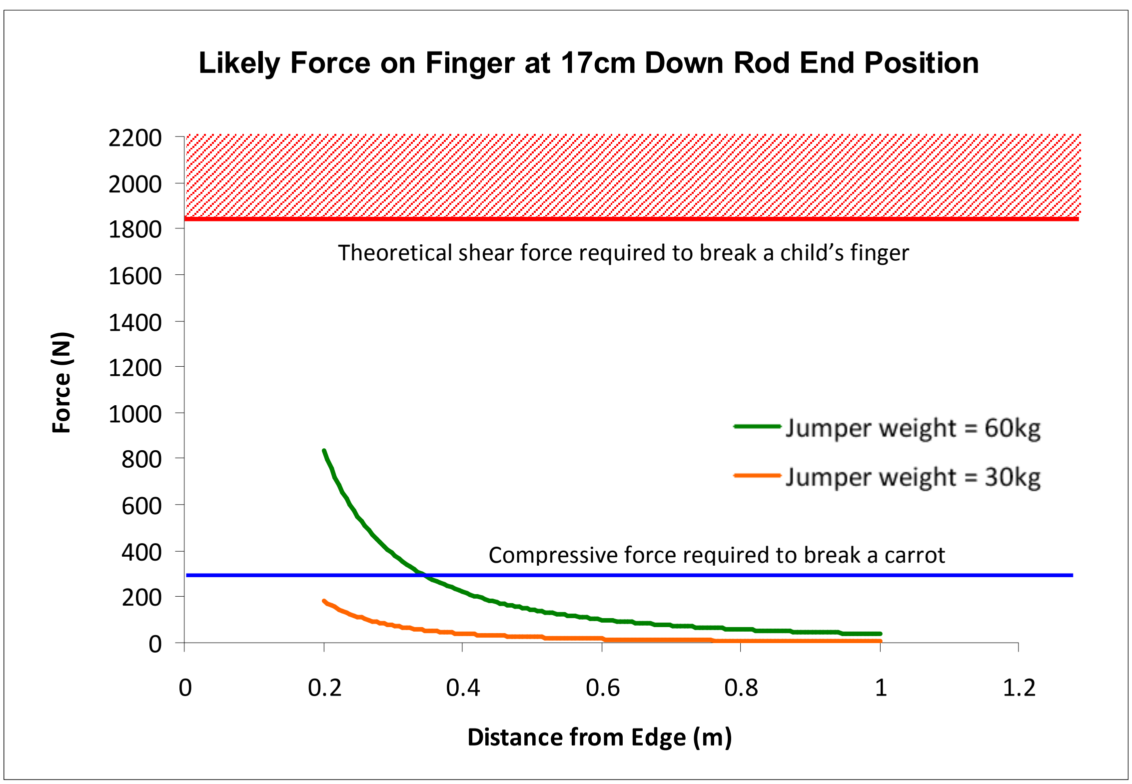

Figure 2.21

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Conclusion

At the time of the test, the Springfree SF90 trampoline did not present any situations that would suggest definitive occurrence of a bystander's finger being broken by closing spring rods, when misplaced.

The maximum force measured out of all test runs was 1385N (141kg). This was for the case of a 60kg test ball weight dropped at 0.1m from the edge of the trampoline, from a height of 0.5m.

The likely force on a bystander's finger will be limited to a safe level as long as the jumper does not jump within 0.2m from the trampoline edge.

In general, mature and knowledgeable supervision should be present **at all time** to prevent the misplacement of bystander's body parts.

It must be noted that calculations and predictions in this report are based on consideration of the normal use of the SF90 trampoline only. Any attempt to deliberately operate the trampoline outside its recommended normal use may result in severe consequences.

Further investigation into the correlation between the force experienced by a finger and the chance of injury is recommended if more meaningful information is to be extracted from this test.